

Physiological Strains of Wearing Aluminized and Non-aluminized Firefighters' Protective Clothing during Exercise in Radiant Heat

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Abstract: This study examined the influences of aluminized (Type A) and non-aluminized firefighters' protective clothing (Type B, C, D and CON) on physiological and subjective responses in radiant heat. Total clothing weight was 6.24, 6.38, 6.06, 5.76 and 3.82 kg for Type A, B, C, D and CON, respectively. Eight firefighters performed exercise at an air temperature of 30°C with 50%RH. Three bouts of 10 min-bicycle exercise in radiant heat (a globe temperature of 70°C) was spaced by a 10 min rest with no radiant heat. Results showed that rectal temperature, mean skin temperature, heart rate, and body weight loss were significantly greater in Type A than in other types ($p < 0.05$). For Type A, thermal gradient of the body reached $0.0 \pm 0.7^\circ\text{C}$, heart rate showed a maximum level of 183 ± 11 bpm and 1.9% of body weight was lost due to sweat secretion. Firefighters felt the hottest and most discomfort in Type A. It appeared that firefighters' thermoregulatory mechanism was severely challenged by wearing aluminized protective clothing during exercise in strong radiant heat. Therefore, it is suggested that the safe upper limits while wearing aluminized firefighters' clothing should be distinguished from those for typical firefighters' protective clothing.

Key words: Firefighters' protective clothing, Latent heat resistance, Clothing weight, Aluminized protective clothing, Thermoregulation, Thermal gradient of the body

Introduction

Tochihara and his colleagues¹⁾ reported that from a survey of 796 Japanese firefighters, approximately 50% of total respondents had experienced heat disorders during firefighting. Physiological strains in firefighting activities are a result of the combination of strenuous physical work, extreme thermal environments, and heavy protective clothing. In particular, firefighters' protective clothing exacerbates the heat strain by a) increasing the metabolic rate due to the addition of clothing weight load and b) inhibiting body heat dissipation from

the skin to the air. For example, firefighters' turnout gear tends to have greater thermal insulation^{2, 3)} and be heavier⁴⁾ compared to other personal protective clothing. Firefighters' protective clothing resulted in the increment of metabolic rate by $15 \text{ W}\cdot\text{m}^{-2}$ at rest and $115 \text{ W}\cdot\text{m}^{-2}$ during heavy work⁵⁾. Increasing clothing weight by 3 or 5 kg raised energy costs by 5 and 9% respectively during exercise, compared to normal clothing⁶⁾. Oxygen consumption increased 13–18% by wearing protective clothing of 9.3 kg⁷⁾.

It is, however, reported that more than half of the increase in metabolic cost could not be attributed to ensemble weight⁴⁾, which indicates that significant influences of other clothing factors (such as evaporative resistance, vapor impermeability, a restriction of

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motions, or pumping effects) are in existence. In particular, despite firefighters often being required to wear aluminized protective clothing against radiant heat and flame to avoid burns, little information exists in regard to the thermoregulatory role of aluminized protective clothing through human trials in high radiant heat. Thermal strains while wearing impermeable protective clothing have been reported^{8, 9)}, but those reports do not reflect the reflective effect of clothing to radioactive heat and was often confounded with the effect of added clothing weight because typical impermeable protective clothing is accompanied by the increase of total clothing weight.

There are a number of reports pertaining to the protective role of flame protective clothing through manikin and fabric tests¹⁰⁾ and human trials that state that wearing aluminized protective clothing in heat at rest caused no differences in body temperatures compared to a situation with normal work clothing¹¹⁾. Thus there is little doubt about the protective role of flame protective clothing at rest. However, during exercise in strong radiant heat, there is a growing interest in the desirability to reduce heat strain in cases where aluminized coating impairs the dissipation of metabolic heat from the body as a result of the restriction of evaporation of sweat. Despite the large body of knowledge concerning the thermal burden of firefighters' clothing, many practical questions remain unanswered. Few reports have been made on the comparison of various types of firefighters' clothing, including research on flame protective clothing during working in strong radiant heat. By understanding the change in physiological burden to which flame protective clothing may contribute, more effective ergonomic intervention should be attempted for firefighters working in radiant heat.

Although the simultaneous accomplishment of both protective and thermoregulatory roles in protective clothing seems to be unachievable without the aid of personal cooling systems, further investigations about the fundamental thermoregulatory properties of firefighters' protective clothing would hold clues to solve the conflict between protection and comfort. As for firefighting in radiant heat, body temperature increased in the aluminized turnout gear due to the factor of water vapor impermeability, whilst providing protection from the radiant heat from the fire. It is important to understand the trade-off between protection from flames, and the additional thermal stress when wearing aluminized protective clothing. Therefore, the purpose of this study was to examine physiological and subjective responses when wearing aluminized and non-aluminized firefighters' protective clothing during exercise in strong radiant heat.

Methods

Subjects

Eight male firefighters from Fukuoka City participated as volunteers. The physical characteristics of the subjects were as follows: 35.8 ± 3.8 yr in age; 169.9 ± 5.0 cm in height; 68.9 ± 11.2 kg in body weight; 23.9 ± 4.0 in body mass index (BMI) and 48.6 ± 6.9 ml·min⁻¹·kg⁻¹ in $\dot{V}O_{2\max}$. Subjects were informed of experimental procedures and associated risks. Written informed consent was obtained from all participants prior to their participation in this study. This research was approved by the Institutional Review Board (IRB) of Kyushu University.

Determination of the maximal rate of oxygen consumption






The maximal rate of oxygen consumption ($\dot{V}O_{2\max}$) was measured at an air temperature of 30°C with a relative humidity of 60%, using an expiration gas analyzer (AE300s, Minato Electronics Inc., Japan) on a bicycle ergometer (Aerobike 75XL, Combi Co. Ltd., Japan). Subjects wore a T-shirt, shorts, socks and running shoes. Fitchetts' protocol¹²⁾ consisted of four phases of four minutes duration each, for a total of 16 min. Heart rate (HR) was monitored every minute (a Life Scope 6, Nihon Kohden Co. Ltd., Japan).

Clothing ensembles and properties

Four types of firefighters' protective clothing that are currently used in Japanese fire offices (Type A to D) and one type of light work clothing (CON) as a Control were selected (Table 1). The firefighter's light work clothing (CON) consisted of basic clothing (T-shirt of 133 g, under shorts 80 g, trousers 327 g, and socks 57 g), a work-shirt 333 g, gloves 128 g, boots 2,243 g, and a helmet 524 g. Type A to D consisted of the basic clothing (T-shirt 133 g, under shorts 80 g, trousers 327 g, and socks 57 g), protective outer jacket and pants, gloves 128 g, boots 2,243 g, and a hood-helmet 933 g. The helmet in CON differed from the hood-helmet in Type A to D. The self-contained breathing apparatus (SCBA) was not worn in any condition in the present study.

The total clothing weight including gloves, boots and a helmet were 6.24, 6.38, 6.06, 5.76 and 3.82 kg for Type A, B, C, D and CON, respectively (Table 1). Thermal insulation of outer protective clothing ranged from 1.54 to 1.65 clo. The resistances to latent heat were 0.045, 0.029, 0.030, 0.029, and 0.022 kPa·m² W⁻¹ for Type A, B, C, D and CON, respectively (Table 1). Thermal insulation of clothing and the Woodcock water vapor permeability coefficient (i_m) were determined

Table 1. Specifications of the five types of protective clothing in the present study

| | Type A | Type B | Type C | Type D | CON |
|---|---|---|--|---|---|
| |  |  |  |  |  |
| Clothing Property | | | | | |
| Inner base material -the 1st layer | Aromatic polyamide 280 g·m ⁻² | Aromatic polyamide 280 g·m ⁻² | Aromatic polyamide 240 g·m ⁻² | Aromatic polyamide 240 g·m ⁻² | Aromatic polyamide 166g·m ⁻² |
| Heat insulated material -the 2nd layer | Stripe geometry 200 g·m ⁻² | Stripe geometry 200 g·m ⁻² | Waffle geometry 150 g·m ⁻² | Waffle geometry 150 g·m ⁻² | - |
| Water resistant layer -the 3rd layer | Moisture-permeable waterproof film 100~140 g·m ⁻² | Moisture-permeable waterproof film 100~140 g·m ⁻² | Moisture-permeable waterproof film 100~140 g·m ⁻² | - | - |
| Surface coated | Aluminum | - | - | - | - |
| Water vapor permeability (g·m ⁻² ·h·kPa) | 1.5 | 110 | 120 | 210 | 490 |
| Water vapor permeability index (<i>i_m</i>) ^{a) b)} | 0.01 | 0.34 | 0.43 | 0.51 | 0.55 |
| Clothing weight: Jacket+Pants (g) | 2,340 (1,350 + 990) | 2,480 (1,480 + 1,000) | 2,160 (1,281 + 879) | 1,860 (1,120 + 740) | 660 (333 + 327) |
| Thermal insulation (clo) ^{b)} | 1.60 | 1.60 | 1.65 | 1.54 | 1.25 |
| Resistance to latent heat (m ² ·kPa·W ⁻¹) ^{b)} | 0.045 | 0.029 | 0.030 | 0.029 | 0.022 |
| Total clothing weight ^{c)} (kg) | 6.24 | 6.38 | 6.06 | 5.76 | 3.82 |

a) Woodcock-Water vapor permeability index as the ratio of I_T to total evaporative resistance. A completely impermeable clothing ensemble has an index value 0; an ideally permeable ensemble would have an index value of 1. A pumping effect may increase i_m .

b) The details of the measurement and calculation of thermal insulation, vapor permeability, and the resistances to latent heat were presented in Tamura (2007).

c) Control (CON) consists of T-shirts (133 g), under shorts (80 g), work shirts (333 g), work pants (327 g), socks (57 g), rubber gloves (128 g), rubber boots (2,243 g), and a helmet (524 g); Ensembles for Type A to D consisted of T-shirts (133 g), under shorts (80 g), work pants (327 g), socks (57 g), rubber gloves (128 g), rubber boots (2,243 g), a hood-helmet (933 g) and outer jacket/pants.

using a dry and a wetted manikin. The details of the measurement and calculation of thermal insulation, vapor permeability, and the resistances to latent heat were presented in Tamura³⁾. Concerning the properties of clothing ensembles, Type A is characterized by the great thermal resistance and smallest i_m among all types; Type B is heavier than other four types; Type C had the greatest thermal insulation among all types; Type D was less heavy, insulates less and lower in thermal resistant than the other four types (Table 1). Outer protective jacket and pants in Type A and Type B were manufactured with identical fabric layers except the outermost layer of Type A that was coated with aluminized silver. Type D had no water-resistant layer. Materials of Type A to C were well defined by ISO 11613¹³⁾.

Thermal environments and experiment procedures

The test-room was maintained at an air temperature (T_a) of 30°C with a relative humidity of 50% (wet bulb

temperature of 22°C). Additional infrared heat radiation (1.1 kW·m⁻²) was used during exercise sessions through a movable lamp panel that was hung from the ceiling of the chamber. The infrared heat radiation was produced using a bank of 375 W photoflood lamps (Toshiba Lighting and Technology Corporation, R100V375WRHE, Japan). During exercise the black globe temperature started at 30°C and then quickly rose to 70°C in several minutes. Wet Bulb Globe Temperature (WBGT) values were estimated at 32.4°C during exercise and 24.4°C during recovery. Each subject rested in the pre-test room that maintained a T_a of 25°C and 50–60%RH for 40 min before entering the test-room. After entering the test-room, subjects rested on a bicycle ergometer for another 10 min, followed by exercise (EXE) and recovery (RCV) of 10 min each for a total of three cycles. The exercise intensity was set at 30%, 45% and 60% of $\dot{V}O_{2max}$ for the first, second and third exercise (Exe 1, Exe 2, and Exe 3, respectively;

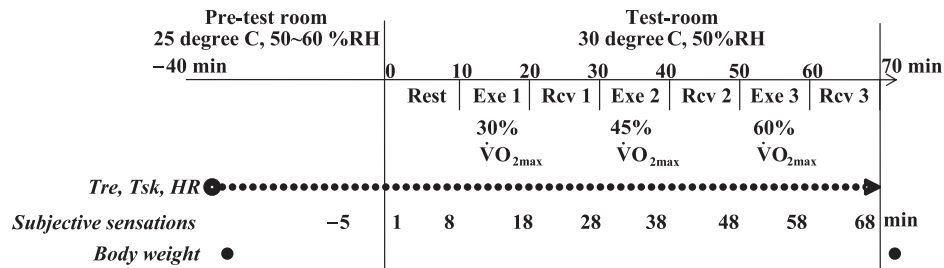


Fig. 1. Experiment protocol and measurement items.

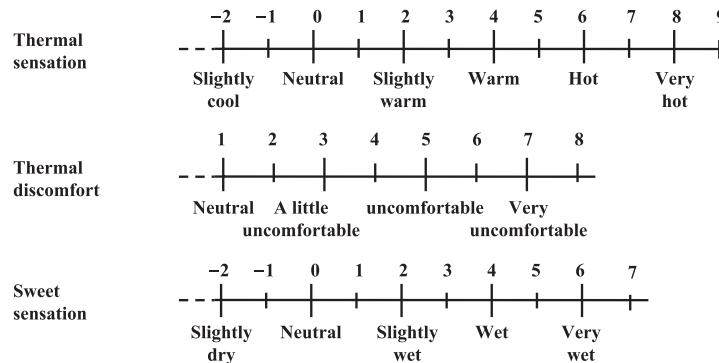


Fig. 2. Categorical scales for the measurement of subjective responses.

Numbers were not presented to subjects.

Fig. 1). The energy expenditures were estimated at 188, 283 and 376 $W \cdot m^{-2}$ during exercising at 30%, 45% and 60% of $\dot{V}O_{2max}$, respectively. Each subject drank 200 ml of water and then urinated before testing began.

Physiological responses

Rectal temperature (T_{re}) was measured by a thermistor probe inserted 15 cm beyond the anal sphincter of the rectum. Skin temperatures (T_{sk}) were measured by thermistor probes at eight body regions (the head, abdomen, back, forearm, hand, thigh, calf and foot). T_{re} and skin temperatures were monitored every two seconds by a data logger (LT-8A; Gram Corporation, Japan). Recovery rectal temperature ($T_{re\ rev}$) was averaged for five minutes from 60 to 65 min of each trial. Mean skin temperature (\bar{T}_{sk}) was estimated using a modified Hardy and DuBois' equation¹⁴). Heart rate (HR) was monitored using a Life Scope 6. Recovery heart rate (HR_{rcv}) was averaged for one minute just after the third exercise stopped (from 60 to 61 min). Body weight loss (BWL) was determined by the change in body weight before and after the experiment (METTLER ID2 MultiRange, Mettler-Toledo GmbH, West Germany, resolution of 1 gram). Absorbed sweat volume in clothing (ASV) was determined by the change in clothing weight before and after the experiment using the above scale. Evaporative efficiency of the clothing was calculated as the ratio of the difference between BWL and

ASV to total body weight loss (BWL): i.e., Evaporative efficiency of the clothing = $(BWL - ASV) \times 100/BWL$. The physiological strain index (PSI)¹⁵ was calculated as follows: $PSI = 5(T_{re_t} - T_{re_0}) \cdot (39.5 - T_{re_0})^{-1} + 5(HR_t - HR_0) \cdot (180 - HR_0)^{-1}$. Where T_{re_0} and HR_0 are the initial T_{re} and HR, and T_{re_t} and HR_t are measurements taken in the last three minutes during the third exercise session (from 57 to 60 min). The PSI was scaled in a range of 0–10 to evaluate heat stress.

Subjective responses

Responses to thermal sensation, thermal discomfort, and humidity sensation were taken every 10 min for 60 min, using categorical scales (Fig. 2). Participants were also asked about their condition using the rate of perceived exertion (RPE) Borg scale¹⁶ ranging from 'light (6)' to 'extremely hard (20)'.

Statistical analysis

Differences in the five types of clothing were examined by a two-way analysis of variances (ANOVA) with repeated measures for rest, followed by exercise and recovery of 10 min each for a total of three separate cycles (experimental conditions: Type A, B, C, D, and CON; time). Scheffe's post hoc comparisons were used to assess the significant main effects using ANOVA. During the third exercise period, Pearson's correlation coefficient of variance was tested. Statistical signifi-

Table 2. Physiological and subjective responses of firefighters

(Values: mean ± SD)

| | Clothing conditions | | | | |
|--|---------------------|----------------|--------------|--------------|-------------|
| | Type A | Type B | Type C | Type D | CON |
| T_{re} (°C) at 3rd exercise | 38.2 ± 0.3* | 38.0 ± 0.4 | 38.0 ± 0.4 | 37.9 ± 0.4 | 37.8 ± 0.2 |
| \bar{T}_{sk} (°C) at 3rd exercise | 38.2 ± 0.8*** | 37.5 ± 0.3 | 37.5 ± 0.3 | 37.3 ± 0.5 | 37.1 ± 0.3 |
| $T_{re}-\bar{T}_{sk}$ (°C) at 3rd exercise | 0.0 ± 0.7* | 0.5 ± 0.3 | 0.6 ± 0.2 | 0.7 ± 0.2 | 0.7 ± 0.4 |
| HR (bpm) at 3rd exercise | 183 ± 11*** | 176 ± 10*** | 176 ± 14*** | 169 ± 11*** | 157 ± 12 |
| $T_{re\ rcv}$ (°C) ^{a)} | 38.5 ± 0.4* | 38.2 ± 0.4 | 38.3 ± 0.5 | 38.2 ± 0.5 | 37.9 ± 0.3 |
| HR _{rcv} (bpm) ^{b)} | 158 ± 20*** | 147 ± 11** | 142 ± 14* | 138 ± 16 | 125 ± 13 |
| ΔT_{re} (°C) ^{c)} | 0.92 ± 0.33* | 0.72 ± 0.24 | 0.73 ± 0.33 | 0.70 ± 0.31 | 0.44 ± 0.17 |
| ΔHR (bpm) ^{d)} | 104 ± 11** | 98 ± 13* | 96 ± 11* | 93 ± 16 | 81 ± 15 |
| PSI | 9.2 ± 2.0*** | 7.8 ± 1.8*** | 8.0 ± 2.1*** | 7.1 ± 2.4** | 5.3 ± 1.5 |
| BWL (g·70 min ⁻¹) | 1,283 ± 327*** | 1,088 ± 288*** | 973 ± 392*** | 966 ± 254*** | 757 ± 260 |
| ASV (g·70 min ⁻¹) | 888 ± 216*** | 626 ± 190*** | 552 ± 210*** | 493 ± 180*** | 267 ± 133 |
| Evaporative efficiency of the clothing (%) ^{e)} | 31 | 42 | 43 | 49 | 65 |
| Thermal sensation at 58 min | 7.9 ± 1.1*** | 6.8 ± 1.6** | 6.9 ± 1.8** | 6.8 ± 1.6** | 5.1 ± 1.5 |
| Thermal discomfort at 58 min | 6.9 ± 1.2*** | 6.0 ± 1.5* | 5.8 ± 1.6 | 6.3 ± 1.5* | 4.8 ± 1.7 |
| Humidity sensation at 58 min | 5.9 ± 0.8** | 5.8 ± 0.7* | 5.9 ± 1.0** | 5.6 ± 0.7 | 4.9 ± 0.6 |
| RPE at 58 min | 16.3 ± 2.1* | 17.0 ± 2.8 | 16.5 ± 2.2 | 16.7 ± 2.3* | 14.5 ± 2.1 |

*** $p < 0.001$, ** $p < 0.01$ and * $p < 0.05$, significant differences in comparison with CON; T_{re} (rectal temperature); \bar{T}_{sk} (mean skin temperature); HR (heart rate); PSI (Physiological Strain Index); BWL (body weight loss); ASV (absorbed sweat volume in clothing); RPE (the rate of perceived exertion); ^{a)} $T_{re\ rcv}$ =average of T_{re} from 60 to 63 min; ^{b)} HR_{rcv}= average of HR from 60 to 61 min; ^{c)} ΔT_{re} =changes in T_{re} between average of 57 to 60 min and the baseline (0 to 10 min); ^{d)} ΔHR =changes in HR between average of 57 to 60 min and the baseline (0 to 10 min); ^{e)} Evaporative efficiency of the clothing (%)=(BWL-ASV)*100/BWL.

cance was set at $p < 0.05$. The values were presented as mean values and standard deviation (mean ± SD).

Results

Rectal temperature (T_{re}) and mean skin temperature (\bar{T}_{sk})

Rectal temperature showed almost the same transition in all conditions until around 30 min, but Type A had significantly higher T_{re} during the third exercise session (38.2 ± 0.3°C), compared to those of other types (38.0 ± 0.4°C, 38.0 ± 0.4°C, 37.9 ± 0.4°C, and 37.8 ± 0.2°C for Type B, C, D and CON, respectively, $p < 0.05$; Table 2, Fig. 3). There was no significant difference in T_{re} among Type B, C, and D (Table 2, Fig.3). For the last recovery, T_{re} in Type A progressively increased with no plateau ($T_{re\ rcv}$ of 38.5 ± 0.4°C). The rise of rectal temperature (ΔT_{re}) from baseline (at 0–10 min) to the end of exercise (at 57–60 min) were 0.92 ± 0.33, 0.72 ± 0.24, 0.73 ± 0.33, 0.70 ± 0.31 and 0.44 ± 0.17°C for Type A, B, C, D and CON, respectively ($p < 0.05$, Table 2, Fig. 3). Mean skin temperature (\bar{T}_{sk}) during the 3rd exercise was significantly higher in Type A (38.2 ± 0.8°C) than the other four types ($p < 0.01$, Table 2), while there was no significant difference in \bar{T}_{sk} among Type B, C, and D. For Type A, the average

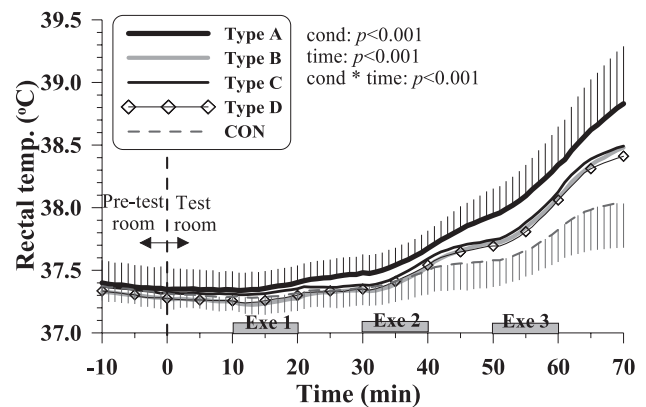


Fig. 3. Time courses of rectal temperature (T_{re}). Values are means and SD. ('Exe' stands for exercise; 'cond' for condition.)

value of \bar{T}_{sk} during the 3rd exercise was the same as the average of T_{re} .

Thermal gradient of the body ($T_{re}-\bar{T}_{sk}$)

The tissue thermal gradient that was estimated as the difference between rectal and mean skin temperature ($T_{re}-\bar{T}_{sk}$) was approximately 3–4°C before starting exercise with no significant differences among the five types, but the gradient gradually decreased as exer-

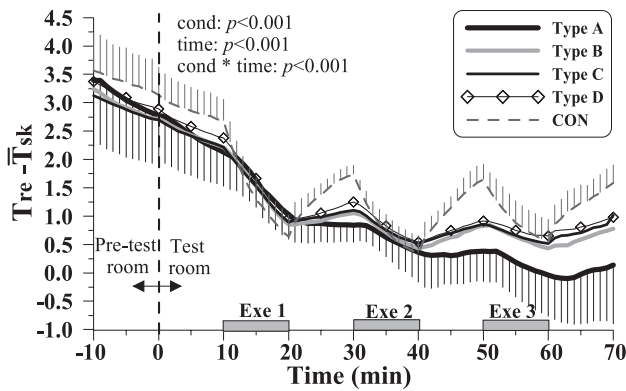


Fig. 4. Time courses of the difference between rectal temperature (T_{re}) and mean skin temperature (\bar{T}_{sk}).

Values are means and SD. (Exe=exercise; cond=condition)

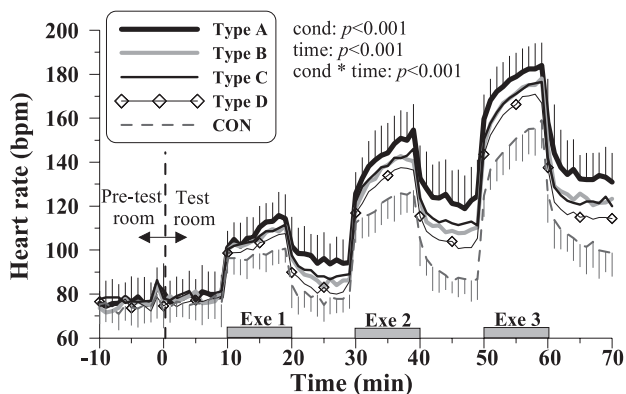


Fig. 5. Time courses of the heart rate (HR). Values are means and SD. (Exe=exercise; cond=condition)

cise was performed (Fig. 4). During the 3rd exercise and recovery, the thermal gradient in Type A reached $0.0 \pm 0.7^\circ\text{C}$, while Type D and CON had the highest values ($0.7 \pm 0.2^\circ\text{C}$ and $0.7 \pm 0.4^\circ\text{C}$, respectively). During each recovery, the thermal gradient of the body in CON tended to increase. Type B, C, and D did not show any significant differences in the body thermal gradient (Fig. 4).

Heart rate (HR)

During the 3rd exercise, heart rate was significantly greater in Type A (183 ± 11 bpm) than in the other four types ($p < 0.001$), and was the lowest in CON (157 ± 12 bpm). No significant difference in HR was found between Type B, C and D (Table 2, Fig. 5). HR_{rcv} was significantly greater in Type A (158 ± 20 bpm). The rise in HR (ΔHR) for 60 min was the greatest in Type A (104 ± 11 bpm, $p < 0.05$), and the rate of rise in HR ($\% \Delta HR$) were 28, 21, 19 and 15% for Type A, B, C and D, respectively, when compared to the change in CON as a baseline.

Physiological strain index (PSI)

The PSI during the 3rd exercise was the greatest in Type A (9.2 ± 2.1), followed by Type B (7.8 ± 2.0), Type C (8.0 ± 2.2), Type D (7.1 ± 2.6), and CON (5.3 ± 1.6) (Table 2). CON had significantly lower PSI than all protective clothing conditions ($p < 0.001$).

Body weight loss (BWL) and absorbed sweat volume in clothing (ASV)

Body weight loss during the repetition of exercise and recovery in heat was significantly greater in Type A (1.28 ± 0.33 kg for 70 min) than in other types ($p < 0.05$). Body weight loss in Type A was 1.7 times greater than that in CON, while there was no significant difference among Type B, C and D. CON had the smallest BWL value among all conditions (0.76 ± 0.26 kg, $p < 0.001$, Table 2). Regarding the absorbed sweat volume in clothing, Type A showed significantly greater value (0.89 ± 0.22 kg) than other types ($p < 0.001$, Table 2). Type A absorbed as much as the 69% of total sweat rate (888 g of 1,283 g), while CON absorbed only 35% of total sweat rate (267 g of 757 g). The evaporative efficiencies of clothing were 31, 42, 43, 49 and 65% for Type A, B, C, D, and CON (Table 2).

Subjective responses

Significant differences in subjective thermal perceptions were observed during the 3rd exercise and recovery ($p < 0.05$, Table 2). Firefighters expressed the hottest sensation, the most discomfort, the highest sensation of being wet, and the hardest perceived exertion for Type A, while CON was evaluated as having the least subjective thermal burden among all clothing conditions. There were no significant differences in thermal sensation among Type B, C and D.

Relationships between clothing properties and the thermal gradient of the body

A significant negative correlation was found between the resistance to latent heat and the tissue thermal gradient ($r = -0.50$, $p < 0.001$), while the tissue thermal gradient showed no relationship with clothing weight or thermal insulation of clothing (Fig. 6).

Discussion

This study compared various types of firefighters' protective clothing, including flame protective attire, through human trials in strong radiant heat. It is not surprising that firefighters' protective clothing induced significant heat stress during exercise. However, significant differences between the aluminized and non-aluminized firefighters' protective clothing are notable,

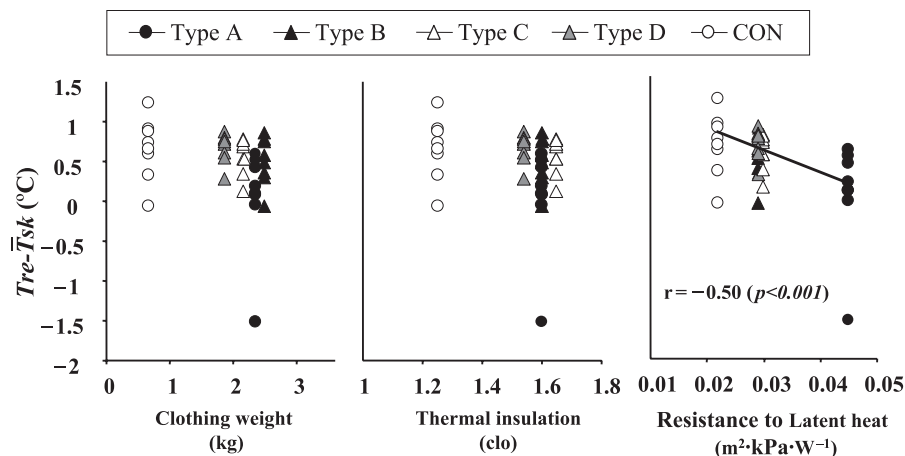


Fig. 6. Relationships between clothing weight, thermal insulation of clothing and resistance to latent heat and difference between rectal temperature and mean skin temperature.

because clothing weight and thermal insulation of all firefighters' protective clothing are within narrow ranges. In this study, rectal temperature, mean skin temperature, and heart rate during exercise were significantly greater in the aluminized clothing (Type A) and these physiological burdens are attributed to smaller water vapor permeability and greater resistance to latent heat of Type A, and not due to the effects of clothing weight or thermal insulation.

The present results are of particular importance in the setting of the Wet Bulb Globe Temperature (WBGT) reference values for workers wearing aluminized protective clothing. Since the WBGT was developed specifically for men working in shirt and trousers¹⁷⁾, a clothing adjustment factor of WBGT for the workers wearing protective clothing has been suggested¹⁸⁾. For example, ACGIH²⁾ suggested lowering the threshold WBGT 10°C for completely enclosed suits, Bernard¹⁹⁾ reviewed that a clothing adjustment factor of WBGT is 11°C for firefighter turn-out gear, and Kenny²⁰⁾ suggested lowering the WBGT 7°C when a worker is wearing an enclosed suit. For the present study, the corrected WBGTs for four types of firefighters' clothing were all 13°C because the work rate was 376 W·m⁻² and all participants were acclimated with a clothing correction factor of -10°C according to ACGIH²⁾ at the measured WBGT index of 32.4°C. However, the present results of physiological responses suggest the WBGT clothing adjustment factor should be distinguished from aluminized and non-aluminized protective clothing in radiant heat.

With regard to the "safe" upper limit for deep body temperatures mostly for rectal temperature, the limit are 38.0°C for daily and prolonged periods²¹⁾, or 39°C in closely controlled conditions²²⁾. For safety reasons, it is suggested that a wear test should be terminated

when the core temperature reaches over 39.2°C²³⁾, or when rectal temperature rises at a rate exceeding 0.6°C in five minutes, or reaches 39.5°C during exercise²⁴⁾. Since heat stroke is associated with core temperatures in excess of 40°C, the range of core temperature between 39 and 40°C may be considered safe. In the present results, however, the progressive rise in T_{re} during recovery sessions indicates that the upper limit in core temperature while wearing aluminized protective clothing should be more conservative. For Type A, rectal temperature rose progressively even during the recovery with no tendency to reach a plateau, despite the termination of exercise. The increasing slope in T_{re} of Type A during the last recovery is indeed distinct from the slopes of Type B, C, and D (Fig. 3). Thus, for work requiring aluminized protective clothing in radiant heat, 'a certain buffer zone' in the upper safe limit to reach T_{re} of 40°C is necessary because T_{re} progressively increased after the termination of exercise, as shown in Type A.

Further, the work/rest schedule should be more carefully planned under the consideration of the buffer zone, while wearing aluminized protective clothing in radiant heat. For example, we found the rectal temperature for Type A had a mean of $38.2 \pm 0.3^\circ\text{C}$ during the final exercise session. For this case, the buffer zone to reach the T_{re} of 40°C will be 1.8°C. For the exercise, intensity was set at the rate of 60% $\dot{V}O_{2\max}$ ($376 \text{ W}\cdot\text{m}^{-2} = 582 \text{ kcal}\cdot\text{h}^{-1}$ on the BSA of 1.8 m²), thus it can be approximated that a subject wearing Type A may store metabolic heat at a rate of 9.7 kcal·min⁻¹. This may cause an increase in the internal body temperature of 0.17°C·min⁻¹ in a 68.9 kg person. Then it can be predicted that if the exercise is continued for a further 10 min, rectal temperature will reach 39.9°C. For the case of starting from a basal rectal

temperature of 37.0°C, 20 min-exercise at the rate of 60% $\dot{V}O_{2\max}$ wearing aluminized clothing may cause critical heat stroke upon reaching 40°C rectal temperature ($0.17^{\circ}\text{C}\cdot\text{min}^{-1} \times 20 \text{ min} = 3.4^{\circ}\text{C}$ rise).

One novel finding of the present study was that mean skin temperature was the same as rectal temperature while exercising in the aluminized protective clothing (38.2°C for both T_{re} and \bar{T}_{sk} in Table 2). The difference between T_{re} and \bar{T}_{sk} dropped below 0°C at the final exercise period only for Type A, for \bar{T}_{sk} rose more than T_{re} (Fig. 4). White and his colleagues²⁵⁾ have also reported that the thermal gradient of the body was reduced to almost zero when wearing chemical protective clothing. The extremely high skin temperature reflects an increased pooling of blood in cutaneous vessels, a decreased cardiac filling pressure and an increased cardiovascular strain with higher heart rate. An increased cutaneous blood flow during prolonged exercise in hot environments is achieved with compromising muscle blood flow and increasing heart rate. For these reasons, it is considered that the difference between T_{re} and \bar{T}_{sk} is a good indicator of heat strain when wearing protective clothing in hot-humid environments²⁶⁾. In particular, the convergence of skin and rectal temperature has been said to predict human tolerance limits for work in heat, especially for those wearing impermeable protective clothing²⁷⁾. Thus, for workers wearing aluminized protective clothing in radiant heat, mean skin temperature itself can be developed as a valid thermal strain index, being independent of core temperature value.

Additionally, it should be noted that both rectal and mean skin temperature are not a significant heat strain indicator to distinguish differences among Type B, C and D. The differences in body temperatures between aluminized and non-aluminized protective clothing were significant, whereas the differences among non-aluminized firefighters' clothing conditions were not significant (Table 2). The result is in good agreement with that if the differences in the clothing coefficients between garment systems are so small ($<0.1 i_{\text{m/clo}}$), human trials is likely indiscernible²⁴⁾. In the present study, the clothing coefficients ($i_{\text{m/clo}}$) were 0.21, 0.26, and 0.33 for Type B, C, and D (Table 1). The thermal gradient of the body did not show any significant relationship with clothing weight or thermal insulation, while there was a negative relationship between the resistance of latent heat and thermal gradient of the body (Fig. 6). Those results indicate that physiological burden when wearing firefighters' protective clothing with similar configurations is driven by the resistance to latent heat rather than clothing weight and thermal insulation.

In a similar way, both body temperature and heart

rate showed the highest value in Type A, reaching their maximal level (183 ± 11 bpm). During work in heat stresses, the overall increase in blood flow is the sum of the demands from the working muscles and the skin, and is mainly accomplished by an elevated heart rate. Thus, the maximum heart rate in Type A is in good agreement with the highest mean skin temperature in Type A (Fig. 5, Table 2). The maximal level in HR of workers during exercise while wearing fireproof jackets was also reported in Ftaiti *et al.*²⁸⁾. The weight of the firefighters' equipment (30 kg) increased heart rate by 25 bpm during light exercise in an air temperature of 15°C²⁹⁾. According to CEN TC 162³⁰⁾, heart rate in a test with firefighters' protective clothing should not increase more than 20 bpm when compared with a test with reference clothing alone. For the present study, heart rate in Type A was 26 bpm greater than the HR in CON, which means a 28% increase in heart rate due to the addition of aluminized outer suits of 2.3 kg, while heart rate increased by 21, 19, and 15% for Type B, C, and D compared to CON as a baseline (Table 2). These figures found in non-aluminized firefighters' protective clothing are similar to those reported by Dorman and Havenith⁴⁾, where two standard firefighters' clothing weighing 7 kg and 6.6 kg increased metabolic rate by 15.7 and 14.5% respectively, during light exercise from the control. The excessive increase in heart rate wearing aluminized protective clothing also suggests that the safe limit for aluminized clothing should be distinguished from those of the typical firefighters' clothing.

Regarding heart rate during recovery (HR_{rcv}), it is interpreted that recovery heart rate greater than 120 bpm was associated with a high level of heat strain and, if below 110 bpm, there was no excessive physiological demand³¹⁾. The present study revealed that all types of firefighters' clothing imposed a high level of heat strain to wearers (Table 2). Recovery heart rate is an index of cardiovascular demands because high heart rates during recovery indicate that the body is not dissipating heat fast enough³¹⁾. For Type A, the recovery heart rate had a mean of 158 ± 20 bpm, which demonstrates that aluminized clothing blocks the dissipation of body heat from the skin.

Total body weight losses were also the highest in Type A with a 1.3 kg loss and the smallest in CON with a 0.8 kg loss, which is estimated as 1.9% loss of total body weight in comparison to 1.1% loss for CON. Participants sweated 70% more in Type A than in CON. Body dehydration begins to present a problem when body water loss exceeds 3% of body weight³²⁾. On the other hand, ISO 7933³³⁾ and ISO 9886³⁴⁾ allow a maximum sweat loss of 1.3 kg. The rate of fluid loss of 1.3 kg per hour was observed during heavy exercise wearing

heavy NBC clothing in 30°C conditions³⁵). The present result from Type A definitely represents the permissible maximum sweat loss.

Along with the total sweat rate, it is important to investigate the evaporative efficiency of protective clothing. Because the resistance of the latent heat of Type A is about 1.6 times larger than that of Type B (0.045 and 0.029 m²·kPa·W⁻¹ for Type A and B), it would be expected that evaporated sweat rate through Type A would be around 40% lower compared to Type B. However, the resulting evaporative sweat rates through Type A and B are 395 and 461 grams respectively, which indicate that the evaporative rate in Type A is about 17% smaller than that in Type B. One reason why the expected evaporation rate cannot be obtained in the study would be that the resistance to latent heat of clothing was obtained using a thermal manikin in a sitting position, which does not reflect a) the effects of dripped sweat and pumping effects during exercise, and b) the effects of heavy sweating on the face and respiratory water vapor exchanges. On the other hand, the evaporative efficiency of Type A in total sweat rate was estimated to be half (31%) that of CON (65%) (Table 2). Herein, the 31% is considered as dripped sweat inside the aluminized clothing, not a net evaporated sweat through Type A, because the water vapor impermeability index was almost zero for Type A (Table 1). The large amount of the absorbed sweat volume in Type A reflects the impermeable property of the aluminized coated cover. While wearing aluminized protective clothing, workers sweated at a maximal rate but most sweat is seldom evaporated when comparing to the conditions of non-aluminized protective clothing. Since the evaporation of sweat represents the major avenue of metabolic heat dissipation from the skin during exercise, excessive sweat loss without effective evaporation is associated with a suppression of heat dissipation from the skin, and finally induces the rise in body temperature.

Among subjective responses, thermal sensation and thermal comfort well reflected physiological responses in the present study, while humidity sensation and RPE were not sensitive enough to distinguish the differences between aluminized and non-aluminized protective clothing. The present study indicates that the aluminized fire gear does impose greater subjective thermal burden than when wearing non-aluminized clothing, in terms of thermal sensation and thermal comfort.

Conclusions

We found that although the aluminized protective clothing (Type A) had a similar clothing weight and thermal insulation as non-aluminized clothing (Type B

and C), the physiological and subjective strains during exercise in radiant heat were the greatest in Type A, due to the greater evaporative resistance and lower water vapor permeability of the aluminized firefighters' clothing. The main contribution of the present study was to reveal distinct physiological features of aluminized clothing, quantifying physiological heat strain wearing aluminized firefighters' protective clothing in radiant heat: Rectal temperature progressively increased even after the termination of exercise; mean skin temperature rose up to the level of rectal temperature or more; heart rate reached their maximum level; and total sweat volume showed the permissible limitation. It appeared that firefighters' thermoregulatory mechanism is severely challenged by wearing the aluminized protective clothing during exercise in strong radiant heat, even though it is known that the reflective property of aluminized coating effectively masks the radiant heat from the fire and flame. The tradeoff between heat protection from the outside and heat dissipation from the inside should be more carefully considered while wearing aluminized protective clothing. The criteria on tolerance time, WBGT reference values, and physiological safe upper limits while wearing aluminized firefighters' clothing should be distinguished from those for typical firefighters' protective clothing. A more considered approach is needed to maximize both safety and performance whilst wearing aluminized firefighters' protective clothing.

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