Thermophysiological Responses Caused by Ballistic Bullet-Proof Vests

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Received 23 January 2006; in final form 24 June 2006; published online 18 October 2006

Background: Little data is available concerning the heat stress experienced by members of staff who wear bullet-proof vests in a warm or hot environment. For this reason, knowledge is limited and, consequently, preventative advice on how to avoid heat sickness or hyperthermia is required.

Study design: Skin and body temperatures, fluid loss and the heart rate of 30 persons (15 test persons versus 15 control persons) were measured in three situations typical of the test participants’ job situations. Environmental data (wind velocity, air humidity, air temperature) were measured during the tests as well.

Results: Whereas there was a significant increase in skin temperatures, there was no difference in the core body temperatures of both groups. Maximum core body temperature remained well below 38°C in all subjects. Test persons wearing vests showed a fluid loss of 1.1 l on average (non-vest wearers in the control group 1.0 l).

Conclusion: There is no increased risk of heat stroke or hyperthermia for employees wearing bullet-proof vests in comparison with employees who do not wear them. Both groups, however, should be advised to ensure an adequate intake of fluid to maintain a healthy body fluid balance when working in hot environments.

Keywords: bullet-proof vest; flak jacket; thermophysiological response; thermal stress

INTRODUCTION AND DESCRIPTION OF PROBLEM TO BE INVESTIGATED

Since 2001, officers of the Federal Customs Administration in the Federal Republic of Germany have been issued with new concealable ballistic bullet-proof vests. The staff affected includes customs patrol officers of the MKG (mobile Kontrollgruppen’) task forces, staff from the Department for the Investigation of Undeclared Work (Finanzkontrolle Schwarzarbeit FKS), and members of the Customs Investigations Services (Zollfahndungssämter ZFA) and of the Border Surveillance Services (GAD).

When the bullet-proof vests were introduced, the question was raised as to whether wearing such body-armour could cause an increased strain on a wearer’s organism. It remained to be established whether, depending on the extent of the increased strain on the wearer, preventative health protection measures were required to avoid health risks caused by excessive thermophysiological stress.

Although a large number of customs officers wear ballistic bullet-proof vests in the widest variety of tasks and activities, in contrast to the heat-stress workers, no comparative studies have as yet been carried out to investigate the heightened thermophysiological stress caused by wearing this kind of body-armour. To date, only one comparative study on the thermophysiological properties of different protective vests has been conducted. However, it was carried out without the participation of a control group of test participants not wearing the vests (Griefahn et al., 2003). The study at hand investigates the thermophysiological stress exercised on staff wearing ballistic bullet-proof vests.

MATERIALS AND METHODS

Experimental design

All tests were performed with a custom-made (computer aided manufacturing) vest (Model P,
protection class 1 according to German Police Regulations; class 1 is safe against projectiles of small arms). The vest’s material is polyethylene with 54.5 g dm\(^{-2}\) and a thickness of 7.6 mm (Fig. 1).

The study was carried out at the Sigmaringen offices of the Bildungszentrum der Bundesfinanzverwaltung in July under summer climate conditions. The test conditions reflect the employees’ usual daily working conditions as realistically as possible: slow walking as an analogue activity to carrying out security checks, fast walking analogue to making an arrest or seizure, sitting in a road vehicle analogue to travelling to the location of patrol duty.

Due to the restrictions on food and fluid intake, the duration of the tests had to be limited to a certain period of time. Each of the test groups from the FKS, MKG and ZFA divisions participated in two tests lasting 3 h respectively on two successive days.

During the afternoon of the first day, the test persons first simulated a shift of duty in their respective service vehicles and then under outdoor summer conditions on the sports field (Table 1). During the morning of the second day, the simulation tests were carried out in the indoor swimming pool of the institute under climatic conditions corresponding to almost unchanging summer conditions.

### Test persons

A total of 30 test persons (8 women, 22 men) from the FKS, MKG and ZFA divisions participated in the study. Half the test persons (4 females, 11 males) wore their uniform together with a personal, tailor-made ballistic bullet-proof vest (Model P armoured vest by the Baumann & Steffen Sicherheitstechnik GmbH–BSSt–company of Nellingen/Germany). The other half of the test persons formed the control

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**Table 1. Test conditions outdoors and at the indoor swimming pool (minimum/maximum values)**

<table>
<thead>
<tr>
<th>Stress variable</th>
<th>Outdoor test</th>
<th>Indoor swimming pool</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Test 1</td>
<td>Test 2</td>
</tr>
<tr>
<td>Air temperature (°C)</td>
<td>23.7/27.8</td>
<td>25.2/32.1</td>
</tr>
<tr>
<td>Air humidity (%)</td>
<td>7/17</td>
<td>39/44</td>
</tr>
<tr>
<td>Steam pressure (kPa)</td>
<td>0.2/0.58</td>
<td>1.22/1.31</td>
</tr>
<tr>
<td>Air velocity (m s(^{-1}))</td>
<td>0.47/2.4</td>
<td>0.55/0.81</td>
</tr>
<tr>
<td>Vehicle: air temperature (°C)</td>
<td>28.6/37.0</td>
<td>32.8/34.8</td>
</tr>
</tbody>
</table>

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**Fig. 1.** Police officers wearing custom-made bullet-proof vests Model P.
group (4 female, 11 males). They wore only their normal uniforms without body armour. One exception was the ZFA group of employees, who wear plain clothes on duty.

In order to ensure the comparability of the group wearing the bullet-proof vests with the control group, matching pairs were selected in respect to the test parameters of gender, age, height and weight (matched-pairs method). The two test persons of each pair were assigned to the respective test group per random selection. The resulting test groups were relatively homogenous in respect to the parameters of age, height, weight and Body-Mass-Index (BMI); there were no statistically significant differences. The anthropometric data of both test groups are listed in Table 2.

**Recording the thermophysiological variables**

- Perspiration
  To determine values for perspiration rates during the tests, the test persons were weighed without clothing prior to and subsequent to the tests. Additional weighing of the test persons when dressed allowed the determination of the amount of perspiration that had been absorbed by the test person’s clothing. Evaporation was minimal.

  The KCC 150 weighing scales by the Mettler-Toledo company was used for the tests. Reading accuracy of the scales is 1 g, calibration accuracy is 5 g.

- Heart rate
  During the tests, the heart rate was calculated continuously from the ECG by means of chest-strap and wireless transmitter (M22 heart rate monitor by the Polar company). It was possible to recall the heart rates measured during the test and, in addition, the actual value was recorded at 15 min intervals. The heart rate monitors were programmed so that an alarm was triggered when the maximum heart rate threshold (220-age) was exceeded. The test persons were instructed to contact the doctor whenever this happened.

- Skin temperature
  The skin temperature was measured before and after the tests: one dorsal measurement on the right and one ventral measurement in the area of the chest. The measuring device used was the Type 1214 indoor climate analyser with surface temperature sensor by Bruel & Kjaer. The accuracy of the system is given as 0.5°C.

- Core body temperature
  The temperature in the auditory canal was taken as a representative value for the core body temperature. The temperature was measured prior and subsequent to the test as well as at 30 min intervals during the test. The Omron Digital Ear Thermometer (made by the Ort company) was used to take the measurements; its accuracy rate is indicated at 0.1°C. The increase in core body temperature for each individual test person was calculated from the difference between the core body temperature measured at the beginning of the test and the highest core body temperature taken during the test.

**Test procedure**

The able-bodied test persons were informed about the test procedures prior to the beginning of the first test. All the test persons agreed to the procedure and were informed that they could withdraw from the study at any time they wished without giving reasons. The tests were conducted under the supervision of a medical doctor. The trial protocol was drawn up in compliance with the Declaration of Helsinki.

At first, the test persons were weighed without clothing, then the skin temperature was taken and the ECG chest-strap was fitted. Following this, the fully dressed test persons wearing the bullet-proof vests were then weighed with their equipment. The initial values for core body temperature and heart rate were recorded. In addition, blood pressure was also measured prior and subsequent to the test.

When these values had been recorded, the test phase began for both groups (one group with and one group without vests) at the same time. The first part involved spending 45 min sitting in the respective service vehicle—for the tests conducted outdoors—or 45 min sitting in the indoor swimming pool. Subsequent to these phases, the test persons were instructed to spend 30 min walking slowly followed by 15 min of walking quickly. The phase of 30 min of slow walking followed by 15 minutes of fast walking was repeated once and then followed by 45 min of sitting. The entire duration of the test was, therefore, 3 h.

During the test, the core body temperature was measured every 30 min, the heart rate every 15 min. On conclusion of the test, the heart rate and core body temperature were once again measured and the test persons then weighed fully clothed followed by a skin temperature measurement. Following this, the test persons were once again weighed without clothing.

During the test, visits to the rest room were only permitted in connection with a weight control. The

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Group without vest (mean value/range)</th>
<th>Group with vest (mean value/range)</th>
</tr>
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<tbody>
<tr>
<td>Age (Years)</td>
<td>37.7/23–53</td>
<td>36.3/23–47</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>175.9/163–188</td>
<td>177.6/168–189</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>81.9/56–105</td>
<td>77.0/55–106</td>
</tr>
<tr>
<td>BMI (kg m⁻²)</td>
<td>26.4/19.8–34.7</td>
<td>24.3/19.5–29.7</td>
</tr>
</tbody>
</table>
test persons did not eat or drink during the tests. Smoking was not permitted.

Data analysis and statistics

The values for core body temperature, perspiration rate, heart rate and skin temperature were analysed. These parameters are considered as representative values for the extent of thermophysiological stress experienced (Hettinger et al., 1980).

The values measured for the test persons were divided into three groups:

1. Values measured for the outdoor tests.
2. Values measured for the tests in the indoor swimming pool.
3. Values measured for all the tests.

The statistical method employed was the Mann–Whitney U-test. This non-parametric method was applied as it is more robust for a limited test-group size and also because it cannot be assumed beyond doubt that all data would meet the requirements of a parametric method, such as, for instance, normal distribution and variance homogeneity for the Student t-test. A mathematical verification of these requirements would, however, not have any significant value due to the size of the reference sample. The significance level was defined as $P < 0.05$.

RESULTS

Core body temperature

The core body temperature underwent varying and individual changes during the study. The test persons did not, for instance, reach the maximum core body temperature all at the same time. Individual values showed an inverse effect, that is, negative temperature differences or decreasing core body temperatures during the tests. The maximum temperature increase was 1.8°C (vest wearer).

During the tests in the indoor swimming pool, the core body temperature of the test persons both with and without vest rose by the same mean value of ~0.8°C. During the outdoor tests, the mean increase in core body temperature of the vest wearers was 0.4°C, in the control group the average increase was 0.5°C. Taking all the results of the tests together, the mean increase for test persons with vests was 0.6°C, for test persons without vests the mean increase was 0.7°C.

The temperature differences between the two test groups are statistically not significant, and furthermore, the absolute difference value for all the tests of 0.09°C lies below the measurement inaccuracy value for a thermometer (0.1°C).

Perspiration

Minimum fluid loss was 336 g, maximum fluid loss 2238 g. The mean value for the vest wearers in the outdoor tests was 1.3 kg (0.479–2.238) and for non-vest wearers 1.1 kg (0.336–1.907). This difference is statistically insignificant. The mean perspiration value for the groups in the indoor swimming pool was 1.0 kg (with vest 0.540–1.940, without vest 0.563–2.320), whereby there was no difference between the vest wearers and the control group. The analysis of all the test results showed a mean fluid loss of 1.1 kg (0.479–2.238) for the group of vest wearers and of 1.0 kg (0.336–2.320) for the group without vests. The difference in the mean values of ~110 g is without significance for the test collective as a whole ($P = 0.246$).

Heart rate

With one exception, where the heart rate of one test person briefly exceeded the upper threshold value under physical duress, the increase in heart rates remained below this threshold.

The mean heart rate value was higher for the vest wearers than for the control group both in the indoor and outdoor tests. The mean value for the outdoor tests was 107 beats per minute with vest (81–129) and 102 beats per minute without vest (84–143). The values for the indoor tests ranged between 92 and 87 beats per minute (with vests 71–113, without vests 63–101). These differences are statistically insignificant.

Skin temperature

Due to a problem with one of the technical devices, the results for the first test group (FKS employees) could not be included in the analyses. As a result, the size of the test collective for these parameters was reduced to nine test persons each in the test group and control group.

The skin temperature of the vest wearers increased more than the skin temperature of the control group. The tests in the indoor swimming pool showed a 2.4°C (0.0–0.6) skin temperature increase for the vest wearers; without vest the skin temperature increase was 0.9°C (0.8–2.5). This difference is highly significant ($P = 0.012$). Vest-wearer skin temperature increased by 2.0°C in the outdoor tests (~0.4 to 3.9), for non-vest wearers it increased by 1.0°C (~0.4 to 2.9). These values indicate the same tendency but in this case the difference is not significant. The total results of both groups showed that the mean increase of 2.2°C for vest wearers (0.4–4.6) compared with 0.9°C for non-vest wearers (0.8–2.9) was relatively high and significant ($P = 0.002$).

DISCUSSION

Although many officers wear bullet-proof vests, under different circumstances, there is a general lack of knowledge about the stress these vests cause,
especially in hot environments. For our study we used Model P, which is the standard model for German police and custom officers now. Users report feeling comfortable with it in comparison with previous types.

All test persons exhibited increased perspiration rates, whereby the vest wearers tended to perspire more strongly than the test persons in the control group, although the difference cannot be statistically documented. Related to the average fluid loss, the additional fluid loss experienced by vest wearers can be considered negligible. One litre of fluid loss corresponds to a loss well below 5% of the body weight. In a healthy adult, this will not impact the person’s capacities or efficiency and certainly does not constitute a health hazard (Hollmann and Hettinger, 2000, p. 339).

The increased blood circulation in the skin for the purpose of temperature regulation results from an inner heat flow, i.e. when the blood volume is increased per unit of time then more heat is transported per unit of time. The skin temperature in the periphery increases and heat dissipation increases. Circulating blood volume is predominantly increased by an increased heart rate ((Hollmann and Hettinger, 2000, pp. 477 ff.). All the test persons reacted in this regard with an increase in heart rate. The vest wearers reacted with a stronger increase in heart rate than the control group members. This indicates that higher thermophysiological stress was experienced by the test group. The physical work performed cannot have contributed to this higher increase, as the physical stress conditions were identical for both groups. The additional increase of the mean heart rate for the vest wearers was 5 beats per minute on average. This additional increase can be considered negligible. The absolute heart rate increase also did not exceed 100 beats per minute when at rest or 130 beats per minute during physical exertion (= criteria for assessing critical heat stress according to Valentin et al., 1985). The overall values constitute physiologically adequate reactions to this type of exertion.

The significant skin temperature increase experienced by the vest wearers is the result of the insulating effect of the bullet-proof vest. The material of these vests is fluid-tight so that perspiration cannot evaporate and, therefore, cannot have a cooling effect as it gathers on the inside of the vest and flows off the surface. This situation is reflected in the increased skin temperature of the vest wearers. Reduced water evaporation on the skin could lead to a temperature build-up and possible hyperthermia. The temperature build-up is analogue to the increase in core body temperature. When the body has exhausted all means of heat exchange, the core body temperature can increase by ~1.5°C without the posing a risk to the person’s health (Hettinger et al., 1980). The increase in core body temperature of all the test persons, with one exception, was well below this threshold value. In the case of the exception, the maximum core body temperature rose to 36.8°C, a level that is significantly lower than the threshold value of 38.0°C indicating a level of normally supportable heat stress.

There was no difference in the extent of temperature increase between the groups of vest wearers and non-vest wearers in spite of the insulation effect of the concealable vests. The vest covers the ribcage and upper portion of the abdomen and consequently ~27% of the body surface. However, part of the torso, the extremities and the head are not protected. In these areas, heat dissipation due to evaporation, convection and radiation remains unaffected to the extent that the insulating effect of the vest apparently is of subordinate importance.

An additional pilot investigation with officers performing highly active operations such as taking a house by storm showed similar results to our study. This is because such operations are performed for a very short time, sometimes only some seconds. Therefore only minimal additional heat is produced during such activities.

CONCLUSION

The overall conclusion of these findings is that wearing a ballistic bullet-proof vest causes a moderately increased thermophysiological response of the wearer. However, the mechanisms of thermal regulations are capable of compensating for the additional stress experienced by the human organism in response to wearing a bullet-proof vest.

The tests conducted showed no indications for a health hazard. Furthermore, it can be expected that regularly wearing the vests improves the adaptive reaction of the body [the so-called heat adaptation (Valentin et al., 1985)]. To avoid health impairment, staff on duty must observe the known rules of conduct while working under high temperatures. The most important measure is to ensure an adequate intake of fluids (Cheung et al., 2000).

Acknowledgements—The authors wish to thank the staff of the Bildungszentrum der Bundesfinanzverwaltung (Educational Institute of the Federal Financial Authorities of Germany) in Sigmaringen and H. Schröder, Bundesministerium der Finanzen, Referat Z C 1, Bonn/Germany for their support and, most particularly, all the test volunteers for their cooperation and assistance in conducting the study.

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E. J. Lehmacher, P. Jansing and T. Küpper