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PREDICTIONS OF HUMAN TOLERANCE TO HEAT STRESS DURING SIMULATED FIGHTER AIRCRAFT MISSION SCENARIOS

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INTRODUCTION

New aircrew integrated garments provide enhanced protection against acceleration (G) and altitude stresses. These ensembles have additional clothing layers, often impermeable to moisture vapor and air, and increased body surface coverage. This can lead to increased thermal load, thereby decreasing G-tolerance[1]. Physiologic responses while wearing these garments during realistic simulated fighter aircraft (A/C) mission scenarios were estimated using Wissler's Texas Model of Thermoregulation (TM)[2] under cool, warm and hot conditions. The aim was to determine if increased G-protection could be provided without inducing the core temperature to rise above 39.5°C or causing excessive dehydration.

METHODS

Rectal (T_{re}) and skin temperatures (T_{sk}, oC), heart rate (HR, beats/min), sweat rate (SR, kg/h) and accumulated sweat (SWT, kg) of a 72.6 kg (160 lb) male (mean skinfold thickness = 10 mm, basal metabolic rate = 100 W) were predicted during the following scenarios: 1) **A5**: "alert 5" with aerial combat maneuvers (ACM); 2) **N-ACM**: normal operations with ACM; and 3) **NOP**: normal operations. All scenarios began with 2.5 h indoors (simulates pre-flight briefing and aircrew preparation periods), followed by 20 min outdoors (pre-flight A/C inspection). During "alert 5 status" (A5), the pilot remained on the flight line for 55 min, without cooling and with the canopy open. Another 5 min were allotted prior to launch to simulate the rise in temperature which occurs after the canopy closes and before the cockpit environment stabilizes. A 5 min "flight to the area" was followed by three ACM (10 min). For N-ACM and NOP, the pilot returned indoors for 25 min after A/C inspection. Prior to launch, the canopy was closed, then, after a 30 min "flight to the area," the A/C was "on station" for 60 min (70 min for NOP), followed by 10 min of ACM (N-ACM only). All scenarios ended with a 30 min return flight, a 20 min A/C re-inspection and a 60 min debriefing. Simulated metabolic rates during these scenarios were: indoors: 110 W, A/C inspections: 175 W, in-flight: 130 W and peak ACM: 260 W[3].

Simulated indoor temperatures and relative humidity (RH) were derived from MIL-STD-1472D. Simulated cockpit conditions were based on mean dry bulb (T_{db}), wet bulb and black globe temperatures recorded outside of and at calf (T_{calf}) and head (T_{head}) level inside the rear cockpit of a NAWC fighter A/C in July 1993 during a simulated alert 5 scenario. With the engines off, outside T_{db} = 29°C, RH = 60%; T_{head} = 30°C, RH = 53%; and T_{calf} = 31°C, RH = 54%. During the first 5 min after closing the canopy with the engines on, T_{head} = 33°C, RH = 24%; T_{calf} = 31°C, RH = 28%. Cockpit temperatures stabilized after 5 min (T_{head} = 29°C, RH = 26%; T_{calf} = 27°C, RH = 36%). The relative changes in these values were then used to scale modeled cockpit temperatures. Using temperatures recorded in the Persian Gulf[4] as a baseline for hot conditions (i.e. outside T_{db} = 39°C), simulated open cockpit T_{db} = 41°C and RH = 54%. Based on operational experience, in-flight cockpit temperatures are not distributed uniformly. Using a mean in-flight T_{db} of 28°C, the cockpit distribution was T_{torso} = 21°C, T_{head} = 24°C, T_{calf} = 29°C and T_{foot} = 38°C. Cool and warm conditions were based on MIL-STD-210C and scaled as above (mean in-flight T_{db} = 16°C, RH = 31% and T_{db} = 24°C, RH = 31%, respectively).

Performance decrements during heat stress can be estimated based on predicted T_{re} and dehydration levels (dehyd). Thermoregulatory function is degraded and central nervous system (CNS) function progressively deteriorates when T_{re} rises above 39.5°C[5]. A 1 to 5% loss in body weight results in a loss of efficiency, while a 6 to 10% loss produces dizziness and motor deficits[6]. Also, G-tolerance is decreased by 8% when individuals are 1% dehyd and by 16% at 3% dehyd[1]. Since TM does not allow for fluid intake, relative dehyd can be estimated from the SWT parameter. Based on the 72.6 kg man used in this simulation, to maintain effectiveness, overall simulated fluid losses should not exceed 4.5 kg.

The ensembles modeled are shown in Table 1. CLO and I_m values corresponding to TM's fifteen body segments were measured using a thermal manikin. Custom TM garment descriptions were developed based on these values and measurements made in our lab. Body regions covered by pneumatic bladders were modeled as having impermeable outer layers. Statistical tests included paired t-tests and ANOVA. Predicted T_{re}, T_{sk}, HR, SR and SWT were compared between WC and WE and E Vs A. Significance was set at $p \leq 0.05$.

RESULTS

Winter Garments: Estimated thermal loads were greater for WE than WC, as expected. For cool A5, peak T_{re} was predicted during the pre-flight inspection period (WE: 38.5°C, WC: 38.0°C) and the pilot was 1% dehyd prior to launch. WE fluid loss was higher than WC ($p=0.0001$). There were only minor differences under warm conditions. Predicted peak T_{re} during hot A5 were: WE = 40.7°C, WC = 39.6°C. Although estimated dehyd reached 3% for both ensembles during the "alert 5 status," 6% dehyd was predicted for WE during ACM. Cool and warm N-ACM predictions were similar to A5. Estimated temperatures during hot N-ACM were less than A5 (e.g. peak T_{re}: WE = 39.3°C; WC = 38.9°C). 3% dehyd was predicted for both ensembles prior to engagement. Predicted physiologic responses for NOP and N-ACM were essentially the same.

Summer Garments: The overall level of heat stress was predicted to be higher for A than E, although overall CLO values were the same (2.1). Note that mean I_m values were different (0.26 (A) Vs 0.34 (E)). During cool A5, while peak and mean T_{re} were the same for both garments, mean E fluid losses were lower than A (SWT: 0.5 Vs 0.6 kg, $p=0.045$; SR: 1.0 Vs 1.3 kg/h, $p=0.015$). 1% dehyd level was predicted during ACMs for A but not until after landing for E. Warm A5 condition estimates were essentially equivalent. Hot A5 predictions were as follows: peak T_{re}: E = 39.8°C (during the initial flight), A = 40.3°C (during ACM); mean T_{re}: E = 38.7°C, A = 39.1°C ($p=0.02$); mean T_{sk}: E = 35.9°C, A = 36.9°C ($p=0.002$); mean SR: E = 8.3 kg/h, A = 11.1 kg/h ($p=0.02$). While the pilot was predicted to be 3% dehydrated during ACMs for both garments, 6% dehyd was predicted to occur during the return flight for A and only after landing for E. Cool and warm N-ACM predictions were similar to A5, though N-ACM peak values were lower. The pilot was estimated to be 1% dehyd while waiting to launch (E and A) and became 3% dehyd during debriefing (E) or during the return flight (A). Hot N-ACM predictions were also less than A5 (e.g. estimated peak T_{re} = 38.7°C (E) and 38.9°C (A), during the initial flight). 3% dehyd was predicted while "on station" for E and A. Predictions for NOP were essentially the same as for N-ACM. No physiologically significant differences in HR were found.

CONCLUSIONS

CNS function was predicted to be critically compromised during the hot A5 while in flight for WE and A. Therefore, based on TM estimates alone, wearing WE or A under these conditions could not be recommended. G-tolerance was also predicted to be reduced prior to engagement for all modeled garments during A5. Hot A5 and N-ACM results indicated that the relatively poorer level of CNS function during A5 was probably due to the period spent on the flight line waiting without external cooling. (Prior to launch, predicted T_{re} for E = 39.8°C (A5) Vs 38.6°C (N-ACM) and for A = 40.3°C (A5) Vs 38.8°C (N-ACM)). The use of portable cooling units on the flight line would probably ameliorate function degradation. Note that TM does not allow fluid intake during the simulations, even though aviators can bring fluids into the cockpit. This would no doubt have reduced the overall predicted fluid loss. Therefore, it is best to interpret these results as "worst case scenarios." During cool and warm conditions, there were few operationally significant differences predicted between WC and WE. While estimated G-tolerance was reduced, predicted $T_{re} \leq 39.5$°C. Note that WC and WE were modeled in a hot environment to simulate the case in which an A/C would be launched from a cool area, e.g. Northern Europe, and land in a hot area, e.g. the Middle East. Without fluid supplements available, TM predictions indicated that flying such a route while wearing WE would be hazardous.

Ensemble		Description
Winter Control	(WC)	US Navy anti-exposure liner (AEL), coverall (AEC), flyers coverall (FC)
Winter EAGLE	(WE)	US Navy Enhanced Anti-G Lower Ensemble (EAGLE), US Navy COMBAT EDGE (CE) jerkin, AEL, AEC, FC
Summer EAGLE	(E)	EAGLE, CE jerkin, FC
ATAGS	(A)	US Air Force Advanced Technology Anti-G Suit (ATAGS), CE jerkin, FC

TABLE 1. Description of ensembles used during modeling.

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