PHYSIOLOGICAL ASSESSMENT OF FIREFIGHTERS' PROTECTIVE CLOTHING IN THE FIELD AND IN THE LAB

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INTRODUCTION

The performance of firefighters strongly depends on the ability of their clothing to avoid heat storage in the body. Thus, protective clothing has to protect the wearer from external heat but also to allow body heat to escape. The thermal transfer and moisture management of firefighters' protective clothing can be assessed either in the field or in the laboratory. Both methods have their drawbacks: tests with human subjects require many tests to allow generally valid predictions. On the other hand, tests in the lab can only reproduce parts of the changing situations in practice. This study analyzes the behavior of clothing during practice-related exercises with firefighters and during simulated situations with a test apparatus.

MATERIALS AND METHODS

Measurements of the microclimate (temperature and humidity) in the clothing layers and the rectal temperature of **16** firefighters during exercises in heated rooms (about **35°C** and **50%** RH) and in firehouses have been performed. Temperature and humidity sensors were placed on the left shoulder **of** each subject, between the different garments. Furthermore, the firefighters swallowed a miniaturized sensor (in the form of a pill), which sent the actual core temperature to a receiver mounted on the stomach.

The exercises consisted of either performing a defined path in a cage in a heated room or standing near a fire in firehouses. The firefighters were fully equipped (with breathing apparatus; weight **of** the equipment: approximately 20 kg). The heat **source was** thus different in both cases: in the heated room, the subjects produced a high rate of metabolic heat. The *dry* heat transfer was reduced to a minimum as the environment temperature was between **30** and **38°C.** In the firehouses, the metabolic heat production was quite low because the subjects were only kneeling in front **of** the fire, but the external heat load was considerable. The radiant heat **flux** measured in the firehouses was typically **5** to **10 kW·m^{-2},** and the temperatures were **100** to **190°C** at 1 m above ground. The firefighters were wearing either breathable (semi-permeable) or impermeable (**PVC** coated) clothing. The test subjects and each part of their equipment were weighed before and after the exercises (precision of the scales: **10** g) to assess the amount of sweat produced and the percentage of moisture released to the atmosphere.

The conditions in the field were then simulated in the lab with a sweating torso. **This** apparatus (1) corresponds in its dimensions to a human **trunk.** It consists of different layers that have similar thermal properties **as** the skin layers.

The interior of the torso can be filled with water to obtain approximately the same heat capacity as the human body. The torso is heated electrically by heating foils and contains 36 sweating nozzles. It can thus be heated to human core and skin temperature (with a constant heating power) and release as much sweat as a human being would during the most strenuous effort. The torso was covered with jackets or material combinations comparable to those used during the practical exercises and put either in a climatic chamber or exposed to a large radiant heat source (heat **flux** up to 40 $kW \cdot m^{-2}$) to simulate the conditions in the field. The torso trial was carried out in 3 phases simulating a human subject at rest (phases 1 and 3, no sweat) and during an effort (phase 2, with sweat release corresponding to 1 $L \cdot h^{-1}$ for a man).

RESULTS

Exercise Courses

The chamber exercise lasted for 11 to 24 min depending **on** how fast the firefighters could maneuver through the cage. Eleven firefighters completed the exercise at a climate of approximately 30°C and 50% RH and ***5*** subjects at **38°C** and ***50%*** RH. In each case, the core temperature of the subjects increased rapidly. **At** 38°C, it increased at a rate of **2.8** to **5.1°C·h**$^{-1}$ (3.5°C·h^{-1} on average). Under these conditions,.the superior evaporative cooling of the breathable jackets showed **no** positive effect **on** the rectal temperature of the subjects, in comparison with the PVC coatings (single results: **2.8** and **3.1°C·h**$^{-1}$ for the PVC coated and **2.8,** 3.9 and 5.1°C·h^{-1} for the breathable jackets). At 30°C, the increase was not as great, 2.7°Ch-1 **on** average **and** ranged from 1.7 to 3.9°C·h^{-1}. In this case, the PVC-coated jacket was associated with the highest rate of increase. Monitoring of the core temperature of 2 firefighters during the whole exercise showed that it increased almost linearly during the effort and continued to rise for a few minutes when the subject was at rest. The results clearly show that at 30°C and 50% RH, the partial water vapor pressure difference between the microclimate in the jacket and the atmosphere is still important enough to allow a certain evaporative cooling through the garment. At 38°C and 50% RH, the pressure difference is too low to allow an efficient cooling through water vapor transfer through the garment. The sweat production of the subjects could not be related to the outside temperature because the body perspires as much as possible when the core temperature starts to rise. The sweat production varied greatly between subjects (0.5 to 2.1 L·h^{-1}), with an average value of 1.0 L·h^{-1} for the 16 firefighters.

The simulation of this exercise in the lab was done by putting the sweating torso (dressed with similarjackets to those used in the practical exercises) in a climatic chamber at 2 different climates (30°C or 35°C and 50% RH). The torso was operated with a heating power and a sweat rate corresponding to 400 W and 1 **L·h**$^{-1}$ for a man. The sweat rate thus corresponded to the amounts released during the practical exercises. However, an estimation of the metabolic rate of the firefighters showed that they had greater energy expenditure during the course than that acheived in the torso. As with the firefighters, the increase of core temperature of the sweating torso was dependent on the climate in the chamber. At 30°C, the core temperature increased by 1.9°C·h⁻¹ in the impermeable jacket and by 1.7°C·h⁻¹ in the breathable jacket. At 35°C, the increase was 2.8°C·h⁻¹ for the PVC-coated jacket and 2.6°C·h⁻¹ for the breathable one. These differences in rates of temperature increase between climates were comparable to the ones measured on the firefighters. During both series of tests, most of the released humidity remained in the textile layers. At 30°C, the breathable jacket could evaporate 17% of the supplied water and at 35°C only 4%. These very small percentages of evaporated moisture during these tests were likely to due to the fact that the jackets were placed tightly round the torso. This avoided any air layers or ventilation openings that could contribute to the overall release of moisture (3). As with the practical tests, the differences between both types of jackets were not very important as soon as the outside temperatures were approaching skin temperatures, even if the highest results were always reached by the impermeable jacket.

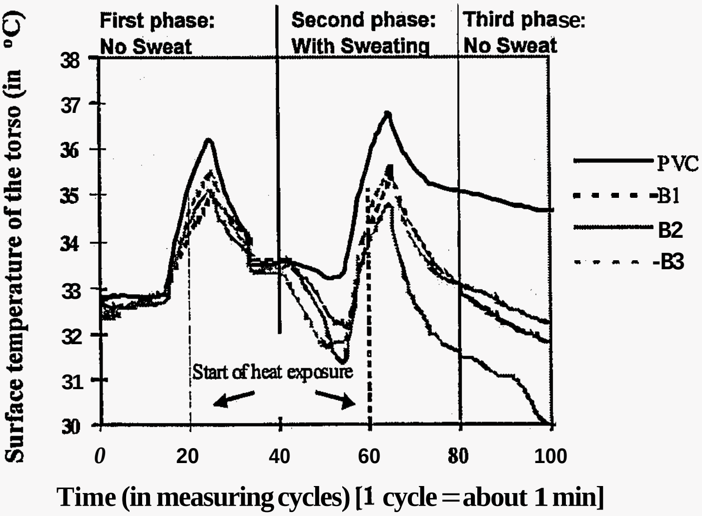

Figure 1. Evolution of the surface temperature of the torso for one PVC-coated combination (PVC) and three breathable combinations (B1-3).

Firehouse

The temperature rise when entering the firehouse was obviously due to the outside temperature and the radiant heat load. In this case, no difference between breathable and PVC-coated clothing could be seen either in the temperature increases inside the jackets or in the RH, which always reached nearly 100%. Nevertheless, measurements in the lab showed that part of the moisture contained in breathable combinations could evaporate and be released to the outside even under high radiant heat exposure, and under certain circumstances, contribute to heat protection (3). When the firefighters left the firehouse, it was interesting to observe that the RH remained near 100% in the PVC-coated clothing but came down rather quickly in the breathable combinations. The temperatures also stabilized at different temperatures: in Jacket C, the temperature remained between 36°C and 38°C; whereas in Jacket B, it came down to near 32°C.

The simulation of the firehouse was done by exposing the sweating torso to a large radiant heat source for a few minutes during the first (dry) and second (sweating) phase. During the first phase, the temperature evolution was due to the thermal insulation of the jackets. The temperature increase when exposed to the radiant heat was the greatest for the PVC-coated sample, showing that its heat protection must be lower than the one of the breathable combinations (B1-3). When the heat source was removed, the surface temperature of the torso decreased to approximately 34°C for all of the samples. At cycle 40, the torso started to sweat, which caused an important temperature reduction for all of the breathable combiuations because of the evaporative cooling of the sweat. The temperature under the PVC-coated combination nearly remained constant. After the radiant heat exposure, the surface temperature of the torso stabilized at 35°C for the PVC-coated material, but it dropped to an average of 32°C for the breathable combinations, similar to the results found during the practical exercise in the firehouse.

CONCLUSIONS

Both series of tests in the field and in the lab have shown that the rectal temperatures of the firefighters rise rapidly when the outside temperature exceeds 30°C (up to 1.3°C in about 15 min). Under these conditions, a large part of the produced sweat remains in the textile layers. The difference between PVC-coated and breathable jackets only becomes important when the firefighters return to a cooler outside temperature.

REFERENCES

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