

Modification of Vernon's globe thermometer and its calibration in terms of physiological strain

by Hans G Wenzel, MD, Alfons Forstthoff, PhD¹

WENZEL HG, FORSTHOFF A. Modification of Vernon's globe thermometer and its calibration in terms of physiological strain. *Scand J Work Environ Health* 1989;15(suppl 1):47-51. Six men wearing shorts performed treadmill work in about 150 climatic chamber experiments at several temperatures of Vernon's globe thermometer (t_{g}) from 25 to 50°C. Each t_{g} was produced partly by an equal air temperature (t_a) and a mean radiant temperature (MRT), partly by a lowered t_a (minimum 5°C) and an MRT elevated up to about 80°C above the t_a . With an increasing MRT and lowered t_a , respectively, body temperature, heart rates, and sweat losses decreased significantly. In another 55 experiments physiologically equivalent combinations of t_a and MRT were derived. According to the results a modified globe thermometer was built. It reduced the errors of Vernon's instrument by about 75 %. The remaining error of 25 % was due to changes in air velocity between 0.5 and 2 m · s⁻¹. The applicability of simple instruments like globe thermometers is obviously limited for the description of physiologically equivalent conditions of unequal t_a and MRT at various air velocities.

Key terms: globe thermometer, physiological equivalence, unequal air and radiant temperatures.

It is well known that radiant temperature may exceed air temperature considerably at many, particularly industrial, workplaces or in the open air and that effects of elevated radiant temperature on man may be compensated by lowered air temperatures within certain limits. In the evaluations of such climates, the globe thermometer of Vernon (1) has been used for many decades under the assumption that those conditions of unequal air and radiant temperature resulting in equal globe temperatures are also physiologically equivalent. However, it is not known if this assumption is correct, particularly in cases of large differences between air and radiant temperatures of, eg, 50 K and more.

There is good reason to conclude that the lack of knowledge about the accuracy of Vernon's globe thermometer is due to the fact that the experimental simulation of the needed climatic conditions requires a technically complicated and expensive climatic chamber. At the end of the 1970s, such a test room was constructed in the Institute of Occupational Health at the University of Dortmund. The chamber is similar to one developed and described earlier (2, 3). Figure 1 shows a horizontal section of the climatic chamber. A test subject sitting or working in the middle of the chamber can be exposed simultaneously to an air stream with temperatures down to the freezing point and to mean radiant temperatures of up to about 140°C. The oblong line, plotted in polar coordinates, in figure 1

demonstrates the distribution of radiation energy, produced in four so-called "radiation towers." In order to help clarify the aforementioned question of whether the physiological effects of unequal air and radiant temperatures are equivalent to those experienced at the resulting equal globe temperatures, four series of more than 400 climatic chamber experiments were carried out. Series 1 revealed inaccuracies in the globe thermometer of Vernon (1), series 2 concerned possibilities of improving Vernon's thermometer, series 3 was used for developing a modified globe thermometer, and series 4 dealt with advantages of the new globe thermometer and its calibration in terms of physiological strain.

Series 1

In about 150 experiments, six healthy young men wearing shorts and footwear were exposed to conditions

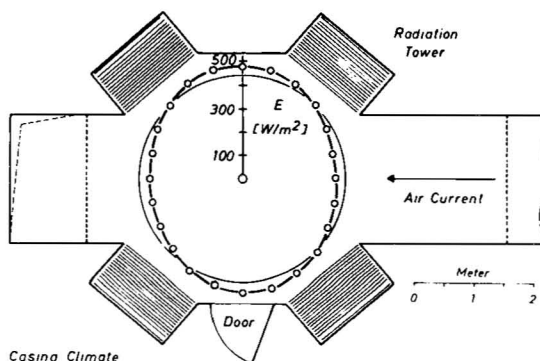


Figure 1. Horizontal section of the climatic chamber.

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.

of globe temperatures between 25 and 50°C (4, 5). The equal radiant and air temperatures were described by the unbroken diagonal line as shown in figure 2. They will be referred to in the text as “reference tempera-

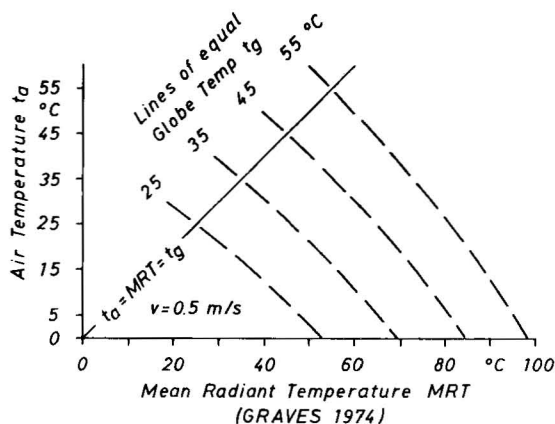


Figure 2. Lines of equal temperatures of Vernon's globe thermometer (t_g) (broken lines) at different air temperatures (t_a) and mean radiant temperatures (MRT) according to Graves (6). (Temp = temperature, v = air velocity)

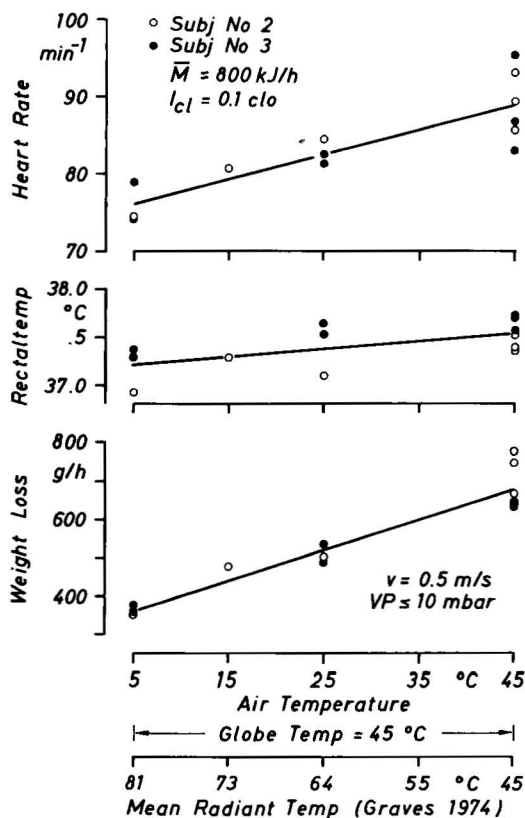


Figure 3. Some physiological responses of two subjects after 3 h of treadmill work in unequal air and radiant temperatures at a constant globe temperature of 45°C. ($\bar{M}$ = mean metabolic rate, I_{cl} = thermal insulation of clothing, v = air velocity, VP = vapor pressure, Temp = temperature)

tures.” The figure also shows the combinations of various air temperatures and mean radiant temperatures which result in equal temperatures of Vernon's globe thermometer according to previous investigations of Graves (6). The respective calculation according to older data of Bedford & Warner (7) results in slightly different curves.

Each desired globe temperature was produced first by an equal air and radiant temperature; in further experiments the mean radiant temperature was increased stepwise in combination with a stepwise reduction in air temperature. In each experiment, the subjects walked 4 km/h on a horizontal treadmill for 3 h in most cases. They were supplied with drinking water ad libitum.

Figure 3 demonstrates the results of 13 experiments carried out on two subjects working in air with a low humidity level, the air velocity being 0.5 m/s. In all the experiments, the globe temperature was kept constant at 45°C. If Vernon's globe thermometer were able to describe physiologically equivalent conditions correctly independent of the combination of air and radiant temperature, equal physiological reactions would be expected when the radiant temperature was elevated and the air temperature reduced respectively. According to figure 3 this result, however, was not obtained. By the end of the third hour the heart rate and rectal temperature had decreased significantly with an increasing radiant temperature and correspondingly a decreasing air temperature. The same applied to body weight (sweat) loss.

Similar experiments were carried out on the other test subjects, partly at other globe temperatures between 25 and 50°C and partly at an air velocity of 2 m/s instead of 0.5 m/s. Some additional experiments were also performed in which radiation from the front or back of the subjects replaced circular radiation. Without exception, unequal combinations of both the ambient temperatures that produced a constant globe temperature resulted in systematically different physiological responses. Sweat loss, for instance, decreased by about 300 g/h under the extreme conditions, corresponding to 50 % of the sweat loss at the reference temperature. Heart rate decreased up to about 30 beats/min. In other words Vernon's globe thermometer considerably underestimated the physiological effects of decreasing air temperature and overestimated the corresponding effects of increasing radiant temperature.

Series 2

In an attempt to determine the combinations of air and radiant temperature equivalent to actual conditions, 55 experiments were carried out with three of the six subjects included in series 1. The slanting line of the example in figure 4 confirms again the findings obtained earlier with a constant globe temperature. In additional experiments, the globe temperature was not

kept constant, but was instead elevated stepwise until the same physiological reactions were reached as had been obtained at the reference temperature. (See the horizontal line in figure 4.) At an air temperature of 15°C, for instance, the globe temperature had to be elevated by 10°C, from 45 to 55°C, to cause the weight loss observed at the reference temperature of 45°C. The results of all the experiments of this series have been summarized in figure 5.

Series 3

As has already been mentioned, Vernon's globe thermometer and the human body show different relationships between heat exchange with the environment by convection and radiation. The aim of the experiments of series 3 was to modify the original globe thermometer so that its heat transfer properties simulated those of the human body. More than 20 modifications were tested (8). Special emphasis was attached to technically simple changes acceptable to the practitioner making use of the instrument in daily life.

One successful modification was to change the diameter of the black globes used. A smaller diameter (diameter of Vernon's globe 150 mm) resulted in a higher heat transfer coefficient for convection. A globe with a diameter of 58 mm reached equal temperatures under the climatic conditions described as being physiologically equivalent at the low air speed of 0.5 m/s (figure 5). A slightly larger globe, 73 mm in diameter, proved to be suitable at an air speed of 2 m/s. This difference corresponds to thermodynamic experiences of physics. In order to save the practitioner the trouble of using different globes at different air velocities, a compromise was made. A globe with a 65-mm diameter, ideal for an air velocity of about 1 m/s, was built. Certain inaccuracies were likely for air velocities of 0.5 and 2 m/s, but they could be expected to be fairly small.

Series 4

To determine whether or not the conclusions drawn on the basis of the experiments in series 3 were valid, additional experiments were carried out which were similar to those performed in series 1. Three young men worked first at reference temperatures and then at stepwise reduced air temperatures and correspondingly elevated radiant temperatures, but partly at a constant temperature of Vernon's globe thermometer (t_{gv}) and partly at a constant temperature of the modified instrument (t_{g65}). Figure 6 shows the final values of the heart rates of two of the three subjects when an air velocity of 0.5 m/s was used. As expected from the results of the experiments in series 1, the heart rates measured under the t_{gv} conditions decreased with lower air temperatures. Under the t_{g65} conditions the heart rate of one subject (subject 9) decreased slightly

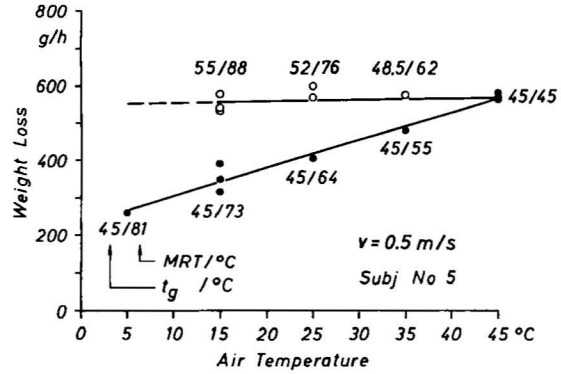


Figure 4. Weight loss of a subject in unequal air and radiant temperatures at a constant globe temperature (t_g) and at globe temperatures elevated stepwise. (MRT = mean radiant temperature, v = air velocity)

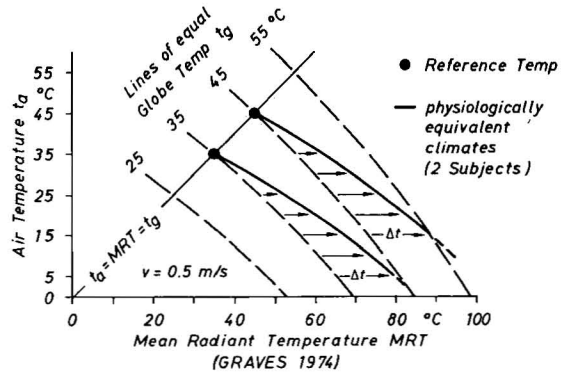


Figure 5. Comparison of some isotherms of Vernon's globe thermometer with lines of physiologically equivalent climates. (Temp = temperature, v = air velocity)

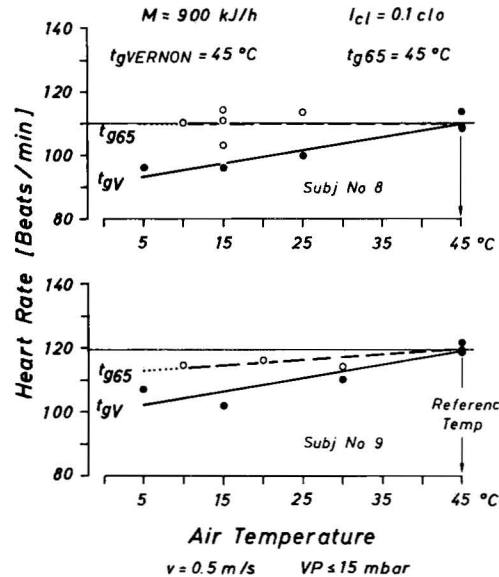


Figure 6. Heart rates of two subjects in different air temperatures at a constant temperature of Vernon's globe thermometer (t_{gv}) and of the modified globe thermometer (t_{g65}). (M = metabolic rate, l_{cl} = thermal insulation of clothing, Temp = temperature, v = air velocity, VP = vapor pressure)

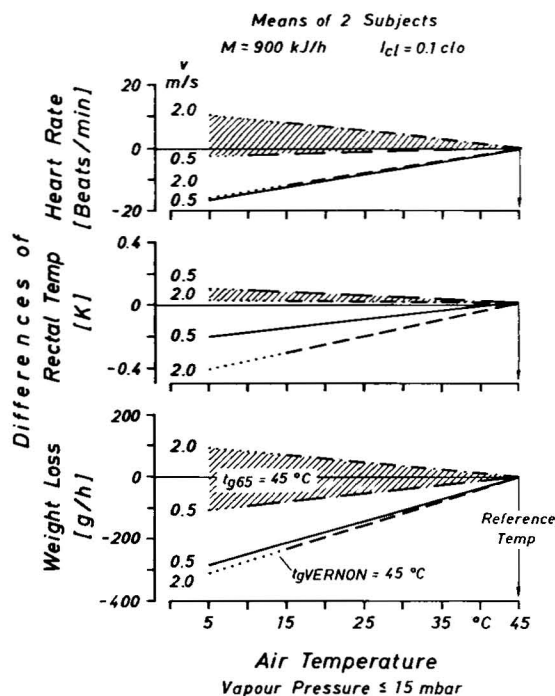


Figure 7. Description of physiologically equivalent combinations of unequal air and radiant temperatures by means of the modified globe thermometer (t_{g65}) at the air velocities of 0.5 and 2.0 m/s. (M = metabolic rate, I_{cl} = thermal insulation of clothing, v = air velocity, Temp = temperature, t_{gV} = Vernon's globe thermometer)

when the air temperatures were lowered. This observation was to be expected from the results of the experiments in series 3. For the other subject (subject 8) the data were practically equal to the data obtained at the reference temperature.

There was henceforth the crucial question of how the physiological responses were influenced by the air velocity of 2 m/s. Figure 7 shows the mean regression lines of the two subjects represented in figure 6 at a constant t_{gV} and a constant t_{g65} with air velocities of 0.5 and 2 m/s. For the sake of clarity, the ordinates in figure 7 have not been made to indicate the absolute values of the physiological response in question, but rather the differences in the values at the reference temperature, as these values differed individually. The results for weight loss demonstrate this comparison in a fairly typical way. The two lowest regression lines, decreasing steeply with a lowered air temperature, refer to experiments in which the t_{gV} was kept constant at 45°C. As has already been mentioned, the sweat loss decreased by about 300 g/h from an air temperature of 45°C to that of 5°C in spite of the constancy of the t_{gV} . The change in air velocity from 0.5 to 2 m/s had no influence. The two other lines refer to experiments at a t_{g65} of 45°C. The upper line, derived from experiments at an air velocity of 2 m/s, increases slightly, whereas the lower line, referring to an air velocity of 0.5 m/s, decreases slightly. This re-

sult was expected from the experiments of series 3. The hatched triangle represents the remaining errors due to changes in air velocity. The heart rate data presented in figure 7 show nearly the same configuration as that of weight loss. For rectal temperature, there was a certain similarity to the findings for weight loss and heart rate, but the differences were fairly small (figure 7).

According to these results, the errors of the t_{gV} could actually be reduced by the simple modification of reducing the diameter of the black globe used. All the physiological data obtained in the experiments of this series were summarized and used for calculating quantitatively the average improvement. It was found that the errors of the t_{gV} were reduced by about 75 % when the mean radiant temperature exceeded the air temperature up to nearly 100 K in the air velocity range of 0.5–2 m/s.

Discussion and concluding remarks

According to similar recent studies, the improvement found with the modified version of Vernon's globe thermometer seems to apply also when subjects are exposed to unilateral instead of circular radiation, perhaps also when heavier work is performed. Additional series of experiments are now being conducted in which men wearing commonly used workclothes are serving as test subjects. The results obtained thus far show that also under these clothing conditions preference should be given to a modified globe thermometer. In a comparison with the values of Vernon's instrument, however, the improvement was smaller than that obtained in the experiments described in this paper. A globe with a diameter slightly smaller than 65 mm might be more suitable for describing combinations of air temperature, mean radiant temperature, and air velocity which are physiologically equivalent to fully dressed subjects. The results which are already available, however, seem to justify the proposal to replace the original globe thermometer of Vernon by a new instrument. This proposal has to be considered with caution, as the effects of various combinations of clothing, work load, individual tolerance, etc. are still incompletely known.

Although the proposal will be helpful to the practitioner in the near future, it should certainly be considered as a temporary solution, there is still an error of 25 %. It seems to be difficult to achieve further improvement however by other modifications under the conditions of the present studies, which are simple and, therefore, acceptable for the practitioner. A simple instrument like a globe thermometer can obviously describe physiologically equivalent combinations of unequal air and radiant temperatures at various air velocities only by approximation.

Anyone who intends to describe and evaluate a climate measures air temperature in degrees centigrade and air velocity in meters per second and uses a psychrometer, for instance, for collecting figures on

air humidity. Curiously, and contrary to this fact, Vernon's globe thermometer was so impressive that, for more than 50 years, the existence of basic physical units of heat radiation have been neglected. A definite solution to the problem can probably be expected only after one liberates oneself from the fascination of a primitive instrument which is supposed to be able to integrate the effects of all the thermal factors resulting in the final reaction of the complicated human body.

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