INFLUENCE OF ACTIVITY AND WIND ON THE LOCAL CONVECTIVE HEAT AND MASS TRANSFER FROM NUDE MAN

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INTRODUCTION

Convection is frequently the dominating mechanism balancing the heat production of the human body. As couvection affects both the heat and the mass transfer, this physical process is of importance in warm as well as in cold conditions. There have been attempts to estimate the convection coefficient at the body surface from the theories valid for simple geometries as spheres and cylinders (1, 2). However, there are few studies on the local convection of the human body (3, 4), especially in regard to shape, activity and interacting parts of the body. The aim of the present investigation was to survey the convection coefficients at various parts of the body and their dependence on characteristic dimensions, wind speed and angle to the wind. An essential part of the investigation was also to compare the formulas describing the human convection coefficients with the empirical correlations valid for simple geometries such as cylinders.

METHOD

In the present investigation heat-flux sensor technique was used to measure the local (30-75 measuring sites) convection coefficients (5) at the various parts of the body of a male subject during standing still, walking (0,9-1,9 m/s) and running (2,0-3,2 m/s) on a treadmill in a wind tunnel. Convection coefficients were also measured on two male subjects during running (1,9-3,8 m/s) on an indoor running track. Duplicate measurements of the whole body convection coefficients of six male subjects with similar physical characteristics were performed using only 10 measuring sites. In this case the activities were standing still at wind speeds of 0 m/s and 1,9 m/s, and walking at 1,4 m/s facing the wind (1,4 m/s).

RESULTS

When standing still at no wind the convective heat transfer coefficient, h_c, depended on height, L (m), according to $h_c=2{,}9 \cdot L^{-0{,}27}$ W/(m^{2}K) up to a height of about 1,1 m. Above this level the h_c-value was almost constant, 3 3 W/(m^{2}K). The average whole body value was 3,6 W/(m^{2}K) at a temperature difference of 9°C. When standing still in wind, v (m/s), the equation, $h_c=a \cdot v^b$ defining the whole body convection coefficient, was $h_c=7{,}3 \cdot v^{0{,}61}$ after correction for turbulence and wind tunnel blockage effects. The convection coefficient was related to the characteristic diameter, d (m), as $a=3{,}8 \cdot d^{-0{,}36}$ and the exponent b ranged from 0.53 to 0,77 for the various parts of the body. The average, weighted Nusselt number of the whole body was $Nu=0{,}17 \cdot Re^{0{,}61}$. The local h_c-value varied with the angle to the wind similar to that of a circular cylinder in cross air flow. Adjacent parts of the body affected the local h_c-values. However, measurements with adjacent cylinders showed that the average h_c-value was only slightly reduced (= 7%) at a wind speed of 2 m/s when the distance between the cylinders was approximately 5 mm. Walking and running on the treadmill at no wind produced more complicated local h_c-pattern especially for the swinging limbs. The convection equations of the whole body were $h_c=7{,}6 \cdot v^{0{,}49}$ and $h_c=6{,}5 \cdot v^{0{,}65}$ during walking and running, respectively. The greatest h_c-values occurred for those parts having the highest velocity, the lower leg and the lower am. Walking and running in the wind tunnel produced very similar equations, $h_c=12{,}9 \cdot v^{0{,}55}$ and $h_c=12{,}7 \cdot v^{0{,}59}$, respectively. During walking the h_c-value of the lower leg was affected almost exclusively by the walking velocity whereas the trunk value was only influenced by the wind speed. In running activity and wind affected the h_c-value equally. The whole body h_c-value obtained at free running on the track was slightly lower than when running on the treadmill in the wind tunnel. However, the h_c-values of the leg were roughly the same. The trunk and arm h_c-values differed between the individuals. The differences between the repeated whole body h_c-values calculated from 10 measuring sites were not statistically significant (5%-level) for any activity. Neither there were any significant differences between subjects when standing in still air or when walking.

However, when standing at a wind speed of 1,9 m/s two subjects showed significantly different h_c-values.

CONCLUSIONS

The h_c-values of a human standing still at no wind were very close to those calculated for a vertical slim cylinder. Consequently, there are reasons to believe that the human convection coefficient can be estimated from the empirical relationships valid for cylinders also in other positions than the vertical one. When *exposed* to wind the dependence on the characteristic *diameter* was similar to that of vertical circular cylinders *resulting* in a cooling effect which is maximum on the windward side of the part of the body. Furthermore, as the convective heat transfer increases at reduced *diameter* the drop in tissue temperature. in cold weather can differ from that expected from the wind speed (wind chill index). Wind chill indices are valid only for a certain diameter and therefore the actual heat loss can be considerably higher for those parts of the body having smaller diameters. The Nusselt numbers of the various parts of the body indicate that the limbs and the trunk can be considered as vertical cylinders with a circular, hexagon or square geometry. The whole body can be considered as a vertical cylinder with a circular *or* hexagon shape with a characteristic diameter of 0,16 m. The swinging arms affected the leg and trunk h_c-values differently during walking compared with running depending on the position of the lower arms. Running technique seemed to influence mainly the position of the swinging arms, affecting the h_c-values especially at the trunk. The differences in h_c-value between the various parts of the body were reduced when wind was added to the activity. Also the difference between the Windward side and the leeward side was less compared with standing still in wind. The *differences* in whole body h_c-value between individuals seemed to be small during standing still exposed to natural convection and walking in the wind. *As* the dependence of the characteristic diameter on the h_c-value is greatest when standing still in wind significant deviations between subjects differing in *size* could be expected in this condition. However, the differences were to small to be detected with the actual number of measuring sites. By using the heat and *mass analogy* (Lewis number) the maximum evaporative mass *transfer* from the nude body can be calculated. When standing still in the wind, the sweat rate must exceed the maximum evaporation rate with roughly 2,5 times to keep the whole body wet. This is similar to those results obtained when investigating the maximum evaporation rate (6, 7). Activities such as walking *or* running affect the convection pattern around the body due to increased turbulence reducing the local differences. Hence, the cooling efficiency should be improved during activity compared with standing still in the wind due to less sweat dripping.

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