Heat Strain with Two Different Ventilation Vests During a Simulated 3-Hour Helicopter Desert Mission

Mikael Grönkvist; Igor Mekjavic; Ursa Ciuha; Ola Eiken

BACKGROUND: The study investigated the heat strain of personnel operating in the rear cabin of a helicopter during desert-climate missions, and to what extent the strain can be mitigated by use of battery-driven ventilation vests.

METHODS: Eight men undertook 3-h simulated flight missions in desert conditions (45°C, 10% humidity, solar radiation). Each subject participated in three conditions wearing helicopter flight equipment, including body armor, and either: a ventilation vest with a 3-dimensional mesh (Vent-1), a ventilation vest with a foam sheet incorporating channels to direct the air flow (Vent-2), or a T-shirt (NoVent); each mission comprised a 10-min walk, followed by sitting for 30 min, kneeling on a vibration platform for 2 h, and finally 30 min of sitting. Core temperature, heart rate, skin temperatures and heat flux, oxygen uptake, sweating rate, and subjective ratings were recorded. Evaporative capacity and thermal resistance of the garments were determined using a thermal manikin.

RESULTS: All subjects completed the NoVent and Vent-1 conditions, whereas in the Vent-2 condition, one subject finished prematurely due to heat exhaustion. The increase in core temperature was significantly ($P \leq 0.01$) greater in Novent (0.93°C) and Vent-2 (0.88°C) than in Vent-1 (0.61°C). Evaporative capacity was significantly higher for Vent-1 (7.8 g · min^{-1}) than for NoVent (4.1 g · min^{-1}) and Vent-2 (4.4 g · min^{-1}).

DISCUSSION: Helicopter personnel may be at risk of heat exhaustion during desert missions. The risk can be reduced by use of a ventilation vest. However, the cooling efficacy of ventilation vests differs substantially depending on their design and ventilation concept.

KEYWORDS: ambient air ventilation, evaporative cooling, heat strain mitigation, microclimate cooling system, thermal comfort.

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Military helicopter crews operating in hot environments can be exposed to marked heat stress, both during standby before flight[6,11] and in flight.[9,10,14] The heat strain can be further aggravated when flying in hostile areas, since the aircrew then may need to use protective equipment such as ballistic body armor and/or nuclear, biological, and chemical (NBC) protective garments that constrain evaporative heat dissipation from the body.[9,15,18] Even though several, but not all, helicopter types possess air conditioning capacity, crewmembers operating in the rear cabin often have to work with the doors open, which may substantially reduce the cooling effect of the air conditioning. In addition, crew in the rear cabin, equipped with heavy garments, typically have to perform physical tasks and move about the cabin during the mission, thereby augmenting heat strain due to endogenous heat production.

Heat strain while wearing heavy garments and/or vapor-resistant clothing can be substantially reduced by microclimate cooling systems.[3,4,12] Microclimate cooling has been shown to be efficient during helicopter in-flight conditions with a reduction in heat strain both with passive cooling with an ice vest[2] or active cooling with a ventilated vest using ambient air as the coolant.[19]

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Since helicopter crew in the rear cabin typically need a relative degree of freedom of movement to perform the required tasks, a microclimate cooling system should preferably be lightweight and standalone. Such a system also has to have a sufficiently long operational time to avoid any risk of added thermal burden in case of power failure of the coolant propulsion system.[7] The main aim of the present study was to investigate the heat strain on the crewmember operating in the rear section of the helicopter wearing the Swedish helicopter flight suit and a ballistic protective vest during a simulated surveillance flight mission in a summer desert climate. We also sought to investigate the potential cooling effects of two different concepts of ventilated vests, both using ambient air as the coolant.

METHODS

Subjects

Eight healthy heat-unacclimatized men participated in the study. Their mean (range) age, weight, and height were 23 (21–25) yr, 80 (61–100) kg, and 181 (166–192) cm. All experiments were performed in a climate chamber (IZR d.d., Skofja Loka, Slovenia) at the Jozef Stefan Institute, Ljubljana, Slovenia. The protocol of the study was approved by the National Committee for Medical Ethics at the Ministry of Health (Republic of Slovenia). Subjects were informed about the experimental protocol before giving their consent to participate in the study, and were instructed that they could terminate any single experiment and were free to withdraw from the study at any time.

Equipment and Materials

To simulate desert conditions, the chamber temperature (ambient temperature; T_{amb}) was set to 45°C and relative humidity (RH) to 10%. The subjects were dressed in helicopter flight garments, with a total weight of 18–19 kg and consisting of underpants, long net underpants, net T-shirt, socks, boots, gloves, flight suit, body armor, life jacket, flight helmet, and knee pads.

Each subject was exposed to three test conditions. In one condition the subjects wore a T-shirt normally included in the ordinary flight garments as the first clothing layer next to the skin (NoVent). In the remaining two conditions the T-shirt was replaced by battery-driven ventilation vests.

In the Vent-1 condition, the vest (Entrak GmbH, Wendelstein, Germany) weighed about 1 kg, and had an inner three-dimensional mesh layer and a windproof outer textile with nonpermeable elastic sealing below the waist. Two fans at the lower front at the level of the hip joints provided an air flow of 200 L · min^{-1} each, i.e., a total flow of 400 L · min^{-1} (**Fig. 1**). The direction of the flow of air was from the microclimate of the vest to the ambient air.

In the Vent-2 condition the vest (Hexonia® GmbH, Nettetal, Germany) weighed about 0.6 kg and had a foam inner liner with channels providing paths for the air flow, one for the front and one for the back of the torso. These foam layers were

Fig. 1. The upper panel shows the Vent-1 vest (Entrak) and the lower panel the Vent-2 vest (Hexonia). In each panel, the left photo reveals the internal structure of the vest and the right photo the vest donned on the thermal manikin.

inserted between a thin permeable textile and an outer nonpermeable textile. The Hexonia vest had two fans, one for the back and one for the front, located at the upper part of the waist level on the left and right side of the torso, respectively; the fans provided an air flow of about 55 $L \cdot min^{-1}$ each, i.e., a total flow of 110 $L \cdot min^{-1}$ (Fig. 1). The direction of the flow of air was from the ambient air into the vest microclimate.

Thus, the principal differences between the two vests were: 1) design, in particular the torso surface area ventilated by the air flow; 2) direction of the air flow where Vent-1 sucked air from the microclimate and Vent-2 blew air into the microclimate; and 3) magnitude of the air flow, where Vent-1 established a flow of 400 $L \cdot min^{-1}$ with both fans, whereas Vent-2 established a flow of 110 $L \cdot min^{-1}$ with both fans at maximum speed.

Procedures

After a subject was instrumented, the test commenced with a 5-min baseline period, during which the subject was seated outside the chamber at room temperature ($T_{amb} \approx 22°C$, RH ≈ 40%) with the fans in the vest turned off. Thereafter the subject entered the chamber, the fans in the vest were turned on if wearing a vest, and he then performed a 10-min simulation of flight preparation, consisting of walking on a treadmill (Woodway PPS Med, Woodway GmbH, Weil am Rein, Germany) at a speed of 4.5 km/h (1.25 $m \cdot s^{-1}$) and a 5% inclination. This was followed by simulation of the flight mission comprising 30 min sitting still, 2 h kneeling on a platform (Iskramedical, Ljubljana, Slovenia), which was vibrating at 5 Hz, and finally 30 min sitting still. During the simulated flight mission, the subject was provided with 1 L of ambient-temperature water (i.e., 45°C) to drink ad libitum.

For 6 of the 8 subjects, a 1000 W lamp was used to simulate solar radiation during the in-flight 30-min seated and 2-h kneeling positions. While seated, the lamp shone on the left frontal surface of the subject from a distance of about 3 m. When kneeling, the subject was positioned in front and below the lamp (the distance between the lamp and the subjects face was 2 m at a 45° angle in the sagittal plane. The subject had a sun protection visor on the helmet covering the upper half of the face.

Core temperature (T_c) was recorded every min with a rectal thermistor (MSR Electronics GmbH, Henggart, Switzerland) inserted about 12 cm beyond the external anal sphincter. Skin temperature (T_{sk}) was measured at 11 sites of the body (foot, calf, front thigh, back thigh, abdomen, chest, lower back, upper back, upper arm, forearm, and forehead) and recorded every min with a data logger (Almemo Model 5990-2; Ahlborn GmbH, Holzkirchen, Germany). Average T_{sk} was calculated as unweighted means for the torso (i.e., abdomen, chest, lower back, and scapula) and for the remaining body sites (i.e., seven locations). Oxygen uptake ($\dot{V}O_2$; $ml \cdot min^{-1}$) and expired minute ventilation ($\dot{V}_E$; $L \cdot min^{-1}$) were measured with a COSMED K4b2 system (COSMED Srl, Pavona di Albano, Rome, Italy), recordings being obtained for 3-min periods during baseline conditions, at the end of the preflight walk, at the end of the first in-flight sitting period, and at the end of each hour of the in-flight kneeling (on the vibration platform) period. The last minute of each recording was averaged and used for further analysis. A weather station (Almemo 2590-9; Ahlborn, Holzkirchen, Germany) provided information regarding the chamber T_{amb} and RH.

The subject's weight and the weight of the body armor were measured with a model TPT 5N Libela Elsi (Celje, Slovenia) weight scale, with range and resolution of 0–300 ± 0.25 kg. All other clothing items were weighed on a model UWE HGM-4000 (Universal Weight Enterprises, Hsin Tien City, Taiwan) weight scale, with range and resolution of 0–4000 ± 0.2 g. The difference in body weight before and after the trial, corrected for intake of water, was assumed to correspond to the amount of total water loss. The difference in loss of body weight and the increased weight of the clothes during the trial was assumed to correspond to the amount of evaporated sweat. Sweat efficiency was calculated as the amount of sweat that was evaporated, divided by total amount of sweat secreted, without correction for water loss from respiration and metabolism.[1,19]

Each subject rated his perception of thermal comfort (TC), thermal sensation (TS), and perceived exertion (RPE). For TC, a 7-point scale was used (0–0.5 = comfortable; 1–1.5 = slightly uncomfortable; 2–2.5 = uncomfortable; and 3 = very uncomfortable). Similarly, for the TS ratings a 7-point scale was used (3 = hot; 2 = moderately hot; 1 = warm; 0 = neutral; −1 = cool; −2 moderately cold; and −3 = cold). RPE was rated using the 15-point Borg scale[5] (ratings ranging from 6 to 20) for the whole body (6–7 very, very light; 8–9 very light; 10–11 fairly light; 12–13 somewhat hard; 14–15 hard; 16–17 very hard; and 18–19 very, very hard). Each subject also rated his overall feeling of wellness (Feel) using an 11-point scale[13] (+5 = very good; +3 = good; +1 = somewhat good; 0 = neutral; −1 = somewhat bad; −3 = bad; −5 = very bad). The first ratings were provided outside the chamber during the baseline measurements. In addition, the subject provided ratings at the end of the preparatory walk and every 15 min of sitting and kneeling.

An experiment was terminated prematurely if rectal temperature increased to >39.5°C or by >2°C from the baseline measurement, or if the subject showed signs or reported symptoms typical of heat exhaustion. The order of the three test conditions was alternated among the subjects. For the individual subject, the trials were performed at the same time of the day and each trial was separated by ≥48 h.

Thermal Manikin Tests of Evaporative Capacity and Thermal Resistance

Evaporative capacity (EC) and thermal resistance (Rt) were estimated using a thermal manikin (Jozef Stefan Institute, Ljubljana, Slovenia) consisting of 19 heated segments. The manikin was supported on a frame inside the climatic chamber, with its head attached to a strain gauge (Libela Elsi Sigma, Celje, Ljubljana). The ambient air in the chamber was maintained at 35°C and 10% RH, and the shell of the thermal manikin was maintained at 35° with electrical heaters embedded in the aluminum shell of the manikin segments. Wetted skin was simulated by donning a wet lycra garment on the manikin. Four test conditions were conducted with the manikin: 1) bare manikin with only the wetted skin; 2) NoVent; 3) Vent-1; and 4) Vent-2. During the test, the mass of the manikin decreased in a linear manner due to the evaporation of sweat from the wetted skin. Once any portion of the wetted skin became dry, the slope of the loss of mass decreased. EC was estimated from the initial linear rate of decrease in mass of the manikin wearing the equipment associated with each of the four conditions. Once a deflection of the slope of the linear decrease in mass was detected, the trial was concluded. The test was repeated three times in each condition (coefficient of variation $<5\%$).

Rt was determined by maintaining the chamber ambient air temperature at 15°C, RH at 40%, and maintaining the manikin shell temperature at 35°C. The electrical power required to maintain the shell temperature of the manikin segments constant was recorded and the segmental Rt derived as:

$$Rt_{segment}\ (K \cdot m^2 \cdot W^{-1}) = \Delta T \cdot A \cdot P^{-1};$$

where $\Delta T\ (K) = T_{segment} - T_{amb}$;

$A\ (m^2)$ = surface area of segment;

P (W) = electrical power delivered to

segment to maintain shell temperature at 35°C.

The total Rt was then calculated as the sum of the $Rt_{segment}$ values. The test was repeated three times in each condition (coefficient of variation $<4\%$).

Statistical Analysis

The statistical significance of differences was evaluated by analysis of variance (ANOVA), followed by a Tukey's post hoc test for all variables except for subjective ratings, which were evaluated by a Friedman, followed by a Wilcoxon nonparametric test (Statistica 13, Statsoft, Tulsa, OK, USA). *P*-values less than 0.05 were regarded as statistically significant and between 0.05 and 0.1 as tendencies.

RESULTS

All eight subjects endured the 3-h simulated helicopter desert patrol both in the NoVent and Vent-1 conditions, whereas in the Vent-2 condition, one subject had to terminate prematurely after 70 min on the vibration platform due to symptoms of heat exhaustion (nausea, headache, neck ache, perceived sudden physical weakness) in combination with a high heart rate and rapidly rising core temperature. There were no incidences of battery failure in any of the vest trials.

In all three conditions, T_c increased steadily from baseline until the end of the second hour on the vibration platform [$F(2,14) = 9.18$; $P < 0.003$; **Fig. 2**], with significantly larger increases in the NoVent (0.93 ± 0.29°C; $P = 0.004$) and Vent-2 (0.88 ± 0.34°C; $P = 0.012$) conditions than in the Vent-1 (0.61 ± 0.16°C) condition. The preflight preparation walk induced a more pronounced heart rate (HR) response [$F(2,14) = 4.70$; $P = 0.027$] in the NoVent (129 ± 15 bpm) than in the Vent-1 (121 ± 12 bpm; $P = 0.026$) condition, but not than with Vent-2 (123 ± 18 bpm). After 2 h on the vibration platform, there was a significant difference in HR between the three conditions [$F(2,14) = 16.49$; $P < 0.001$], with lower HR observed in the Vent-1 (107 ± 23 bpm) compared to both the NoVent (134 ± 23 bpm; $P < 0.001$) and Vent-2 (122 ± 30 bpm; $P = 0.022$) conditions; HR in the Vent-2 condition was also significantly ($P = 0.044$) lower than in the NoVent condition.

There were no intercondition differences for $\dot{V}O_2$ or $\dot{V}CO_2$ during any period of the test, whereas during the vibration period, $\dot{V}_E$ was lower [$F(2, 28) = 41.3$; $P = 0.016$] in the Vent-1 (16.2 ± 6.6 $L \cdot min^{-1}$) compared to either the NoVent (18.8 ± 4.4 $L \cdot min^{-1}$; $P = 0.057$) or Vent-2 (19.3 ± 7.2 $L \cdot min^{-1}$; $P = 0.019$) conditions.

All interventions caused a reduction of body weight [$F(2,14) = 5.97$; $P = 0.013$] during the course of the trial, with the reduction in the Vent-1 (1.63 ± 0.46) condition being smaller than in the NoVent (1.97 ± 0.48; $P = 0.012$) condition, and a tendency, albeit not significant, for the reduction to also be smaller in the Vent-2 (1.87 ± 0.35; $P = 0.077$) condition. There was a significant difference in the mass of sweat accumulated in the clothes between the conditions [$F(2,14) = 26.0$; $P < 0.001$], with less sweat contained in the clothes in the Vent-1

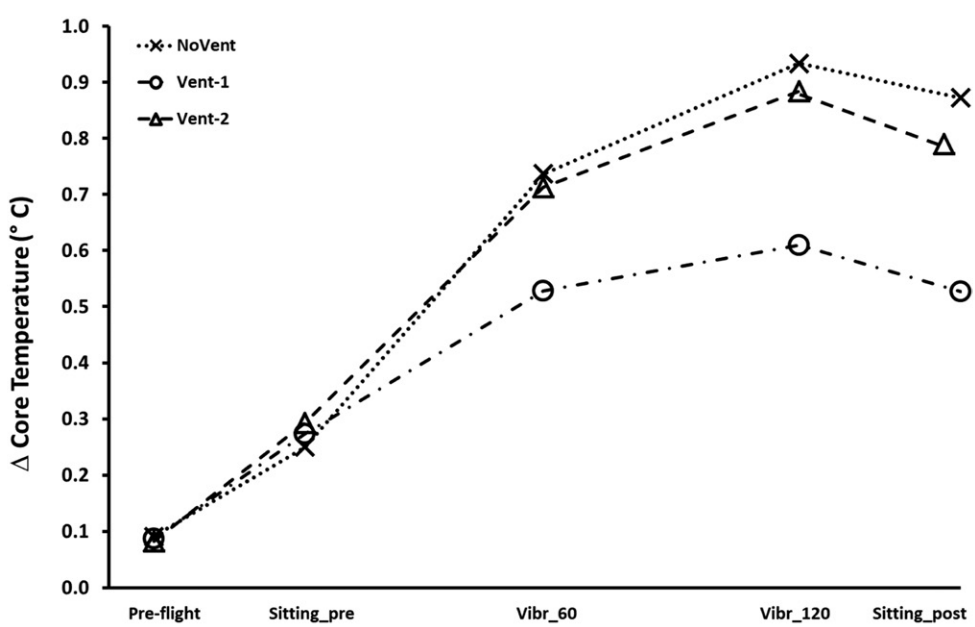

Fig. 2. Changes in core temperatures from the pretest baseline measurements outside the climate chamber. The last data point, i.e., Sitting_post, in the Vent-2 condition is the average of the final data point for all eight subjects, both in time (x-axis) and temperature (y-axis). Values are means; $N = 8$.

(146 ± 94 g) compared to both the NoVent (479 ± 188 g; $P <$ 0.001) and Vent-2 (392 ± 139 g; $P < 0.001$) conditions. Whereas there was no significant difference between the sweat rate in the three conditions, sweat efficiency was significantly higher in the Vent-1 (91.6%) than in the NoVent (76.0%) and Vent-2 (79.2%) [$F(2,14) = 59.3$; $P < 0.001$] conditions.

Inside the chamber, torso T_{sk} differed significantly between the three conditions (**Fig. 3**); lower back T_{sk} was lower in the Vent-1 (38.9° ± 0.9°C) than in both the NoVent (40.6° ± 1.2°C; $P < 0.001$) and Vent-2 (40.2° ± 0.6°C; $P < 0.001$) conditions, but was also lower in the Vent-2 compared to the NoVent ($P =$ 0.011) condition; T_{sk} on both the scapula and abdomen were lower in the Vent-1 (39.6° ± 1.1°C and 39.1° ± 0.8°C) compared to the NoVent (40.9° ± 0.6°C and 40.2° ± 0.7°C, respectively; $P < 0.001$) and Vent-2 (40.9° ± 0.4°C and 40.4° ± 0.7°C, respectively; $P < 0.001$) conditions. There was no intercondition difference in T_{sk} on the chest (NoVent = 40.3° ± 0.7°C, Vent-1 = 40.1° ± 0.8°C; Vent-2 = 40.3° ± 0.3°C). Average T_{sk} for the remaining seven sites (i.e., excluding the torso) increased over time during the 45°C exposure [$F(4,24) = 58$; $P < 0.001$] from 35.9° ± 0.1°C during the premission preparation to 37.2° ± 0.2°C while seated at the end of the mission, with no difference between the three conditions.

There was a significant difference in the torso heat flux (Q) between the conditions [$F(8,38) = 51.4$; $P < 0.001$]. Lower back Q was higher in the Vent-1 (37.7 ± 15.2 W · m^{-2}) than in both the NoVent (−0.6 ± 4.4 W · m^{-2}; $P < 0.001$) and Vent-2 (22.2 ± 7.1 W · m^{-2}; $P =$ 0.004) conditions, and lower back Q was higher in the Vent-2 than in the NoVent ($P < 0.001$) condition. Scapula Q was higher in Vent-1 (19.7 ± 14.8 W · m^{-2}) than in both the NoVent (−4.7 ± 24.1 W · m^{-2}; $P < 0.001$) and Vent-2 (−1.3 ± 16.3 W · m^{-2}; $P < 0.001$) conditions. Abdomen Q was higher in the NoVent (12.2 ± 17.3 W · m^{-2}) compared to Vent-1 (−0.2 ± 9.1 W · m^{-2}; $P < 0.001$), but not Vent-2 (6.1 ± 5.1 W · m^{-2}). Chest Q was lower in Vent-1 (−17.7 ± 9.3 W · m^{-2}) compared to both NoVent (5.7 ± 12.1 W · m^{-2}; $P < 0.001$) and Vent-2 (5.5 ± 5.9 W · m^{-2}; $P <$ 0.001) conditions.

The subjective ratings from one subject were excluded from the data analyses because the subject did not follow the rating instructions. Thus, he reported no thermal strain in any condition, despite several signs of the opposite, such as profuse

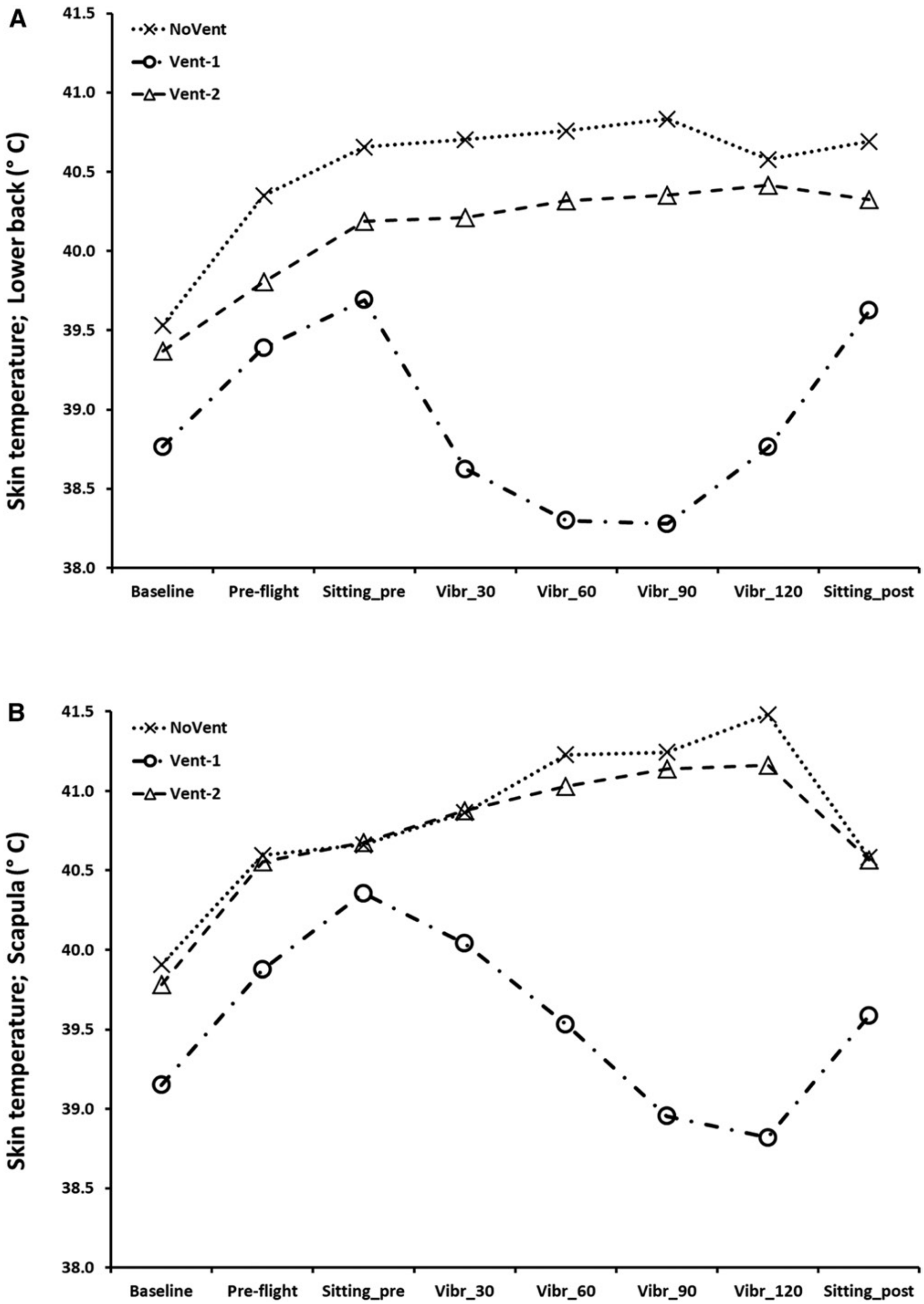

Fig. 3. Skin temperatures on the A) lower back, B) scapula, C) abdomen, and D) chest during the simulated desert helicopter missions. Values are means; $N = 7$.

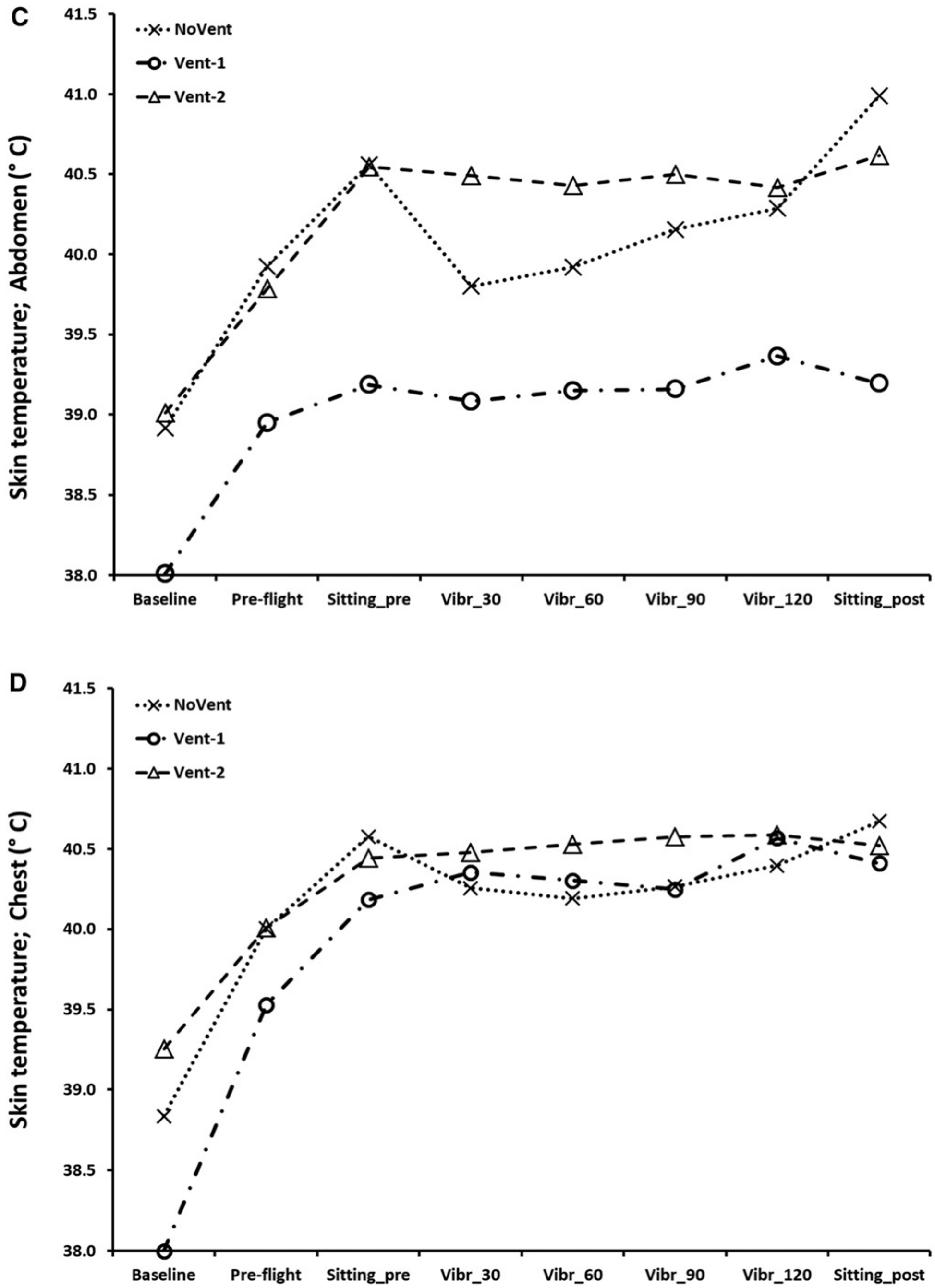

Fig. 3. *(continued).*

sweating and significant increases in T_c and HR. There were no differences between the three test conditions either before entering the chamber (baseline) or during the premission preparation walk for any of the subjective RPE, TS, TC, and overall Feel (**Table I**). During the 2 h on the vibration platform, there was an intercondition difference in RPE [$\chi^2(N = 52, \text{df} = 2) = 8.16$, $P = 0.0169$] with lower ratings in Vent-1 than in both NoVent ($P < 0.001$) and Vent-2 ($P = 0.003$); during this period, there was also an intercondition difference in TS [$\chi^2(N = 52, \text{df} = 2) = 24.97$, $P < 0.001$] with lower ratings for Vent-1 than in both the NoVent ($P < 0.001$) and Vent-2 ($P < 0.001$) conditions, and a tendency of a lower TS in the NoVent compared to the Vent-2 ($P = 0.091$) condition. Likewise, TC exhibited intercondition differences during the 2-h vibration period [$\chi^2(N = 52, \text{df} = 2) = 24.12$, $P < 0.001$], with lower ratings in the Vent-1 than in both the NoVent ($P < 0.001$) and Vent-2 ($P < 0.001$; Table I) conditions. For the overall Feel on the vibration platform, there was also an intercondition difference [$\chi^2(N = 52, \text{df} = 2) = 12.61$, $P = 0.0018$], with higher ratings in Vent-1 than in both NoVent ($P < 0.017$) and Vent-2 ($P < 0.001$) conditions, and a tendency of a higher Feel in the NoVent compared to Vent-2 ($P = 0.076$) condition (Table I).

EC was significantly reduced when the manikin was dressed [$F(3,6) = 688.7$; $P < 0.001$], from 11.5 g · min^{-1} for the naked manikin, to 4.1, 7.8, and 4.4 g · min^{-1} in the NoVent, Vent-1, and Vent-2 conditions, respectively. EC in the Vent-1 condition was higher ($P < 0.001$) than in both the NoVent and Vent-2 conditions.

Total Rt (i.e., the sum of all 19 segments) differed between the conditions [$F(2,4) = 38.5$; $P = 0.002$]. Rt for the Vent-1 ensemble was lower (2.64 K · m^2 · W^{-1}) than for the NoVent (3.33 K · m^2 · W^{-1}; $P = 0.003$) and Vent-2 (3.21 K · m^2 · W^{-1}; $P = 0.006$) clothing ensembles (**Table II**). For the front and back torso segments, there were significant interactions between conditions and front/back [$F(2,4 = 48.0$; $P = 0.002$], with lower Rt on the front and back torso segments for Vent-1 than for both NoVent ($P < 0.001$) and Vent-2 ($P < 0.001$), whereas for the NoVent ensemble, Rt for the back segment (0.686 K · m^2 · W^{-1}) was higher than for the front segment (0.686 K · m^2 · W^{-1}; $P = 0.005$). By contrast, for the front thigh segments, Rt was higher for the Vent-1 (0.385°C · m^2 · W^{-1}) compared to the NoVent (0.232 K · m^2 · W^{-1}) and Vent-2 [0.227 K · m^2 · W^{-1}; $F(2,10) = 134$; $P < 0.001$] ensembles (Table II).

Table I. Subjective Ratings of Perceived Exertion, Thermal Sensation, Thermal Comfort, and Overall Feeling of Wellness During the 5-min Baseline, 10-min Preflight Walk, 30-min In-Flight Sitting, 2-h In-Flight Kneeling, and 30-min In-Flight Sitting [Median (Range); *N* = 7].

	PERCEIVED EXERTION (RPE)			THERMAL SENSATION (TS)			THERMAL COMFORT (TC)			OVERALL FEEL OF WELLNESS (FEEL)		
	NO VENT	VENT-1	VENT-2	NO VENT	VENT-1	VENT-2	NO VENT	VENT-1	VENT-2	NO VENT	VENT-1	VENT-2
Baseline												
5 min	7 (6–12)	6 (6–12)	7 (7–10)	0 (−1–2)	0 (0–2)	0 (0–2)	0.5 (0–1)	0 (0–0.5)	0.5 (0–0.5)	4 (1–5)	3 (1–5)	3 (−1–5)
Preflight: Walking												
10 min	11 (7–12)	9 (8–13)	11 (8–13)	2 (1–3)	1 (0–3)	2 (1–3)	1 (1–2)	1 (0.5–1.5)	1 (0.5–2)	3 (−1–4)	1 (0–5)	3 (0–5)
In Flight: Sitting												
15 min	8 (7–12)	10 (7–12)	11 (7-12)	2 (1–3)	2 (1–3)	2 (1–3)	1.5 (1–2)	1 (0.5–1.5)	1 (1–2)	3 (0–4)	1 (0–4)	3 (0–4)
30 min	8 (7–12)	11 (7–12)	10 (7–12)	2 (1–3)	2 (0–3)	2 (1–3)	1.5 (0.5–2)	1 (0.5–1.5)	1 (0.5–2)	3 (0–4)	0 (−1–4)	2 (0–4)
In Flight: Kneeling on vibration platform												
15 min	9 (7–13)	12 (8–13)	11 (8–14)	2 (1–3)	2 (1–3)	2 (1–3)	2 (0.5–2)	1.5 (0.5–2)	1 (0.5–2)	3 (−1–4)	0 (0–4)	1 (−1–4)
30 min	12 (8–13)	11 (8–13)	12 (8–13)	2 (1–3)	2 (1–3)	2 (1–3)	2 (1–2)	2 (0.5–2)	2 (1–2)	1 (−1–4)	1 (−1–4)	1 (−2–4)
45 min	13 (8–13)	11 (8–14)	13 (8–14)	2 (1–3)	2 (1–3)	2 (1–3)	2 (1–2)	2 (0.5–2)	2 (1–2.5)	1 (−3–4)	1 (−2–4)	0 (−1–4)
60 min	13 (9–15)	11 (8–14)	13 (8–14)	2 (1–3)	2 (1–3)	3 (1–3)	2 (1–2.5)	2 (0.5–2)	2 (1–3)	2 (−4–3)	1 (−2–4)	0 (−1–4)
75 min	13 (9–14)	12 (8–15)	13.5 (8–15)	2 (1–3)	2 (1–3)	3 (1–3)	2 (1–2.5)	2 (0.5–2)	2 (1–3)	1 (−2–3)	1 (−2–4)	−1 (−2–4)
90 min	13 (10–14)	12 (9–15)	14 (8–16)	2 (1–3)	2 (1–3)	3 (1–3)	2 (1.5–2.5)	2 (0.5–2)	2.25 (1–3)	0 (−2–3)	1 (−2–4)	−1 (-2–3)
105 min	14 (10–15)	12 (9–15)	14.5 (9–17)	3 (1–3)	2 (1–3)	3 (1–3)	2 (1.5–2.5)	2 (1–2)	2 (1.5–3)	0 (−2–3)	1 (−2–4)	−0.5 (−3–3)
120 min	15 (10–16)	12 (9–15)	14 (9–18)	3 (1–3)	2 (1–3)	3 (1–3)	2 (1.5–2.5)	2 (0.5–2.5)	2 (1.5–3)	0 (−3–3)	1 (−2–4)	−0.5 (−3–2)
In Flight: Sitting												
15 min	12 (8–14)	10 (8–12)	12 (8–14)	2.5 (1–3)	2 (1–3)	2.5 (1–3)	1 (1–2.5)	1.5 (0.5–2)	1.5 (1–2.5)	1 (0–3)	1 (0–4)	0.5 (−1–3)
30 min	12 (8–14)	9 (8–12)	10.5 (8–13)	2.5 (1–3)	2 (1–3)	2.5 (1–3)	1.5 (1–2.5)	1.5 (0.5–1.5)	1.5 (1–3)	1 (0–3)	1 (0–4)	−0.5 (−1–3)

DISCUSSION

The present study demonstrated a substantial heat strain during the simulated helicopter summer desert mission and that this heat strain could be reduced by a ventilated vest with ambient air as the coolant. However, only one of the two vest concepts, namely the Entrak vest (Vent-1 condition), was capable of substantially mitigating the heat strain.

The basis for a ventilated vest using ambient air as coolant is to improve heat dissipation by facilitating sweat evaporation from the surface of the skin. For optimal efficiency, the flow of ambient air in the microclimate of the vest should cover a large skin-surface area on the torso. Flow rate, temperature, and humidity of the inlet air are other important factors for removal of excess heat when using an ambient air ventilated vest.[16] In extreme temperature conditions, when, as in the present high-fidelity experiments, the ambient temperature markedly exceeds that of the body core, it is evidently imperative that the humidity of the inflowing air is sufficiently low to produce net heat dissipation in such a system.[16] Since in summer desert conditions RH is typically very low, several previous studies using a ventilated vest with ambient air as coolant have shown a reduction in thermal strain even at high ambient temperatures.[3,8,19] It is noteworthy in this connection that, for technical reasons, the majority of laboratory studies investigating ambient air ventilated vests in summer desert conditions have applied a RH that is more than double that commonly encountered in the field (i.e., 20 rather 10% RH), hence underestimating their cooling efficacy.[17]

Table II. Thermal Resistance ($K \cdot m^2 \cdot W^{-1}$) Values for the Three Test Conditions as Obtained with a Thermal Manikin for the Front and Back of the Torso Segments, the Front Thigh Segments, and Sum of All 19 Segments on the Manikin.

THERMAL RESISTANCE (Rt)	NO VENT	VENT-1	VENT-2
Torso front	0.686	0.411	0.727
Torso back	0.848	0.345	0.706
Right Thight front	0.237	0.395	0.232
Left Thight front	0.226	0.374	0.221
Summary of 19 segments	3.331	2.641	3.207

The two vest systems in the present study both used ambient air as the coolant but had quite different design/working principles (Fig. 1). Several of our findings support the notion that the Vent-1 concept, with air flowing through a mesh covering the entire torso, was capable of substantially reducing the heat strain. Thus, not only the ratings of perceived thermal discomfort and temperature, but also the elevations of T_c and HR were substantially lower in the Vent-1 than the NoVent condition. Judging by the lower torso skin temperature and the higher Q from the back in the Vent-1 than the NoVent condition, it would appear that the cooling effect of Vent-1 was indeed attributable to augmented evaporative heat loss from the torso, despite the fact that the overall sweat evaporation from the body during the course of an experiment (i.e., the net loss of body mass and increase in mass of the clothing) did not differ between the Vent-1 and NoVent conditions. Q and T_{sk} responses of the trunk also suggest that, during the 2 h of kneeling on the vibration platform, the distribution of air flow and, hence, the main cooling effects of the Vent-1 were on the back, whereas there was less cooling on the chest, presumably because the weight of the body armor acted to compress the mesh, reducing the air flow over that area. By contrast, when the Entrak vest (Vent-1) is used by a foot soldier performing a simulated desert patrol mission while carrying a heavy back pack, the difference in body stance and distribution of external load results in a compression of the mesh on the back rather than the front of the trunk.[8] Notwithstanding, even when carrying an external load of >30 kg over the shoulders and back, Vent-1 appears to provide sufficient air flow to facilitate evaporative heat dissipation in summer desert conditions.[8] Albeit speculative, it cannot be ruled out that the high sweat-rate efficiency noted for Vent-1, with less pronounced reduction in body mass, reflected a reduced need for cooling and thus sweat production in this than the other two conditions. The superior removal of sweat in Vent-1 vs. NoVent and Vent-2 was confirmed by the manikin tests, with considerably higher evaporative capacity and overall lower thermal resistance in Vent-1. An exception from this was that thermal resistance was higher for the front thighs for Vent-1. This is most likely due to the exhaust from the fans blowing warm humid air from the torso down on the thighs. It thus appears that an ambient air-ventilated vest with a design similar to that of Vent-1 can be recommended as a simple, lightweight, stand-alone system to alleviate heat strain in helicopter rear crewmembers acting in summer desert conditions. By contrast, the Hexonia vest (Vent-2), with ambient air flowing through the channels in the foam lining, covered a limited area of the torso and did not reduce heat strain to any significant degree. Ratings of perceived thermal discomfort and sensation and the T_c and torso T_{sk} responses were similar in the Vent-2 and NoVent conditions, as were the values from the manikin experiments regarding evaporation capacity and thermal resistance. In fact, Q was negative on a few torso locations, suggesting that the body was gaining rather than dissipating heat in certain regions covered by the Vent-2 vest. It remains to be resolved whether it was the low air flow rate,[16] i.e., 110 $L \cdot min^{-1}$, amounting to about a fourth of that in the Vent-1 condition, or the limited skin surface area for evaporative heat exchange that was critical for the lack of heat loss provided by the Vent-2 vest. To wear a ventilated vest that provides no or limited evaporative cooling should also be viewed in the context that it will add a barrier to heat loss upon battery failure or other malfunction of the fans.[7]

The observation that, in the Vent-2 condition, one subject had to terminate prematurely after 70 min on the vibration platform due to signs and symptoms of heat illness confirms anecdotal information from helicopter personnel that, as regards rear crew operating in summer desert conditions, heat strain may be operationally limiting and constitute a medical risk. In addition, the observation corroborates the above reasoning that the Vent-2 vest is incapable of counteracting such heat strain. It should be noted that the physical work conducted during the present simulated mission was limited to the preflight preparatory simulation consisting of a 10-min walk on a treadmill together with the very low-intensity work of kneeling on the vibration platform for 2 h. In a real-flight scenario, rear cabin crew might need to perform substantially harder work, leading to a higher endogenous heat production and thus a larger heat strain. Moreover, in the present experiments, two of the subjects were not exposed to simulated solar radiation. Thus, if anything, the present experiments toned down the heat strain that might be experienced during worst-case conditions.

Our study clearly demonstrates that rear cabin helicopter personnel may be at risk of heat exhaustion during summer desert missions. It is possible to substantially reduce heat strain with an ambient air ventilated vest in low air humidity conditions. However, the design of the ventilation vest is critical to produce an efficient air flow over the torso. In addition to the magnitude of the air flow, critical design factors are also the direction of the flow, and the surface area ventilated by the air flow. It is also important to define the relative humidity of the coolant at which the efficacy of the ventilated vest becomes negligible.

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