

Evaluation of tolerance limits for humans under heat stress and the problems involved

by Hans G Wenzel, MD, Claus Mehnert, MD, Paul Schwarzenau¹

WENZEL HG, MEHNERT C, SCHWARZENAU P. Evaluation of tolerance limits for humans under heat stress and the problems involved. *Scand J Work Environ Health* 1989;15(suppl 1):7-14. Investigators are divided about the limits of tolerable ambient temperatures and air humidities, even under equal boundary conditions. In 266 climatic chamber experiments, mostly lasting 4 h, 13 young healthy men were exposed to combinations of ambient temperature (20 to 55°C) and relative humidity (5 to 97 %) at an air velocity of 0.3 m · s⁻¹. They were lightly clad and performed equal treadmill work (metabolic rate about 850 kJ · h⁻¹). Mean rectal isotherms and their standard deviations were calculated from the final rectal temperatures of the 13 men and plotted on a psychrometric chart. The slopes of the isotherms were compared with those of various "indices of heat stress." The probability of reaching the potentially critical rectal temperature of 39°C was calculated according to data of Wyndham & Heyns. It increased from about 1:500 000 to 1:150 in climates corresponding to mean isotherms of 37.6 and 38.2°C, respectively. Most of the limits thus far proposed are situated between these two isotherms, and they differ merely in regard to health risk. It is useless to discuss "correct" or "incorrect" limits until society has decided what risk is to be accepted. An upper tolerable limit per se does not and cannot exist. For several reasons the 37.6°C isotherm might be taken into consideration as a limit.

Key terms: criteria of heat tolerance, heat stress indices, individual health risk.

Climatic conditions above the thermally neutral, comfortable zone may produce unwanted effects on humans which can roughly be divided into three different groups (1). Relatively mild warm climates lead only to uncomfortable thermal sensations of warmth. Higher heat stress also results in a reduction of both physical and mental performance. Finally, if the conditions are severe enough and influence a person long enough, a person's health can be affected, and perhaps even death may ensue.

Although most warm climates cause only uncomfortable sensations in daily life and perhaps a decrease in work performance, one of the main questions asked in connection with heat stress is the limits tolerable in regard to the health of exposed persons. This question can be answered from the following two points of view: what maximum changes in physiological responses can be considered as being still harmless and what are the climatic limits corresponding to such harmless physiological changes?

In regard to the first question of limits, the predominant opinion is that conditions of thermal equilibrium are permissible. Heat accumulation is reflected by a continuous increase in body temperature and by an acceleration of heart rate. Thus heart rate may also be used as a criterion for distinguishing conditions of permissible heat strain from those potentially patho-

logical. In order to avoid continuous or frequently repeated measurement of responses under practical conditions, it is desirable to know what maximum levels of physiological responses can be considered safe. This knowledge is also important when thermal stress is very high but lasts only a short time. Most investigators describe rectal temperatures up to 38°C or slightly higher as being "acceptable" or "easy" or "safe," while temperatures around 39°C have been described as being "undesirable" or "excessive" or "unsafe" or "intolerable" (2-8). These values were derived in many laboratory experiments and field studies. They are particularly supported by Morrison & Wyndham's observations (9) on 314 heat stroke cases. Morrison and Wyndham found that a few deaths occurred at rectal temperatures of about 39 to 40°C on admission to the hospital. The probability of death increased significantly with increasing rectal temperature, reached 50 % at 42°C, and approached 100 % above about 45°C.

Several years ago, a working group of the World Health Organization also discussed the significance of heart rate elevations (10). The conclusion was reached that the degree to which both physical work and hot climate contribute to the actual heart rate has to be taken into account. Thus different values of maximum permissible heart rate, depending upon metabolic rate, have been recommended. Some investigators have also proposed limits in terms of sweat loss. For various reasons, however, it is doubtful whether this response can actually provide useful information (11-13).

If the body core temperature, or perhaps the heart rate, of humans exposed to hot climates is known, an evaluation is possible. However, practitioners often

¹ Institute of Occupational Health at the University of Dortmund, Dortmund, Federal Republic of Germany.

Reprint requests to: Professor Dr med HG Wenzel, Institut für Arbeitsphysiologie an der Universität Dortmund, Ardeystrasse 67, D-4600 Dortmund 1, Federal Republic of Germany.

prefer limits in terms of stress instead of strain, in other words, limits of climatic conditions. They do so mainly for two reasons. Data on climatic elements can be obtained fairly easily because instruments for such measurements, and people trained to use them, are usually available when such evaluations are required, eg, in industrial plants. However, this situation does not always apply for the collection of physiological data. The second reason might even be more important. Knowledge of physiological data enables an evaluation only during exposure to heat. Often, however, it is necessary to predict effects before a person is exposed to a possibly dangerous climate. Such predictions can be made if the climate is known and previous experience with humans in comparable climates is available.

Many upper tolerance limits have been published for climates. They have been partly proposed or recommended in the scientific literature and partly established in official regulations, eg, for the mining industry in a number of countries (14–16). They usually take into account the fact that at least four climatic variables contribute to heat stress simultaneously, ie, temperature, velocity, humidity of the air, and radiant temperature. In addition two nonclimatic variables play an essential role, ie, metabolic heat production in the body and the thermal resistance of clothing. In this paper, interactions between all six of these main factors have not been discussed; instead attention is drawn to another aspect, which is based on principle. For this reason, the following data are restricted to certain conditions visible at first glance, and they are used for discussing only some questions on the tolerable limits of ambient temperature (air temperature equal to mean radiant temperature) and corresponding air humidity applying to equal additional conditions, ie, to a given metabolic rate, to a given clothing, and to a given air movement.

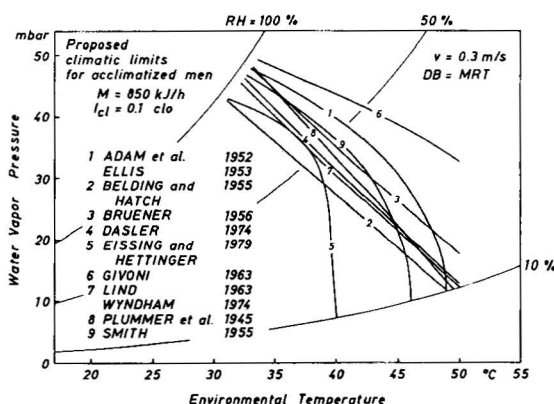


Figure 1. Climatic limits proposed for equal boundary conditions by various investigators (2, 3, 13, 17–24). (RH = relative humidity, v = air velocity, DB = dry bulb temperature, MRT = mean radiant temperature, M = metabolic rate, I_{cl} = thermal insulation of clothing)

One would expect that the limits proposed by various authors would be fairly similar. However, figure 1 proves that this is not the case. Such differences must irritate every practitioner. It should be mentioned that similar discrepancies appear when other values of the parameters are considered (25).

When the procedures for deriving the various limits presented in figure 1 are analyzed, some, but not all, of the reasons for the differences may be detected. Some limits, for instance, were based on practical experience collected in only a few climates. Others are results of more systematic studies in climatic chambers. When physiological measurements were made, different responses of the body were used as criteria, or different maximum values of the chosen criterion were applied. Furthermore, some limits were not derived from physiological investigations, but were instead calculated from heat balance equations. In such cases, sometimes different assumptions were made concerning the mean temperature, the wetness of the body surface, heat transfer coefficients, etc. Finally, it must be remembered that individual differences in heat tolerance are also reflected in the limits.

Subjects and methods

This situation induced us to start trying to answer some of the remaining questions with the use of a climatic chamber and the conditions presented in figure 1. A group of 13 young healthy men, acclimatized to heat, volunteered to participate, and 266 experiments, mostly walking up to 4 h on a treadmill, were conducted. We recorded rectal temperature, skin temperature at six sites, and heart rate continuously. Work was interrupted every 30 min for 3 min, during which body weight was measured. Ad libitum water intake, oxygen uptake, and carbon dioxide loss were taken into account in the calculations of extrarenal water loss. Respiratory measurements were made every hour. The experiments were always performed in the morning after about 1 h of rest in bed under thermally neutral conditions. The measuring methods have been described elsewhere (26).

Results

The arrangement of the climatic conditions of one of the series is presented in figure 2, showing the elevation of rectal temperature of one of the lightly clothed subjects at the end of work. Forty experiments were carried out in this series at ambient temperatures between 24 and 50°C and relative air humidities from about 10 to 95%. The relationship between rectal temperature and climate was described by a mathematical equation (28), which is represented in the figure by the drawn curves. Although rectal temperature was not affected by air humidity at an ambient temperature of 24°C, it increased in very dry air as the am-

bient temperature increased, and it also increased in higher humidities at elevated temperatures.

It would now have been an easy step to transfer these results onto a psychrometric chart and to derive rectal isotherms, lines of equal rectal temperatures in relation to ambient temperature and air humidity. Diagrams similar to figure 2, however, were obtained from the respective results of other physiological responses measured in the same experiments. For this reason, we analyzed the relationships between the various responses first to make sure whether or not parametric influences existed. An example is given in figure 3. Our observations showed that equivalence lines plotted on psychrometric charts are identical when based on heart rate and rectal and mean skin temperature as shown in figure 4. It should be mentioned that a comparison of the measured values and those calculated as indicated by the curves resulted in correlation coefficients usually ranging from 0.90 to 0.95.

When the time courses of the aforementioned physiological responses were investigated, we found that, by the second hour of exposure at the earliest, either none of the responses had increased continuously (ie, they reached steady states under the relatively light conditions of the series) or they all continued to increase (under the heavier conditions). The "steady state limit" occurred at an average heart rate of 97 beats/min, a rectal temperature of nearly 37.8°C, and a mean skin surface temperature of nearly 36°C under the given work conditions (figure 4).

The next step was to analyze the behavior of weight loss, which corresponds approximately to sweat loss. Contrary to the results of figure 3, the relationship between body temperatures and heart rate, respectively, and weight loss was not independent of the combination of ambient temperature and air humidity (12, 29). Combinations of climatic conditions equivalent in regard to body temperature and heart rate were unequal to those found to be equivalent in regard to weight loss. Figure 4 shows climatic conditions of equal weight loss from 100 to 900 g · h⁻¹. This divergency between the behavior of sweat loss and the other responses was found in every series of experiments.

The existence of two equivalence systems raises the essential question of whether body temperature and heart rate or sweat loss should be used as the criterion for describing climatic conditions of equal heat stress. When figure 4 is examined, one obviously important consideration becomes apparent, ie, that the steady state limit is intersected by various lines of equal weight loss. This situation applies, for instance, to the curve of 500 g · h⁻¹ weight loss. Along this curve, thermal equilibrium was reached when the ambient temperature was about 40°C at relative humidities of up to 50 %, while heat accumulation occurred in higher humidities combined with lower temperatures. It seems to be a fundamental biological principle that conditions of thermal equilibrium on one hand and heat accumulation on the other cannot be regarded as being

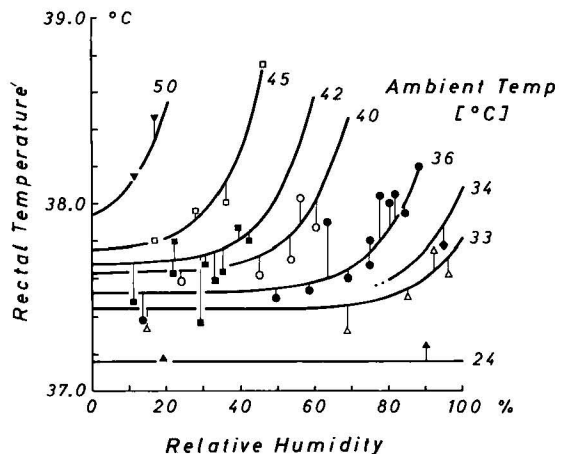


Figure 2. Rectal temperatures at the end of work in different ambient temperatures (Temp) and air humidities (subject OF, 40 experiments) (27).

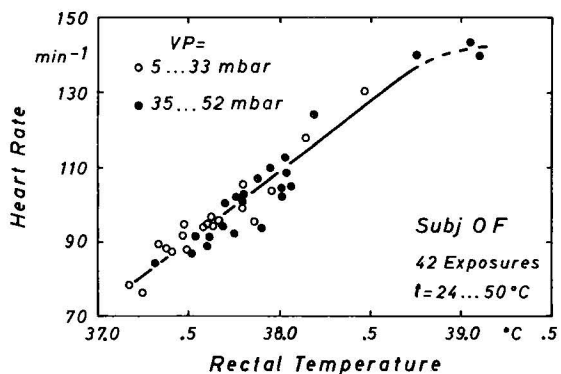


Figure 3. Relationship between final rectal temperature and heart rate (12). (VP = vapor pressure, subj = subject, t = temperature)

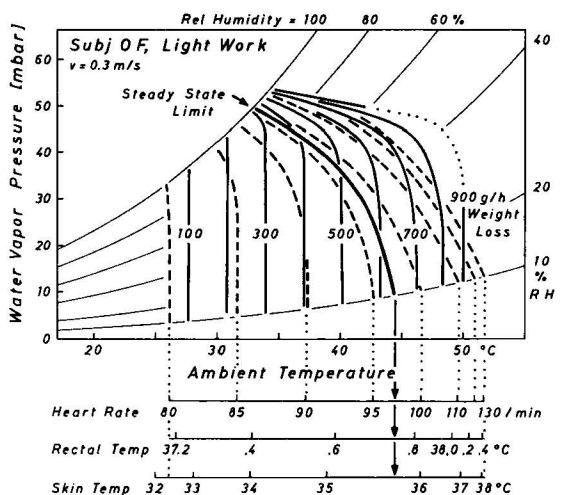


Figure 4. Equivalence lines derived from one of the experimental series (12). (Rel = relative, subj = subject, v = air velocity, RH = relative humidity, Temp = temperature)

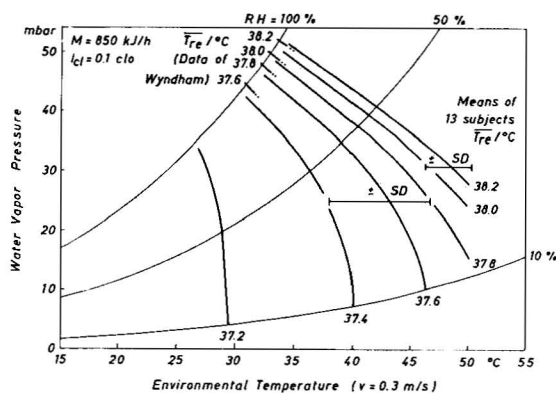


Figure 5. Mean rectal isotherms (SD 1.0) of 13 acclimatized young healthy men. (RH = relative humidity, M = metabolic rate, T_{re} = mean rectal temperature, I_{cl} = thermal insulation of clothing, v = air velocity, SD = standard deviation)

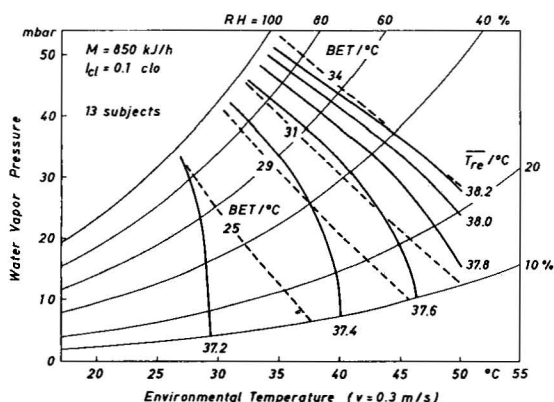


Figure 6. Lines of equal basic effective temperature (BET) (33) in comparison with mean rectal isotherms. (RH = relative humidity, M = metabolic rate, I_{cl} = thermal insulation of clothing, T_{re} = mean rectal temperature, v = air velocity)

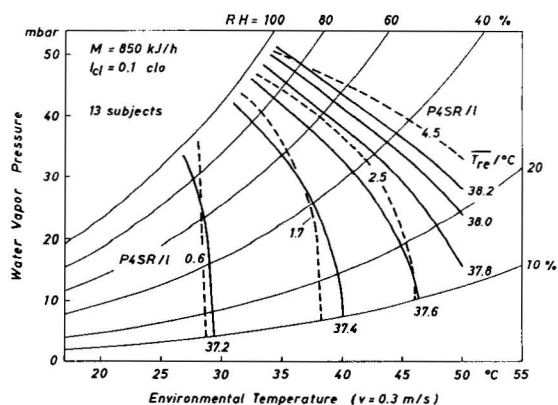


Figure 7. Lines of equal predicted 4-h sweat rates (P4SR) (35, 36) in comparison with mean rectal isotherms. (RH = relative humidity, M = metabolic rate, I_{cl} = thermal insulation of clothing, T_{re} = mean rectal temperature, v = air velocity)

equivalent merely because weight loss does not differ. Thus weight loss was excluded as a criterion, and the physiological responses mentioned first were used as the criteria of equal heat stress conditions.

The results of figure 4 were obtained with a single subject as an example. During the last several years about 50 similar series of experiments have been carried out in which the effects of various work levels (12), clothing ensembles (29), or air movements (30, 31) were also studied. In 13 of these 50 series, 13 different men served as test subjects under the same parametric conditions as in the series presented in figure 4. These 13 series enabled us to study interindividual differences and to derive mean rectal isotherms as shown in figure 5. The individual differences were considerable, as shown by the standard deviations, in spite of the fact that only young, healthy, seemingly equal men were investigated (32).

Figure 5 also shows data obtained by Wyndham (13), who seems to be the only investigator having carried out similarly comprehensive and comparable studies, although he restricted his experiments to climates with high humidity. It can be seen that both series of isotherms agree fairly well.

The derivation of mean rectal isotherms provides the opportunity for comment upon a fairly old question, namely, upon the extent to which various climatic indices actually describe physiologically equivalent climatic conditions. Together with the mean rectal isotherms, figure 6 shows the basic effective temperature (BET) (33), an index more than 60 years old, but still somewhat in use today. It can be seen that, under the conditions used, the BET overestimates air humidity under relatively mild heat conditions, but is nearly parallel to the mean rectal isotherm at 29 and 31 °C, except when the air humidity is low and the environmental temperature is correspondingly high. The same applies to still heavier climates corresponding to slightly higher effective temperatures.

It is not surprising that a very similar diagram results from a comparison of the mean rectal isotherms with curves of equal wet bulb globe temperatures (WBGT) (25). This index is frequently used, for instance by the National Institute for Occupational Safety and Health (34) in 1986, for describing "recommended heat stress exposure limits." This similarity goes back to the fact that, according to an unpublished notice of Yaglou, WBGT is nothing more than a "simplified version of the Effective Temperature Scale best suited to practical use in the field by personnel unskilled in psychrometry." The historical connection between the BET and WBGT is often unrecognized even though Yaglou participated in the development of both these indices.

Figure 7 demonstrates lines of equal values of the predicted 4-h sweat rate (P4SR) index (35, 36). Contrary to slopes of the BET in figure 6 the P4SR values coincide fairly well with the rectal isotherms, particularly in the range of mild and medium climates. The systematic intersections of the isotherms correspond

to the results shown in figure 4. These comparisons have been restricted to only a few indices even though others might also be of interest. However, the question of heat indices will be taken up again in the discussion of another aspect of the findings.

Now let us reconsider the different upper tolerable limits proposed by various authors (figure 1). Figure 8 demonstrates the whole climatic range in which these limits are situated. In addition, the mean rectal isotherms have been inserted. Although rectal temperatures up to about 38.2°C are usually tolerable, the mean rectal isotherm of 38.2°C must probably not be considered as a tolerance limit applicable to a greater population. Because of individual differences in heat tolerance, it has to be expected that, under the climatic conditions described by the mean isotherm of 38.2°C in figure 8, less heat tolerant men will reach higher rectal temperatures and, therefore, may be endangered.

Discussion

The fact that some subjects will always reach higher rectal temperatures leads to the question of the actual health risk of a greater population in climates described by various mean isotherms. It was not possible to answer this question from the results of the climatic chamber experiments that have been presented in this report. For safety reasons the exposure time was usually shortened if the rectal temperature of the respective test subject exceeded the "safe" level of about 38.3°C. "Potentially critical" rectal temperatures near or above 39°C were reached by the subjects in only a few experiments. More daring studies have been carried out, however, by other investigators (8, 13, 38). Wyndham (13) and his co-workers exposed men to severe conditions of work and ambient climate producing rectal temperatures of 39°C or higher in a number of cases. They derived distribution curves of rectal temperatures applying to greater groups of subjects. Using these data, they calculated mean rectal temperatures on one hand and the risk of reaching various temperatures above the mean values on the other. As shown in figure 5, the mean values worked out by Wyndham and the corresponding mean rectal isotherms agreed very well. For this reason, it seemed justified to make use of Wyndham's data, indicating how often higher rectal temperatures are observed. They demonstrated that under climatic conditions producing the "safe" rectal temperature of 38.2°C on an average, the rectal temperature of one man out of 150 can be expected to reach 39°C (figure 8).

In fact the very point at which the various proposed limits of figure 1 differ from each other can be seen in figure 8 as the conditions under which the risk is 1:500 000 (37.6°C isotherm). For many years, discussions have been under way about which proposed limits are "too high" or "too low." Such discussions are useless, as the suppositions necessary for answering this

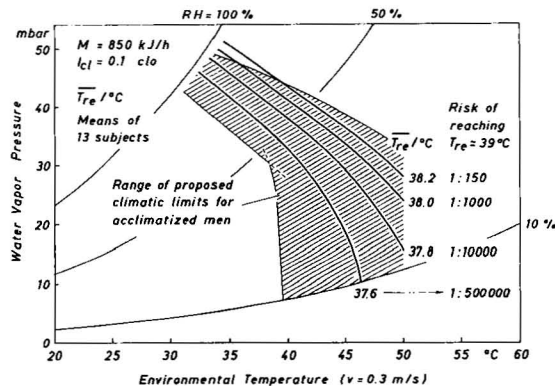


Figure 8. Range of proposed climatic limits (from figure 1), mean rectal isotherms (from figure 5) and risk of reaching a rectal temperature of 39°C according to Wyndham & Heyns (37). (RH = relative humidity, M = metabolic rate, I_{cl} = thermal insulation of clothing, T_{re} = mean rectal temperature)

question are still missing. It is first necessary to answer the essential question of what particular health risk should be accepted. However, the answer to this question has, in the end, to be provided politically. It is certainly a medical task to evaluate data of risk, but it is doubtful whether the answer should be expected from the field of medicine. It has to be realized that an upper tolerance limit per se does not and cannot exist. Data like those presented in this report permit permissible environmental conditions to be specified, but only after society has decided what health risk is to be accepted.

In spite of his great experience with heat stress, Wyndham abstained from making this decision. There seem to be only two very careful remarks in his publications that one might perhaps take into consideration, a climatic limit which — under the parametric conditions already mentioned — would be situated in the range of the mean rectal isotherm of 37.6°C (ie, the level at which the risk of a potentially critical rectal temperature of 39°C being reached is 1:500 000). The proposals — partly higher, partly lower — of some authors were formulated in a more apodictic way. Others, however, have formulated their proposals fairly carefully and with certain reservations.

The next obvious step is to compare the various proposals with particular reference to the 37.6°C isotherm and, in addition, to its relatively large standard deviation. This comparison is shown in figure 9. The diagram shows that the majority of the proposed limits are situated fairly close to the isotherm, at least within the hatched range of individual variability of the 13 subjects. Only a few exceptions exist. The highest limit, proposed by Givoni (21), corresponds roughly to the mean rectal isotherm of 38.2°C, which is not plotted in figure 9. When developing his "index of thermal stress," Givoni calculated this curve for describing climatic conditions producing a sweat rate of 1100 g · h⁻¹, which he considered "as the upper limit under prolonged exposure for healthy and ac-

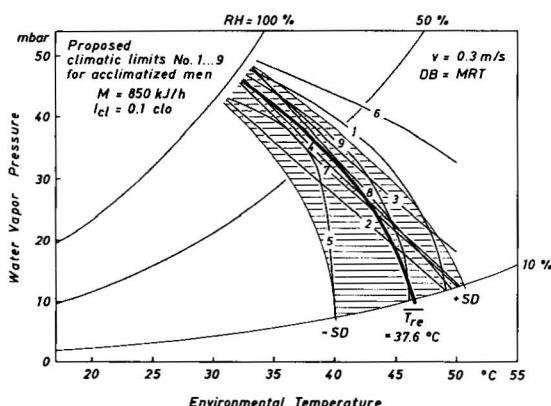


Figure 9. The 37.6°C rectal isotherm (thick solid line) in comparison with the proposed climatic limits of figure 1. (Hatched range of climate = 1.0 SD, 1 = Adam et al and Ellis, 2 = Belding & Hatch, 3 = Bruener, 4 = Dasler, 5 = Eissing & Hettinger, 6 = Givoni, 7 = Lind and Wyndham, 8 = Plummer et al, 9 = Smith)

climatized men [p 8].” He found in his experiments that “when average weight loss was approximately 1100 g/h, rectal temperature was 38.3°C [p 3].” His calculation of the mean curve was fairly correct. However, he did not consider the risk of reaching rectal temperatures above 38.3°C, in particular the possibly critical temperature of 39°C.

The limit of Adam et al (17) and Ellis (20) corresponds to a P4SR of 3.01. It is situated slightly above the upper range of the standard deviation of the isotherm in figure 9. On the other hand, the lower part of Eissing & Hettinger’s limit (19) approaches the lower range of this standard deviation. It is based on calculations of the so-called “required sweat rate” by Vogt et al (39, 40).

The limit proposed by Lind (22) and Wyndham (13), corresponding to Wyndham’s proposal of an effective temperature of 31°C, is similar to that of Dasler (3) (WBGT = 32°C). Both these limits coincide with the 37.6°C isotherm at high air humidities, but deviations occur for dry and correspondingly hot climates. It has to be remembered, however, that the studies of Wyndham were restricted to the climatic conditions of South African gold mines, which are characterized by high humidity.

If one considers the standard deviation of the isotherm presented in figure 9 generously, the conclusion could be reached that neither most of the limits proposed nor the indices differ extremely. However, the slopes of the limits could be analyzed more in detail. Some of the limits are linear or nearly linear, while others are curved. Although nearly all of the limits are situated within the area of the standard deviations, the differences should not be underestimated. As already mentioned, exposures to climates of this range generally result in a relatively small health risk. However, the risk for conditions in the upper part of the standard deviation range may be about a hundredfold of the risk for conditions in the lower part. Thus a con-

siderable increase of risk with increasing ambient temperature would apply to those limits which are linear and relatively flat, for instance, the limit of Belding & Hatch (18).

Numerous results from systematic physiological studies on humans have indicated that physiological equivalence is nonlinear, ie, is slightly curved in this range of climate. One of the oldest of these studies (41) was published in 1945. Under these circumstances, linear equivalence lines or — in the present case — linear limits can be suspected to contain errors or simplifications.

On the other hand, the limits of Adam et al (17) and Ellis (20), Eissing & Hettinger (19), and Smith (24) are more curved than the isotherm. They are the very limits with sweat rate as the criterion. It has already been pointed out that there are two opinions about the question of whether this response is a suitable criterion for describing climatic conditions producing equal heat stress. For this reason, a line only slightly curved, like the 37.6°C isotherm, can be suggested as an equivalence line. Whether this isotherm is considered simultaneously as the upper tolerance limit under the parametric conditions discussed, however, depends upon the pivotal question of whether the corresponding health risk will be accepted by society.

Concluding remarks

The heat stress conditions chosen as an example for this survey are easily visible at first glance. However only two of the six main factors contributing to heat stress were considered, ambient temperature and air humidity. Nevertheless, even this simple example shows that the evaluation of an upper tolerable limit includes several problems. The first is the divergency of the different limits proposed previously by various authors. This divergency led to the question of which physiological responses of humans under heat stress can be used as criteria for describing tolerable conditions. Carrying out a total of about 1000 whole-day climatic chamber experiments over a number of years produced another problem in so far as much patience was required of all those concerned, ie, both the investigators and the test subjects. The results obtained made it possible, however, to touch the old problem of the reliability of various heat stress indices.

The fact that 13 subjects were studied under comparable conditions proved the importance of individual differences for any statements about tolerance limits. The results proved that an upper tolerance limit per se does not exist and that the essential problem is to obtain the inevitable decision of society on what health risk should be accepted. One observation was made which might be helpful to those involved in this work. The range of climate in which most of the various diverging limits proposed in the past are situated is similar to the range of climate corresponding to the individual variability of the 13 subjects who volun-

teered for the described experiments. The survey may offer some information with which to obtain an answer to the question under discussion.

References

- Leithead CS, Lind AR. Heat stress and heat disorders. London: Cassell and Co Ltd, 1964.
- Bruener H. Über Grenzbelastungen des menschlichen Organismus. *Z Flugwiss* 1956;4:150—6.
- Dasler AR. Ventilation and thermal stress ashore and afloat. In: Department of the Navy, Bureau of Medicine and Surgery. Manual of naval preventive medicine. Chapter 3 (Ventilation and thermal stress ashore and afloat). Department of the Navy, Bureau of Medicine and Surgery, 1974.
- Eichna LW, Ashe WF, Bean WB, Shelly WB. The upper limits of environmental heat and humidity tolerated by acclimatized men working in hot environments. *J Ind Hyg* 1945;27:59—84.
- Grandjean, E. Die Luftfeuchtigkeit. *Z Präventivmed* 1962;7:405—18.
- Humphreys CM, Imalis O, Gutberlet C. Physiological response of subjects exposed to high effective temperatures and elevated mean radiant temperatures. *Heat/Piping/Air Cond* 1946;18:101—6.
- Ladell WSS. Effects on man of restricted water-supply. *Br Med Bull* 1947/48;5:9—12.
- Wyndham CH, Strydom NB, Morrison JF, Williams CG, Bredell GAG, Maritz JS, Munro A. Criteria for physiological limits for work in heat. *J Appl Physiol* 1965;20:37—45.
- Morrison JF, Wyndham CH. Report on some clinical features of the heat-stroke cases occurring in the 3 year period June 1956 to July 1959. Johannesburg, 1961. (APL report no 6.)
- Belding HS, Givoni B, Gupta MN, et al. Health factors involved in working under conditions of heat stress. Geneva: World Health Organization, 1969. (WHO tech rep ser no 412.)
- Belding HS. The search for a universal heat stress index. In: Hardy JD, Gagge AP, Stolwijk JAS, ed. Physiological and behavioral temperature regulation. Springfield, IL: Charles C Thomas, 1970:193—202.
- Wenzel HG. Heat stress upon undressed man due to different combinations of elevated environmental temperature, air humidity, and metabolic heat production: a critical comparison of heat stress indices. *J Human Ergol (Tokyo)* 1978;7:185—206.
- Wyndham CH. Research in the human sciences in the gold mining industry. *Am Ind Hyg Assoc J* 1974;113—36.
- Bundeswirtschaftsminister (Federal Republic of Germany). Bergverordnung zum Schutz der Gesundheit gegen Klimaeinwirkungen (Klima-Bergverordnung-KlimaBergV) vom 9. Juni 1983. Dortmund: Bellmann, 1983.
- Wenzel HG. Physiologische Bewertung bergbehoerdlicher Klimagrenzen für Untertagebetriebe. Verhandlungen der 20. Jahrestagung der Deutschen Gesellschaft fuer Arbeitsmedizin, Innsbruck 1980. Stuttgart: Gentner, 1980:63—76.
- Wenzel HG, Piekarski C. Klima und Arbeit. Bayerisches Staatsministerium für Arbeit und Sozialordnung, ed, Muenchen: 4, auflage, 1985.
- Adam JM, Ellis FP, Irmin JO, Thomson ML, Weiner JS. Physiological responses to hot environments of young European men in the tropics. London: Medical Research Council, Royal Naval Personnel Research Committee, 1952. (Report no 721.)
- Belding HS, Hatch TF. Index for evaluating heat stress in terms of resulting physiological strains. *Heat/Piping/Air Cond* 1955;27:129—36.
- Eissing G, Hettinger Th. Belastungsgrenzen bei Hitzearbeit. *Z Arbeitswiss (SNF)* 1979;33:224—8.
- Ellis FP. Tolerable and desirable levels of warmth in warm climates, with special reference to the requirements of men in the Royal Navy. *Ann R Coll Surg Engl* 1953;13:369—91.
- Givoni B. A new method for evaluation industrial heat exposure and maximum permissible work load. Paper submitted to the Third International Biometeorological Congress, Pau, 1963.
- Lind AR. Tolerable limits for prolonged and intermittent exposures to heat. In: Hardy JD, ed. Temperature — its measurement and control in science and industry 3, part 3. New York, NY: Reinhold Publ Corp, 1963: 337—45.
- Plummer JH, Ionides M, Siple PA. Thermal balance of the human body and its application as an index of climatic stress. Climatology and Environmental Protection Section, Military Planning Division, Office of QM General, 1945. (Report.)
- Smith FE. Indices of heat stress. London: Her Majesty's Stationery Office, 1955. (Medical Research Council, memorandum no 29.)
- Minard D, Belding HS, Kingston JR. Prevention of heat casualties. *JAMA* 1957;165:1813—8.
- Wenzel HG. Muscular work in heat combined effects on various physiological responses. *Arch Sci Physiol* 1973;27:A225—38.
- Wenzel HG. Contribution of air humidity and heat radiation to heat stress due to elevated air temperature. In: Khogali M, Hales JRS, ed. Heat stroke and temperature regulation. Sydney: Academic Press, 1983:273—82.
- Bronstein IN, Semendjajew KA. Taschenbuch der Mathematik. 11. Auflage, Zürich/Frankfurt: H Deutsch, 1971.
- Ilmarinen R. Einflüsse verschiedener Bekleidung auf einige physiologische Groeßen des Menschen bei Körperarbeit in unterschiedlich erhöelter Umgebungstemperatur und Luftfeuchtigkeit [Dissertation]. Koeln: Deutsche Sporthochschule, 1978.
- Piekarski C, Kampmann B, Wenzel HG. Einfluß verschiedener Windgeschwindigkeiten bei unterschiedlich erhöhten Umgebungstemperaturen und Wasserdampfdruck auf die Beanspruchung des arbeitenden Menschen. Verhandlungen der 23. Jahrestagung der Deutschen Gesellschaft für Arbeitsmedizin. Stuttgart: Gentner, 1983:317—22.
- Wenzel HG, Sakate T, Piekarski C. Experimentelle Untersuchungen ueber den Einfluß verschieden hoher Windgeschwindigkeiten auf den Menschen bei Hitzearbeit. Verhandlungen der 21. Jahrestagung der Deutschen Gesellschaft fuer Arbeitsmedizin, Berlin 1981. Stuttgart: Gentner, 1981:377—82.
- Wenzel HG. Beurteilung von Hitzebelastungen des Menschen durch Klimasummenmasse. *Mod Unfallverhuet* 1984;28:47—54.
- Yaglou CP. Temperature, humidity and air movement in industries: the effective temperature index. *J Ind Hyg* 1927;9:297—309.
- National Institute for Occupational Safety and Health. Criteria for a recommended standard: occupational exposure to hot environments. Revised criteria 1986. US Department of Health and Human Services, Public Health Service, April 1986.
- MacPherson RK. Physiological responses to hot environments. London: Medical Research Council, Her Majesty's Stationery Office, 1960. (Special report series no 298.)
- McArdle B, Dunham W, Holling HE, et al. The prediction of the physiological effects of warm and hot environments. London: Medical Research Council, Royal Naval Personnel Research Committee, 1947. (Report no 47/391.)

37. Wyndham CH, Heyns AJ. The probability of heat stroke developing at different levels of heat stress. *Arch Sci Physiol* 1973;27:A545—62.
38. Wyndham CH. A survey of the causal factors in heat stroke and of their prevention on the gold mining industry. *J S Afr Inst Min Metall* 1965;November:125—55.
39. Vogt JJ, Candas V, Libert JP, Daull F. Required sweat rate as an index of thermal strain in industry. In: Cena K, Clark JH, ed. *Bioengineering, thermal physiology and comfort*. Amsterdam: Elsevier, 1981:99—110.
40. Vogt JJ, Candas V, Libert JP, Hoeft A. Die erforderliche Schweißabgabe als Index der Waermebelastung. *Z Arbeitswiss (4NF)* 1978;32:241—4.
41. Robinson S, Turrell ES, Gerking SD. Physiologically equivalent conditions of air temperature and humidity. *Am J Physiol* 1945;143:21—32.