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U.S. military forces are currently using the Interceptor Body Armor (IBA) system which can increase human thermal stress when worn in arid environments. This study investigated a spacer vest (SV) designed to distance the IBA from the wearer's skin surface, increasing evaporative cooling around the torso. A series of lightweight SV designed to be worn under the IBA was tested for thermal insulation (clo) and water vapor permeability (im) on a sweating thermal manikin (TM). The TM was dressed in 3 configurations: with the U.S. Army Temperate Battle Dress Uniform (TBDU); with the IBA over the TBDU; and with the IBA over the various SV and the TBDU. TM results were used as input to a computer model predicting core temperature (Tc,oC), skin temperature (Tsk, oC), heart rate (HR,bpm), sweat rate, (SR,g/min), skin wettedness (SW,%), and total body water loss (WL,l). Output described responses when exposed to desert environments with air temperatures of 30, 40 and 50oC during repeated, intermittent exercise (10 min rest/ 30 min walk). TM results showed thermal insulation increased and water vapor permeability decreased when IBA was worn over the TBDU. Use of a SV between the IBA and TBDU reduced thermal insulation and increased water vapor permeability. This translated into a theoretical increase in whole body evaporative cooling potential (im /clo) of approximately 20% when wearing a SV compared to wearing the IBA without a SV. Predictive model results showed thermo-physiological benefits when using a SV with lower SW at 30oC, lower Tc, Tsk, HR, SR, SW, and WL at 40oC and lower Tc at 50oC.

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Use of a Spacer Vest to Increase Evaporative Cooling Under Military Body Armor

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Abstract

U.S. military forces are currently using the Interceptor Body Armor (IBA) system which can increase human thermal stress when worn in arid environments. This study investigated a spacer vest (SV) designed to distance the IBA from the wearer's skin surface, increasing evaporative cooling around the torso. A series of lightweight SV designed to be worn under the IBA was tested for thermal insulation (clo) and water vapor permeability (i_m) on a sweating thermal manikin (TM). The TM was dressed in 3 configurations: with the U.S. Army Temperate Battle Dress Uniform (TBDU); with the IBA over the TBDU; and with the IBA over the various SV and the TBDU. TM results were used as input to a computer model predicting core temperature ($T_{c,}$ ^oC), skin temperature (T_{sk}, ^oC), heart rate (HR,bpm), sweat rate, (SR,g/min), skin wettedness (SW,%), and total body water loss (WL,l). Output described responses when exposed to desert environments with air temperatures of 30, 40 and 50^oC during repeated, intermittent exercise (10 min rest/ 30 min walk). TM results showed thermal insulation increased and water vapor permeability decreased when IBA was worn over the TBDU. Use of a SV between the IBA and TBDU reduced thermal insulation and increased water vapor permeability. This translated into a theoretical increase in whole body evaporative cooling potential (i_m /clo) of approximately 20% when wearing a SV compared to wearing the IBA without a SV. Predictive model results showed thermo-physiological benefits when using a SV with lower SW at 30^oC, lower $T_{c,}$ T_{sk}, HR, SR, SW, and WL at 40^oC and lower T_c at 50^oC.

1. Introduction

U.S. military forces are currently using the Interceptor Body Armor (IBA) system consisting of an outer vest, front and rear ballistic plates, and attachments for throat, groin, and upper arm protection. When fully configured, the IBA weighs 9.9 kg and covers 30-35% of the body surface area, including the entire torso, with multiple layers of impermeable, synthetic materials (Figure 1). Specifically, the IBA utilizes fine-weave Kevlar™ fibers for small arms/fragmentation protection and boron-carbide ceramic plates for stoppage of higher-velocity projectiles. Use of the IBA can contribute to heat stress and limit wearer performance.

Figure 1. Photographs showing tactical wear configurations of Interceptor Body Armor (IBA) during combat operations in Iraq.

This study investigated the use of a spacer vest (SV) designed to distance the IBA from the wearer's skin surface, increasing the potential for evaporative cooling around the torso. Wearing body armor in humid environments has been associated with increasing the wet bulb globe temperature around the wearer by about four centigrade degrees (Goldman, 1). It is hypothesized that an increase in evaporative cooling could reduce overall sweat rates and consequent soldier dehydration. The negative impact of heat stress and dehydration on soldier performance is well recognized by the U.S. Military (U.S. Army and Air Force, 2).

2. Methods

A series of seven lightweight (average weight=0.29 kg), 1 cm thick SV designed to be worn under the IBA was tested for thermal insulation (clo) and water vapor permeability (i_m) on a sweating thermal manikin (TM). The thermal insulation represents the total resistance to dry heat transfer between the skin's surface and the ambient environment. Water vapor permeability is the total conductance for latent heat transfer between the skin and environment. Both properties are functions of wind speed with increased air velocity resulting in lower clo and higher i_m measurements.

The TM was dressed in 3 test configurations: with the U.S. Army Temperate Battle Dress Uniform (TBDU); with the IBA over the TBDU; and with the IBA over the various SV and the TBDU (Figure 2).

Figure 2. Photographs showing the thermal manikin (TM) configured with the Temperate Battle Dress Uniform (TBDU), and a spacer vest (SV, both left), and under the Interceptor Body Armor (IBA, right).

The SV test series was designed to evaluate if there was any difference between a separate, stand-alone SV and one intended to be permanently integrated into the inner lining of the IBA. Furthermore, the SV test series included two types of material construction: an open mesh style and a waffle style with indented dimples. Table 1 shows total and regional clo and i_m values when the thermal manikin (TM) was dressed in the Temperate Battle Dress Uniform (TBDU), Interceptor Body Armor (IBA), and the various spacer vests (SV).

The TM results were used as input to a computer model predicting core temperature (Tc,°C), skin temperature (T_{sk}, ^oC), heart rate (HR,bpm), sweat rate, (SR,g/min), skin wettedness (SW,%), and total body water loss (WL,l). The human responses of a standard soldier (70kg, 1.7 m tall) were simulated with the model to quantify the thermo-physiological effects of adding a SV under the IBA. Output described responses when exposed to desert environments with air temperatures of 30, 40 and 50^oC during repeated, intermittent exercise (10 min rest/ 30 min walk). The simulated soldier was walking on a hard smooth surface and began the activity from a comfortable thermal neutral state. The humidity level for the environments was constant with a dew point of 15°C and wind speed was 1 m/s. Solar radiation was modest such that the mean radiant temperature was 10°C warmer than air temperature.

3. Results and Discussion

SV type	Total manikin			Front torso	Rear torso
	clo	i_m	i_m/clo	i_m	i_m
Prototype separate mesh	1.28	0.41	0.32	0.51	0.20
Integrated waffle-in	1.23	0.42	0.34	0.64	0.18
Integrated mesh	1.21	0.43	0.36	0.70	0.14
Separate waffle-in	1.16	0.40	0.34	0.45	0.31
Separate mesh	1.19	0.37	0.31	0.46	0.26
Integrated waffle-out	1.14	0.39	0.34	0.34	0.15
Integrated+separate mesh	1.18	0.38	0.32	0.36	0.25

TBDU only: i_m /clo=0.44   TBDU+IBA: i_m /clo=0.27

Table 1. Total and regional thermal and water vapor resistance values when the thermal manikin (TM) was dressed in the Temperate Battle Dress Uniform (TBDU), Interceptor Body Armor (IBA), and the various spacer vests (SV).

TM results showed average clo increased by 16% and i_m decreased by 26% when only IBA was worn over TBDU. However, average changes were reduced (clo=9%, i_m=14%) when wearing the various SV under IBA. Table 1 shows that on average, these lowered resistances to heat and water vapor transmission translated into a theoretical increase in whole body evaporative cooling potential (i_m / clo) of approximately 20% when wearing a SV compared to wearing the IBA without a SV.

Table 1 shows that there were no significant differences in total TM i_m /clo when comparing SV with material construction in the open mesh style or a waffle style with indented dimples. There were no significant differences between SV designed to be a separate component or those designed to be integrated into the inner lining of the IBA. Table 1 also shows that attempting to increase the distance between the IBA and TBDU by wearing two SV did not provide any increase over that provided by one SV.

Regional front torso TM i_m values were generally higher with integrated-style SV while rear torso i_m values were higher with separate-style SV.

The unique profile of torso-protective body armor, requiring very specific surface area coverage, does not allow for numerous design variations that could significantly improve wearer thermal comfort. A study that tested six different configurations (closed, open front, open sides, all with and without additional armor) of a modular body armor system, found no significant differences in final core temperatures, final heart rates, rates of heat storage, sweating rates, and evaporative heat loss when subjects walked on a treadmill for 100 minutes at 40°C, 20% rh (Cadarette, 3).

The prediction model results presented in the following graphs show selected soldier responses to desert outdoor environments with air temperatures of 30, 40 and 50°C. The SV selected for analysis was the prototype separate mesh item described in Table 1.

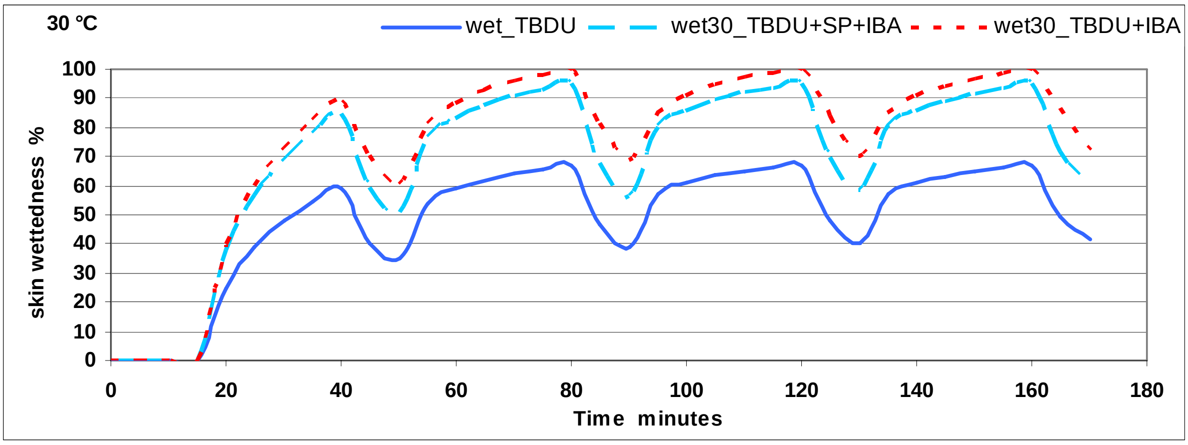

Figure 3. Predictive model results of skin wettedness (SW, %) for the 3 clothing configurations at 30°.

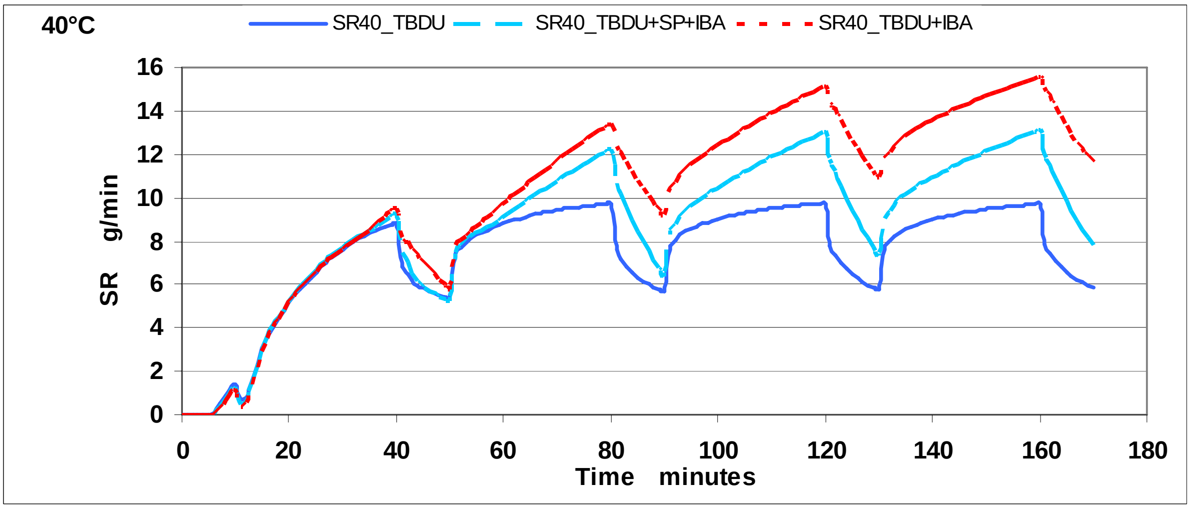

Figure 4. Predictive model results of sweat rate (SR, g/min) for the 3 clothing configurations at 40°C.

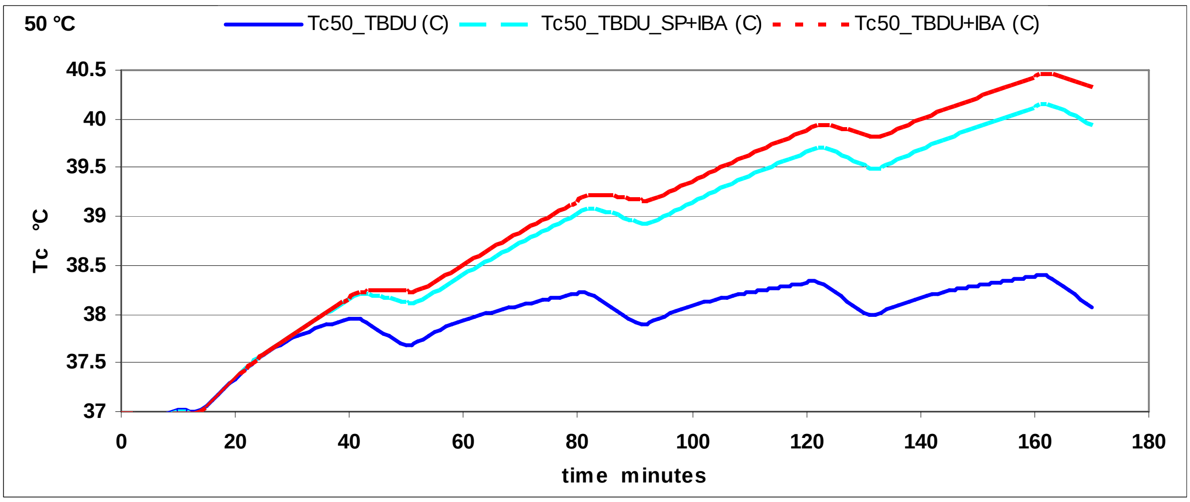

Figure 5. Predictive model results of core temperature (T_c,°C) for the 3 clothing configurations at 50°C.

Figure 3 shows that use of the SV reduces SW, particularly during rest periods. However, in this modeled scenario, SW remains above approximately 50%, which would probably be perceived as uncomfortable by most wearers.

Figure 4 shows that SR is lower when wearing SV and this could lessen rates of dehydration while improving both physical and cognitive performance and decreasing the risk of heat injury.

Figure 5 shows use of the SV resulted in consistently lower T_c throughout the entire simulated exposure even at the highest ambient temperature of 50°C.

Overall, the model results predicted thermo-physiological benefits when using a SV with lower SW at 30^{o}C, lower $T_{c,}$ Tsk, HR, SR, WL at 40^{o}C and lower T_c at 50^{o}C.

4. Conclusions

The U.S. military is developing numerous products in an attempt to mitigate heat stress for personnel deployed in the Middle East. Wearing body armor around the torso impedes the evaporation of sweat over a large percentage of body surface area. The SV concept was designed to provide a continuous air channel between the TBDU and the entire inner surface of the IBA. These results show that this "stand-off" distance reduced the inherent thermal and evaporative resistances of the IBA, allowing for increases in predicted human sweat evaporation and overall thermal comfort during exposure to simulated desert environments. Military research and development in this area is ongoing. Future evaluations will be investigating new torso cooling vests that actively deliver cooled air to the open channel created by the spacer materials.

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6. Disclaimer