GLOBE OPERATIVE TEMPERATURE IS NOT A GOOD INDEX FOR DESCRIBING THE EFFECTS OF AIR AND RADIANT TEMPERATURES ON MAN.

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INTRODUCTION

New heating systems often involve sources of radiant heat as it reduces convection in order to provide thermal comfort. In a recent paper (Bothorel et al., 1993), we showed that the skin temperatures of resting men as well as the associated thermal subjective estimates were different in convective and radiant climates. We also concluded that operative temperatures were similar under both tested conditions. However, it appeared that the equivalent temperature as determined by the manikin was somewhat lower under radiant heat: this was due to increased coefficient of convective heat exchange, because of the rise in the difference between the temperature of the air and that of the skin. This was not observed under the convective climate.
The aim of the present study was to test the similarity or discrepancy between the heat fluxes of a thermal manikin exposed either to a convective or to a radiant environment. The experiments involved minimal variations in air temperature in order to modify, only slightly, the convective heat transfer coefficient, compared to that of a standard uniform climate.

METHODS

A calorimetric manikin (Heatman®, Sweden) was used in a sitting position in the center of the climatic chamber (length 5.1 m, width 2.7 m, height 2.5 m). Four walls (right, left, floor and ceiling) could be adjusted as desired, while the front and rear walls were passively maintained close to air temperature since the air passed through filters in these walls. Because of the different regulating systems, air and wall temperatures could be controlled at different levels, rewarming the environment either by convection (warm air, cool walls) or by radiation (cool air, warm walls). To simplify the tests, the 35 parts of the manikin were temperature–controlled at 34°C, and the floor temperature (24°C), dew–point temperature (8°C), and air velocity ($0.1 m.s^{-1}$) were always kept constant. The temperature of the air (Ta) and that of three walls (T3w: left wall, right wall and ceiling) were adjusted depending upon conditions. Recordings were carried out for one hour: steady states were always obtained and at least 40 minutes of exposure were used for further calculations. Two Bruel and Kjaer (BK) devices were also installed in the chamber:
– the BK type 1212 for measurements of "operative temperature" (45° inclination),
– the BK type 1213 for measurements of air temperature and velocity.
A black globe thermometer was also used for measures of globe temperature. BK devices were located at 1 m in front of the manikin (h = 1.1 m) while the globe was suspended above the BK device (h = 1.5 m).
Three **basic tests** were performed

HOMO: air and wall temperatures were set at 24.0°C: homogeneous environment,
CONVECT 1: because of cooling (by 5°C) three walls (T3w = 19°C), air temperature was increased so as to reach a steady BK value as close as possible to 24°C,
RADIANT 1: because of warming (by +5°C) three walls (T3w = 29°C), air temperature was decreased to maintain the BK value close to 24°C.

Additional tests were carried out:
CONVECT 2 and 3 under which the temperature of the three walls was decreased by 5 °C in each condition, respectively T3w = 14 and 9°C.
RADIANT 2 and 3 under which T3w were increased by 5°C leading them respectively to 34 and 39°C, with no other thermal readjustments.

Registered **parameters:** In addition to continuous measures of globe temperature (±.1°C), BK operative temperature (±.1°C), air temperature (±.1°C), and wall temperatures (±.2°C), the total heat flux produced by the manikin to maintain constant a uniform 34°C surface temperature as well as local fluxes of large body areas (head, front–trunk, rear–trunk, upper limb, lower limb) were registered.

TABLE1

Condition	To, BK, °C	T3w, °C	Ta, °C	Tg, °C	Flux, $W.m^{-2}$	SD Flux, $W.m^{-2}$
HOMO	24.1	24.0	24.1	24.1	82	1.0
CONVECT 1	24.2	19.0	25.6	24.6	79	0.6
RADIANT 1	24.1	29.0	22.0	24.9	93	0.6

It appears that to compensate for a symmetrical variation (±5°C) in the three wall temperature, the air temperature adjustments for To compensation under CONVECT 1 or RADIANT 1 were not of the same amplitude (+1.5 against -2.1°C). Moreover, Tg increased from HOMO to CONVECT 1 and again to RADIANT 1 in which the highest values was found : at the same time, the heat flux generated by the manikin for thermal equilibrium was very similar in HOMO and CONVECT 1 but was larger under the RADIANT condition (>13%).

TABLE 2

	To, BK,°C	T3w,°C	Ta,°C	Tg,°C	Flux,W.m^{-2}	SD Flux,W.m^{-2}
CONVECT1	24.2	19.0	25.6	24.6	79	0.6
CONVECT 2	22.9	14.0	24.9	24.0	92	0.4
CONVECT3	21.8	9.0	24.5	22.9	103	0.3
RADIANT 1	24.1	29.0	22.0	24.9	93	0.6
RADIANT2	25.7	34.0	22.5	26.5	82	0.5
RADIANT3	27.3	39.0	23.0	28.1	71	0.6

Data of additional tests (Table 2) show that a 10°C decrease in wall temperatures (to 9°C) in CONVECT 1–3 induced a manikin heat flux increase of 24 W.m^{-2} (79–103 W.m^{-2}). Symmetrical value (–22 W.m^{-2}, from 93 to 71 W.m^{-2}) was found under a 10°C increase in wall temperature (RADIANT 1–3). But, the 10°C reduction in wall temperature (CONVECT 1–3) was associated with a 1.1°C reduction in air temperature and a 1.7°C reduction in globe temperature, while the 10°C rise in wall temperature also associated with a 1.0°C increase in air temperature (RADIANT 1–3) led to a 3.2°C increase in globe temperature.

On the basis of absolute values of manikin heat fluxes, it could be concluded that similar climates were obtained either under Tg of 24.0 (CONVECT 2) or of 24.9°C (RADIANT 1 - heat flux 92–93 W.m^{-2}) or under Tg=24.1 (HOMO) or 26.5°C (RADIANT2, heat flux : 82 W.m^{-2}).

DISCUSSION

Our results clearly illustrate the discrepancy between climate estimations, deduced either from globe or BK device measure and those deduced from thermal manikin flux determination. The data found here in an homogeneous environment allow an estimation of the value of the combined heat transfer coefficient of the sitting manikin by dividing the heat flux (82 W.m^{-2}) by the difference of temperature (10°C) between the manikin surface and the homogenous environment : a 8.2 W.m^{-2}.°C^{-1} is derived which, taking into account a 4.7 W.m^{-2}.°C^{-1} as linear radiant heat coefficient, (ASHRAE, 1992) yields an hc of 3.5 W.m.$^{-2}$.°C^{-1}, a value within the range usually reported at low air velocity level (Nishi and Gagge, 1970). This point confirms the validity of the heat exchange measures in an homogeneous environment and presupposes that the manikin will also be representative of the human heat exchanges in heterogeneous climates.

In reality, the manikin is more sensitive to climate changes than the globe is, because it can integrate the variations of the surface areas which are exposed to radiant heat exchanges. As an obvious consequence, a manikin will reflect more accurately the overall thermal exchanges than a globe would. The manikin gives worthwhile information on the local distribution of heat fluxes, which might be of major importance for generating subjective sensations in humans. In the simulations reported above, we found that the difference between the highest and the lowest heat flux was between the front-trunk (74 W.m^{-2}) and the bald head (95 W.m^{-2}) in the HOMO condition (21 W.m^{-2} difference). The CONVECT 1 condition which led to the same overall heat flux, generated a 35 W.m^{-2} difference between both segments. Under RADIANT 2 however, globally similar to either HOMO or CONVECT 1 (82W.m^{-2}), the largest difference (20 W.m^{-2}) was observed between front-trunk (68 W.m^{-2}) and legs (88 W.m^{-2}). Therefore, in view of the heat loss redistribution, it is easy to understand that local skin temperatures and/or mean skin temperatures as well as subjective estimations can be fundamentally different in radiant and convective climates. Thus, climate estimation based on globe temperature measures (or on any other device not really appropriate) does not necessarily reflect the heat fluxes exchanged (inferred from manikin) in the case of non-uniformity of ambient parameters. As a consequence, non uniform thermal environment may provoke undesired discomfort, especially when the radiant heat fluxes have not been correctly estimated.

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