PHYSIOLOGICAL RESPONSE TO BREATHING HOT AIR.

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Introduction.

The following investigation was made, at the request of the Mine Rescue Research Committee of the Safety in Mines Research Board, as to the upper limit of temperature at which air can be breathed without distress under various conditions. During the use of self-contained breathing apparatus in rescue work, the air circulating in the apparatus becomes heated and saturated with moisture, and the question arises of the limiting temperature of inspired air that a man can tolerate while resting and while doing work, and which is therefore permissible for an apparatus.

Most of the data collected and published on this subject relate to the physiological effects on man of exposure to a heated atmosphere, whereas in connection with self-contained breathing apparatus the problem arises in a modified form, since the effects of breathing heated air must be considered independently of the environmental conditions to which the subject is exposed.

Haldane (1914) has published certain data with regard to the local effect of air at a high wet-bulb temperature on the upper respiratory passages. In these experiments, the subjects entered a chamber where the temperature and humidity could be controlled. It was found that at 130° F. wet bulb, there was a sharp burning sensation in the throat when breathing became deep, which made work impossible; ordinary quiet breathing was more or less painful. The same effects were observed, though to a lesser degree, at 125° F. and at 121° F. wet bulb. At a wet-bulb temperature of 113° F., the air was not too hot to breathe freely, even during hard work.

This is the only information yielded by a study of the literature as to the local effect of breathing heated air. The experiments to be described were therefore planned in order to yield data relating in the first place to the local effects on the respiratory tract of breathing heated air—moist and dry: secondly, to give information as to the effect of breathing such air on the subject's physiological state.

Methods.

The apparatus used to supply air of the desired temperature and degree of moisture had to be modified according to whether moist or dry air was wanted. The general arrangement, however, was as follows. Room air was driven through a series of heated chambers by a small motor-driven blower, to be

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delivered at the subject's mouthpiece. The air first entered a chamber of about 10 cubic feet capacity heated by an electric radiator; from here, it passed through a length of 6-inch iron piping heated by gas burners into a second chamber similar in size to the first, heated by a radiator and containing an electric fan to ensure thorough mixing of the air so that the temperature was uniform. From the side of this second chamber a short length of rubber and metal tubing led to the mouthpiece. In this tubing, a few inches from the mouthpiece, were inserted two thermometers, a dry bulb and a wet bulb. No valves were used, as the air-flow past the mouthpiece was sufficient to prevent any rebreathing. When moist air was required, steam was passed into the mixing chamber until the air was saturated. The subject breathed through an ordinary rubber mouthpiece, wearing a nose clip. It appeared possible that with this arrangement there might be some cooling of the heated air between the thermometers and the mouth; during several experiments therefore a wet-bulb thermometer was inserted in the metal holder of the mouthpiece. In most cases the difference in temperature readings was found to be negligible, but in one series of experiments, when the air flow was less rapid than usual, a difference of about 5° F. was recorded; in this series the wet-bulb readings were taken directly from a thermometer held in the mouthpiece connection.

The subjects who underwent the tests were by occupation miners and members of rescue teams. They may therefore be considered healthy, intelligent men and accustomed to wearing respiratory apparatus. Each subject was examined before the test, special attention being paid to the chest, cardiovascular system, and the state of the mouth and pharynx. The temperature of the inspired air, the subject's body temperature (axillary), respiration rate, pulse rate and blood pressure were recorded at regular intervals throughout each test. Fifteen-minute intervals were used when the subject was resting, and ten-minute intervals while working. The work consisted in pedalling a bicycle ergometer, and was roughly equivalent to walking at four to five miles per hour. During a prolonged period of work, five-minute rest intervals were allowed after each thirty-minute working period.

RESULTS.

A. *Water-saturated air.*

(i) *Subjects at rest.* A series of ten tests was carried out on subjects sitting at rest. The temperature of the inspired air was allowed to rise in steps of approximately 5–10° F. during the test, commencing with wet-bulb temperatures between 95° and 110° F. The duration of the tests varied from 1 hr. 10 min. to 2 hr. 30 min., the average being 2 hr.

No subject experienced any discomfort until the wet-bulb temperature of the inspired air reached 130–135° F. Above 135° F. complaints were made of the heat of the air, and the experiment was terminated when the subject found the heat distressing. The wet-bulb temperature at this point varied from 138–

150° F.; six of the ten subjects found that the limiting temperature lay between 145° F. and 148° F. wet bulb.

When the inspired air reached a wet-bulb temperature of 140–145° F. the subjects began to complain of a burning sensation, which was felt most constantly over the hard palate and at the back of the throat. Some subjects also complained of "burning of the tongue and gums," and one subject spoke of a peculiar sensation in the chest, as though his lungs "were being drawn together," while breathing air at a wet-bulb temperature of 150° F. Several subjects said they subsequently suffered from slight soreness of the gums, which lasted a few days, but no other after effects were observed, the burning of mouth and throat disappearing as soon as the mouthpiece was taken out.

In none of the ten tests was any change observed in body temperature or blood pressure as a result of varying the wet-bulb temperature of the inspired air. The pulse and respiration rates of certain individuals showed some change; a slight rise of pulse rate was observed in two subjects when the wet-bulb temperature of the inspired air rose above 130° F., but the change was not significant. Five subjects, however, showed a rise in respiratory rate either at temperatures above 130° F., wet bulb, or just before the limiting temperature of 145° F., wet bulb, was reached. The change in rate was usually accompanied by a change in the type of breathing. In some subjects the rate became irregular, in others the depth of respiration diminished; in a certain number of subjects both changes were observed. The greatest changes in respiration rate observed were from 10 to 18, and from 18 to 26 per minute.

The mouth and throat of the subject were re-examined after each test; some reddening of the fauces and pharynx was constantly found, and in one instance a patchy reddening of the hard palate was observed.

Consideration of these results suggested the possibility that on account of the gradual rise in temperature of the inspired air the subject was able to tolerate higher temperatures than would otherwise be possible. Two experiments were therefore made, in which the subject breathed air at a temperature just below the limit of tolerance for a period of 2 hours. Two subjects were chosen: one (limit of tolerance, 150° F.; inspired air, 141–145° F., wet bulb) who had shown no appreciable change in respiratory or pulse rate in the previous test; the other (limit of tolerance, 148° F., inspired air, 134–140° F., wet bulb) had shown a rise in respiratory rate at the upper limit of temperature and a slight rise in pulse rate. Neither subject showed any marked response. The respiratory rate of the second subject rose slightly when the temperature of the inspired air was allowed to rise to 148° F. at the end of the test, but no appreciable change in pulse rate occurred. In each case the highest temperature at which the air was tolerated agreed closely with the limit found in the previous test.

These two experiments indicate:

(*a*) That the temperature of inspired air which can be borne is the same whether the temperature is raised gradually or suddenly.

(*b*) That a prolonged period (up to 2 hr.) of breathing air at a wet-bulb temperature above 135° F. has no more effect on pulse or respiration rate than a similar period during which the temperature of the air is raised from 95 to 145° F.

(ii) *Subjects doing work.* A similar series of experiments was carried out on subjects doing work. The series comprised eleven experiments. Five subjects had already undergone a test in the previous series.

The subject pedalled the ergometer at a speed of 60 revolutions per minute for 2 or 3 half-hour periods; the load was such that the work done was equivalent to walking at 4 to $4\frac{1}{2}$ miles per hour. During the experiment the temperature of the inspired air was allowed to rise gradually; the pedalling was stopped when the heat of the air caused distress. Each subject was tested for his limit of tolerance while sitting at rest, to serve as a comparison with the previous series of experiments.

In no case was any discomfort experienced until the wet-bulb temperature of the inspired air reached 125° F.; between 125 and 130° F., most of the subjects began to complain of the heat. The heat was felt in every case on the roof of the mouth, and less frequently on the back of the throat, the tongue and the gums.

On examination of the mouth and throat, seven of the eleven subjects showed definite reddening of the palate, fauces and posterior pharyngeal wall. No pain or discomfort persisted, however, after the test was over.

There appeared to be little variation in the body temperature, blood pressure, pulse or respiration rate with changes in the wet-bulb temperature of the air breathed. The average axillary temperature was higher than when the subjects were at rest, as might be expected. Three subjects showed a slight rise in respiratory rate at temperatures of 125–135° F.; four subjects showed a similar slight rise in pulse rate. The changes, however, were not sufficiently clearly marked to be of importance. These variations were not of sufficient magnitude to affect the averages for the group, with the exception of the pulse rate, where the average figure does show a slight rise with temperatures above 125° F. (wet bulb). The temperature at which the air became distressingly hot to breathe varied from 129–147° F. (wet bulb); eight of the eleven subjects, however, had a limit of tolerance lying between 130 and 138° F. (wet bulb).

It was observed during the experiments described above that marked sweating occurred in most cases. The onset of sweating was usually noted when the wet-bulb temperature of the inspired air reached 115–120° F. This may have been due merely to the fact that the temperature conditions were kept as uniform as possible, and the onset of sweating may have been related rather to the duration of work than to the temperature.

In an attempt to elucidate this point, and to confirm the conclusion that there was no appreciable variation of pulse or respiration rate with changes in temperature, a further series of experiments was undertaken.

Each subject performed a measured amount of work under conditions

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which varied only in the wet-bulb temperature of the inspired air; the same amount of work was done while breathing room air (wet-bulb temperature about 50° F.), air between 90 and 100° F. wet bulb, and air at about 130° F. wet bulb. Two half-hour periods of work were done in each experiment, and the wet-bulb temperature of the inspired air was kept as nearly as possible constant at the chosen level.

A series of four subjects was tested in this way: each subject stated that the temperature of the air breathed made no difference to the apparent ease of working; that, on the whole, air at 90–100° F. wet bulb was most pleasant, as the drying effect of room air was not experienced. Air at 130° F. wet bulb was felt to be too warm for comfort.

No consistent change in pulse or respiration rate was observed as a result of raising the wet-bulb temperature of the inspired air. There was, however, a general tendency for the respiratory rate to rise with temperature, and transient rises of pulse rate were frequent, while air at 130° F. was breathed. This accounts for the marked rise in pulse rate at 130° F. observed in two subjects. No appreciable change was observed in body temperature or in blood pressure. It was not possible to make quantitative measurements of sweating, but gross differences in the amount of sweat could be detected by careful observation of the subject. It was found that sweating was definitely greater in amount when the subject breathed air at 95° F., wet bulb, than when air at 50° F. wet bulb was breathed; indeed, in several instances this was commented on by the subject himself. In two cases the sweating, while breathing air at 130° F. wet bulb, was thought to be more than at 95° F., but in another two cases no difference could be detected.

B. *Dry air.*

(*i*) *Subjects at rest.* The inspired air during these experiments was kept as dry as possible; the wet-bulb temperature never rose above 120° F.

Five subjects were tested while sitting at rest. As in the experiments with moist air, the temperature of the inspired air was gradually raised until a point was reached when the subject began to feel distress. Until the temperature of the inspired air rose to 250–300° F. no serious discomfort was experienced; above this temperature the most constant complaint was of dryness of the mouth and throat, eventually becoming intolerable. Two subjects complained also of a feeling of heat on the roof of the mouth and at the back of the throat, but this was not enough to cause distress.

With the exception of one subject, who found air at 270° F. too hot for comfort, the limit of tolerance varied between 330 and 367° F. When the temperature rose above 300° F., coughing was a frequent and troublesome symptom.

Examination of the mouth and throat after the test revealed that three subjects showed some reddening of the fauces, the palate, and the posterior pharyngeal wall; this effect, however, was not as marked as was the case after breathing hot moist air. In no case was there any change in body temperature, blood pressure, pulse or respiration rate as the temperature of the inspired air was raised.

(ii) *Subjects doing work.* The same subjects were also tested while pedalling the ergometer. Again the chief complaint, as the temperature of the inspired air rose, was of dryness rather than of burning. There was a marked difference, however, between the temperature that was tolerated while resting and while working.

When the subjects were doing work, no complaint of discomfort was made until the temperature of the inspired air reached 200° F. Above this temperature the subjects complained of extreme dryness of mouth and throat, and coughing was frequent. The limit of tolerance for the five subjects lay between 200 and 220° F.

No change in body temperature, blood pressure, pulse or respiration rate could be detected as a result of raising the temperature of the inspired air. Examination of the mouth and throat showed effects similar to those found after the subjects had breathed hot air dry while sitting quiet.

Three subjects showed a considerable degree of sweating after 10–15 min. work, while breathing air at a temperature of 190–210° F., but in the absence of quantitative measurements it was impossible to decide whether the onset of sweating was earlier, or its degree more marked than in subjects doing an equal amount of work while breathing room air.

DISCUSSION.

The local effects of breathing heated air must depend on the susceptibility of the mucous membrane of the respiratory tract to heat, and on the extent of cooling which is possible as the air passes through the upper passages into the lungs. It is a matter of common experience that the mucous membrane of the mouth is less sensitive to heat than the skin, and the results described are in agreement with this fact. When the breathing is quiet, air at a wet-bulb temperature of 145° F. can be tolerated by the majority of subjects. This is about the temperature at which proteins begin to undergo a change, and is probably therefore approaching the temperature at which the physico-chemical state of cell protoplasm is affected.

It must be remembered that in quiet breathing the air flow in the respiratory tract is comparatively slow, and considerable opportunity is given for the inspired air to cool before it reaches the lungs. During quiet breathing, therefore, the limiting temperature probably only gives information as to the highest temperature tolerated by the mucous membrane of the mouth.

When the subject is doing work, his total ventilation is increased four- or five-fold, with a corresponding increase in the rate of air-flow through the respiratory passages. The volume of air taken in at each breath increases too in relation to the volume of the dead space. Both factors must combine to increase the temperature of the air in contact with the lower respiratory passages and lung alveoli. This may serve to explain the lower limiting temperature found for the inspired air when the subjects were doing work.

When dry air is breathed, it rapidly becomes saturated with water, as expired air is practically saturated whatever the percentage saturation of the inspired air. The evaporation of water from the respiràtory tract to effect this saturation must cause considerable cooling of the air. In this connection it is interesting to note the extreme discomfort caused by dryness of the mouth and throat in subjects breathing hot dry air. The same considerations apply to the rate of saturation and therefore of cooling as were advanced in discussing the cooling of hot moist air. But, as would be expected, this mechanism of evaporation is much more effective than the conduction and radiation of heat that supposedly bring about the cooling of moist air. For this reason the limiting temperature during quiet breathing of hot dry air is very high.

This process of saturation, though rapid, must occupy an appreciable time. When the air flow through the respiratory passages is greatly increased, as during the increased ventilation resulting from bodily exertion, the air must reach saturation at a lower level of the respiratory tract. Thus, the difference observed between the limits of tolerance for hot dry air when the subject is resting, as compared with the working periods, can be explained along the same lines as when hot moist air is breathed. The more marked difference found when dry air is breathed is due to the greater efficiency of evaporation as a cooling mechanism. For when dry air is breathed, the gradient of temperature fall of the air in the respiratory tract is steeper than with moist air. The result, therefore, of hastening the air flow will be quantitatively greater with dry than with moist air.

General effects on the subject's physiological state might be brought about by (*a*) impeding the normal heat loss, (*b*) reflex actions set up by local stimulation of the respiratory tract by heat.

As regards heat-loss, the importance of the respiratory tract depends on the environmental conditions of the subject. Bazett (1927) states that 4 to 5 calories per hour are lost from the lungs during quiet breathing of moderately dry air: this is about 7 per cent. of the total heat-loss per day. When saturated air at or above body temperature is breathed, this method of heat-loss is abolished: obviously, in a moderately cool atmosphere this is unimportant, but as the temperature and humidity of the atmosphere increase, impeding heat-loss from the skin, the possibility of heat-loss from the lungs becomes relatively important. The investigations described are limited to the effects of breathing hot air on subjects in a moderately cool environment, and further discussion of this point is therefore outside the scope of this paper.

There is no evidence of any reflex action on the circulation or respiration as a result of raising the temperature of the inspired air, with the possible exception of the increased respiratory rate found when air at a wet-bulb temperature over 130° F. was breathed. This is of interest in view of Heymans' (1919) work on the effects of heating the blood supply to the brain.

CONCLUSIONS.

1. When subjects sitting at rest in a cool environment breathe hot moist air, the limit of tolerance lies between 140 and 150° F. (wet bulb), average 146° F. (63·3° C.).

2. When subjects under similar environmental conditions are doing work, the highest temperature at which moist air can be breathed is between 130 and 140° F. (wet bulb), average 135° F. (57·2° C.).

3. The local effects of breathing air at temperatures approaching these limits are: (*a*) A transient sensation of burning in mouth and throat, (*b*) reddening of palate, fauces, and posterior pharyngeal wall.

4. With subjects at rest, the only general effect usually observed as the temperature approaches the limit of tolerance is an increase in the rate of respiration, with some irregularity of rhythm.

5. With subjects doing work, sweating is noticeably greater when the wet-bulb temperature of the inspired air is above body temperature.

6. The limits of tolerance for subjects breathing hot dry air lie between 270 and 367° F. (dry bulb), average 335° F. (168° C.), while subjects are at rest. The corresponding limits while the subjects are doing work lie between 200 and 220° F. (dry bulb), average 212° F. (100° C.).

7. The local effects of breathing dry air at temperatures approaching these limits are: (*a*) extreme dryness of mouth and throat, with a slight sensation of burning in some subjects; frequent coughing, (*b*) slight reddening of palate, fauces, and posterior pharyngeal wall in some subjects.

8. No general effects were observed as a result of breathing hot dry air.

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