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Influence of heat exposure on productivity

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Axelson, O. **Work-environm.-hlth 11 (1974) 94—99.** *Influence of heat exposure on productivity.* An approximate and computationally simple formula for the prediction of relative reduction in work capacity due to heat stress is proposed. The applicability of the proposed model is tested using experimental data on heart rates, sweat rates, and metabolic rates accounted for in the literature. The agreement between the predicted and observed values on productivity reduction was in most situations found to be fairly good. Recommendations for the air velocity parameter value and the temperature scale to be used are suggested. Consideration is also given to the nature of the basic data as well as to the need for complementary practical observations.

Heat stress involves cardiovascular strain because of demands for blood flow to the periphery for thermoregulatory purposes. Thus, with increasing heat load the cardiac output available to active muscles will be reduced. When the combined demands from thermoregulation, i.e., for transportation of heat from body core and active muscles to surface and from oxygenated blood supply for working muscles exceed the maximum cardiac output, then the upper limits of tolerance are reached and work output must be reduced.

High humidity and low air velocity in combination with heat exposure will particularly tend to reduce working capacity by restricting sweat evaporation. Work performance in the hot environment is also influenced by the possibility of adequate salt and water supplementation as well as by individual characteristics, acclimatization, etc.

Sometimes climatic conditions make it impossible to reduce the undesired influence from heat stress on a group of workers, e.g., in outdoor work in a tropical or subtropical climate. Tropical forest work and farming are examples of this type of work. In these situations it may for different purposes be desirable to predict the costs of production as influenced by the heat stress on the workers.

INCREASING HEAT STRESS IN RELATION TO DECREASING PRODUCTIVITY

Wyndham (10) provides data about decrease in productivity with increase in effective temperature concerning miners in a high state of acclimatization and carrying out physical work at a moderate rate under direct supervision. He estimated that, at 25.5°C effective temperature (ET),** productivity is at 100 %; at 27.7° ET, it has fallen to 95 %; and at 32.2° ET it is as low as 70 % of the value at 25.5.° Wind was found to influence the reduction of productivity to a great extent, and the figures above refer to air velocities of 0.5 —2.0 m/sec.

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** Normal scale presumed and used in the text (centigrade).

PREDICTING THE THERMAL REDUCTION OF WORK OUTPUT

Obviously an attempt to generalize Wyndham's results on the reduction of productivity due to heat stress would be of great interest. However, such a generalization should not only be reasonably valid but also simple enough to permit convenient and practical applicability in predicting loss of work capacity with increasing heat stress. The previously mentioned data from Wyndham seem to imply a somewhat computationally laborious prediction model,* which hardly will achieve general and practical use. Therefore, a trial and error approach was undertaken to find a computationally simple approximation, fig. 1, which resulted in the following reasonably unsophisticated formula

$$R(t)\,\% = \frac{k(t - t_0)^2}{2t_0 - t} \qquad \text{(I)}$$

where R (t) % is the %-reduction of work capacity at temperature t°ET and $t_0 = 24°$ ET. The constant k might be taken as depending on air velocity with the value 9, when air velocity is about 0.5 m/sec (or k = 9.8—1.6 v, where v is air velocity in m/sec, varying from 0.5—2.0 m/sec in Wyndham's data). Also it should be pointed out that t, considering all day work, hardly will exceed 34° ET for obvious physiological reasons. (For rough approximations the formula might be taken as $R(t)\% = 0.5\ (t-t_0)^2$.)

APPLICATION OF PREDICTED LOSS OF WORK OUTPUT

Considering heart rates

It is necessary to ensure applicability for the proposed formula (I) by testing its predicting ability in different situations accounted for in the literature. First, therefore, consider some data provided by Brouha (5). In one of his experiments he used a work load of 540 kpm/min for 30 minutes followed by another 5 minutes of work at an output of 900 kpm/min at two different thermal conditions corresponding to 19° ET and 31.5° ET, respectively. The oxygen consumption did not differ, but at a work output of 540 kpm/min the heart rate averaged 130 and 150 beats/min, respectively, in the two situations. A total of 1,796 heart beats in excess of heart work in a resting state were needed at 19° ET whereas the same amount of work required 2,282 heart beats when heat stress was added. Also during the following 65 minutes of recovery, the hot environment resulted in 2,168 heart beats versus 1,212 beats for the more optimal condition. The difference in number of heart beats for the time of work and recovery will be 1,442 heart beats.

If this 100-minute experiment of Brouha's is extrapolated to an 8-hour working day, the first situation, i.e., 19° ET, will result in a total of 52,358 heart beats. This fairly well seems to correspond to the number of heart beats which can be expected during a day (8 hours) of hard work (3), if about 110 beats/min is assumed as a reasonable maximum time-weighted average of heart rate. However, in the hot condition the same number of heart beats is reached already after 5.4 hours, i.e., the heat stress will result in a theoretical work capacity reduction of (8 — 5.4)/8 × 100 % = 32.5 %, whereas actual loss of productivity probably would be considerably greater. Using the above proposed formula (I) the productivity reduction will be 30.7 % with $t_0 = 24°$ and 44.8 % by using $t_0 = 23°$ ET.

Considering sweat rates

A further possibility for evaluating the formula (I) is offered by calculations on sweat rates, i.e., by means of P4SR. Several authors have proposed different limits for heat stress as expressed by the P4SR. Thus, Löfstedt (8) used 1.6 l as the maximum P4SR in young, unacclimatized individuals. Hall (6) and Hall (7) proposed 3.0 l in African farming and railway maintenance, whereas Smith (9) suggested 2.5 l as a general recommendation. Man may reach a sweat rate of about 1 liter per hour, but a P4SR of 4 l during an 8-hour work period will probably result in a high dehydration if not very effective precautions are undertaken to provide water

* $R(t)\% = k_1e^{-at} - k_2e^{-bt}$ where $k_1 \sim 151$; $k_2 \sim 2 \times 10^{-6}$; $a \sim 1.8$ and $b \sim 0.5$ as suggested by computer analysis of work reduction data at an air velocity of 0.5 m/sec.

(and salt) supplementation. Therefore, a P4SR of about 2.0—3.0 l may be a more reasonable value during an 8-hour work shift in order to avoid adverse dehydration. Also, it should be observed that P4SR is a stress index not necessarily corresponding to the actual sweat rate.

However, if the average P4SR is assumed not to exceed a certain value, say 2 to 3 liters, during an 8-hour work shift, this means work capacity decreases when temperature increases so that P4SR will be stable in spite of the thermal load. Therefore, the productivity reduction predicted by the proposed procedure should be such that P4SR will stabilize at the same value independent of heat stress. Table 1 shows P4SR to be reasonably stabilized by using formula (I) with $t_0 = 22°$ ET instead of $t_0 = 24°$ ET as above was found to satisfy the data of Wyndham. Using the WBGT, $t_0 = 22.5,°$ will be consistent with the same order of work reduction as given by 22°ET. WBGT may even be preferable to the ET, making a somewhat better allowance for the deleterious effect of hot and humid conditions (see table for P4SR at 90 % relative humidity as well as reference 9).

Considering metabolic rates and proposed thermal limits

The predicted loss of productivity by formula (I) should also be compared to other, different limit values, which have been proposed to protect workers from adverse effects of heat stress. Botsford (4) used values from different authors (Yaglou, Lind, Blockley, Belding and Hatch) for indicating the maximum Wet Globe Temperature, which might be acceptable at various metabolic rates. His paper also indicates a reasonable consistency between these different authors considering permissible levels of heat exposure in relation to the metabolic rates. Thus, at 27° ET (derived from the corresponding Wet Globe Temperature) a metabolic rate of 330 kcal/h (which will correspond to a work output of 350 kpm/min (2) and which will be a maximal output (1) for long-term work) is tolerable but work capacity approaches zero when temperature increases through 32° ET. Further calculations show that about 50 kcal/h will be lost per incremental degree of ET. Therefore, a metabolic loss of about 100 kcal/h might be suggested at 29° ET, i.e., 200 kpm/min of work output remains of the original 350 kpm/min, or the productivity reduction is about 42 %. Correspondingly, at 30° ET the productivity reduction will be about 63 %. If the formula (I), $t_0 = 24°$ ET, is used, only 12 % and 18 %, respectively, are predicted. However, with $t_0 = 21°$ ET the loss will be 44 % and 61 %, respectively, which is in fairly good agreement with the data derived from Botsford's paper (see the following text).

Considering the recommendations by ACGIH

Finally, if the heat stress limiting curves of ACGIH (1) are compared to the predictive ability of formula (I), it is found that $t_0 \sim 21$—22° WBGT will give the best but not good consistency. Obviously, these curves, as well as the limit values taken from Botsford's paper and discussed above, are expected to protect even the more sensible individuals from adverse heat effects, and do not reflect the average heat sensibility of a group, which sensibility, however, will determine the productivity of the group under conditions of heat stress. Nevertheless, this discussion indicates that t_0 should be lower than that which would satisfy Wyndham's data, as his study group presumably represents an extremely good acclimatization, seldom at hand elsewhere. Therefore, a t_0 of ET 22 (— 23)° or a WBGT of 22.5 (— 23.5)° will probably give the best estimation by formula (I) for productivity reduction due to heat stress.

PRODUCTIVITY REDUCTION AND HEAT STRESS AS A RISK FACTOR TO HUMAN HEALTH

It must also be emphasized in this context that the proposed formula (I) for calculating the loss of productivity offers no protection of the workers concerning adverse effects from heat exposure. For this purpose other considerations and calculations should be made. On the contrary, Wyndham (10) also found heat strokes to occur at effective temperatures above

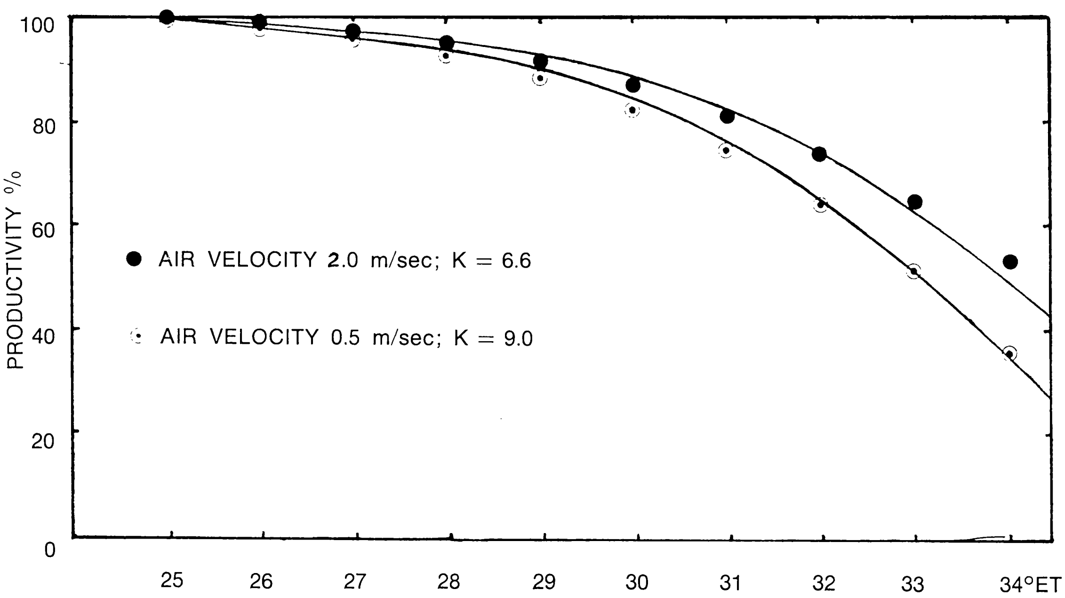

Fig. 1. Productivity reduction due to heat stress. The curves represent data provided by Wyndham (10), and the dots result from applying the proposed predictor formula (I).

Table 1. Investigating validity of formula $R(t)\% = \frac{k(t - t_0)^2}{2t_0 - t}$ by means of P4SR, air velocity at about 0.5 m/sec and k = 9, t_0 appears in the table. Moderate and hard work (192 W/m^2 resp, 262 W/m^2) is presumed to be carried out in overalls and shorts, respectively.

WB 70 % RH	DB 70 % RH	ET 70 % RH	WBGT 70 % RH	R(t)% at 70 % RH and t_0 = 22° ET	P4SR at the predicted loss R(t)%: t_0 = 22° ET 70 % RH — Work rate at 192 W/m^2	P4SR at the predicted loss R(t)%: t_0 = 22° ET 70 % RH — Work rate at 262 W/m^2	R(t)% at 70 % RH and t_0 = 22.5° WBGT
28	33	29.0	29.5	29.4	2.4 (1.6)	3.3 (2.2)	28.5
29	34	30.0	30.5	41.1	2.4 (1.6)	3.2 (2.1)	39.7
30	35	30.7	31.5	51.2	2.4 (1.6)	3.2 (2.1)	54.0
32	37	32.5	33.5	86.3	2.4 (1.7)	3.3 (2.0)	94.7

WB 90 % RH	DB 90 % RH	ET 90 % RH	WBGT 90 % RH	R(t)% at 90 % RH and t_0 = 22° ET	P4SR at the predicted loss R(t)%: t_0 = 22° ET 90 % RH — Work rate at 192 W/m^2	P4SR at the predicted loss R(t)%: t_0 = 22° ET 90 % RH — Work rate at 262 W/m^2	R(t)% at 90 % RH and t_0 = 22.5° WBGT
28	29.5	27.7	28.5	17.9	2.2 (1.3)	3.2 (2.0)	19.6
29	30.0	28.5	29.3	24.5	2.2 (1.3)	3.2 (2.0)	26.5
30	31.5	29.6	30.5	36.1	2.3 (1.5)	3.3 (2.1)	39.7
32	33.4	31.5	32.4	65.0	2.8 (1.7)	4.1 (2.1)	70.0

WB = wet bulb temperature
DB = dry bulb temperature
RH = relative humidity
ET = effective temperature (normal scale)

WBGT = wet bulb globe temperature, i.e., 0.7 × WB + 0.3 × GT
(Without radiation GT = DB; GT = globe temperature)

The work rates are the expected ones, from which reduction takes place.

27.7° and with a slowly increasing frequency up to 32.2°; then the risk of heat stroke becomes very substantial even among well acclimatized persons performing moderate or heavy work.

PROPOSALS FOR A METHOD OF CALCULATING PRODUCTIVITY LOSS DUE TO HEAT STRESS

The predictor formula

The approximative loss of productivity due to heat stress seems to be possible to predict by using the formula

$$R(t)\% = \frac{k(t - t_0)^2}{2t_0 - t}$$

where $k \sim 9$ at a wind velocity of about 0.5 m/sec (and lower at higher wind velocities). The temperature value $t_0 = 22$ $(-23)°$ ET or $t_0 = 22.5$ $(-23.5)°$ WBGT should be used when acclimatization is good (or very good for the higher t_0-values) and presuming moderate or hard work is carried out.

Recommended temperature scales

The WBGT may be preferable to the ET because of simplicity and also tends to give somewhat higher values than the ET at high humidity; this might be beneficial as high humidity is particularly deleterious to human heat tolerance and productivity. In this particular context of predicting productivity loss, WBGT = 0.7 × (wet bulb temp) + 0.3 × (globe temp) may be used (without radiation globe temp = dry bulb temp). Thus, little account is given to the influence from different air velocities, which might be questionable.

Basic data and considerations for predicting productivity loss

Since temperature will vary considerably during a work shift, the (8-hour) time-weighted average temperature should be used. Short periods of high temperatures might, however, tend to reduce productivity even more than calculated, since, for example, recovery time in such situations may be comparatively long. Also, the prediction of productivity loss due to heat stress should not be applied to individuals or small groups in order to avoid influence from the individual variation of tolerance to heat in the relation of predicted to finally observed productivity reduction.

The need for complementary practical observations

As the above attempt to predict heat induced productivity reduction is entirely based on fitting the model (I) to data from physiological experiments and experiences reported in the literature, it should be kept in mind that the consistency with observations in practical situations might turn out to be less good. However, such observations should be analyzed and used to modify the prediction procedure, which should remain simple to achieve general applicability. Thus, the influence from high or low air velocity is one of the factors which probably needs further consideration as do clothing and the relation between increasing heat radiation (contributing to the WBGT and perhaps a reason for using CET, corrected effective temperature, instead of ET) and loss of productivity. However, it should be emphasized that the prediction procedure introduced here is an approximation with simplicity as its most valuable feature.

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