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TITLE

HEAT BALANCE OF SUBJECTS WEARING PROTECTIVE CLOTHING WITH A LIQUID- OR AIR-COOLED VEST

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Heat Balance of Subjects Wearing Protective Clothing with a Liquid- or Air-Cooled Vest

ANDRÉ L. VALLERAND, Ph.D., ROBERT D. MICHAS, B. Eng.,
JOHN FRIM, Ph.D., and KENNETH N. ACKLES, Ph.D.

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The goals of this study were, first, to determine the extent of the heat strain induced by wearing the Canadian Forces (CF) aircrew chemical defence individual protection ensemble (CD IPE) under simulated hot cockpit conditions, and second, to determine the effectiveness of a liquid cooled (LC) and an air-cooled (AC) vest in relieving such heat strain. Seven (7) healthy male subjects were subjected to three heat exposures (37°C, 50% r.h., for 150 min, time-weighted metabolic rate of about 240 W, 1 week apart) either with no cooling (NC), LC or AC vests. NC was only tolerated for 95 ± 5 min, whereas all subjects completed the 150-min tests with AC or LC ($p < 0.01$). The large rate of increase in rectal temperature (T_{re}) during NC (1.00 ± 0.05°C/h) was attenuated by 51% with LC and by an even greater amount with AC (64%, $p < 0.01$). NC entailed a sweat rate of almost 1 kg/h, which was reduced 38% by LC and 51% by AC ($p < 0.01$). The combined dry and evaporative heat losses (H_{EKC} of LC and AC vests were significantly greater than that of NC (164 ± 7 and 181 ± 9 vs. 124 ± 9 W, respectively; $p < 0.01$). The results demonstrate that subjects wearing CF aircrew IPE under simulated hot cockpit conditions can only tolerate 95 min of the 150-min test, and experience significant heat strain. In contrast, this heat strain is significantly alleviated by either cooling vest, although greater improvements in T_{re} sweat rate, heart rate, evaporative efficiency index, and thermal comfort were observed with AC, possibly the result of its slightly greater total cooling and three times higher evaporative cooling.

COCKPIT TEMPERATURES can reach very high levels in modern aircraft. Indeed, dry bulb temperatures (T_{db}) as high as 40–50°C and globe temperatures (T_g) as high as 50–60°C have been recorded (4,19). The present environmental control systems do not always have the capability to handle the heat stress that can be associated with solar radiation, high ambient temperatures, and the reduced heat dissipation with chemical defence (CD) protective ensembles (4,19). The insulation and low moisture permeability of CD Individual Protective Ensembles (IPE) now being introduced into the Canadian Forces (CF) severely limit the capacity of the body for metabolic heat dissipation through both dry and evaporative heat exchange to the environment. There is a growing concern that the interaction of such heat stress and protective clothing could produce an unacceptable level of thermal strain, reduced comfort, and deterioration of aircrew performance (1,7,16).

The use of individual microclimate cooling systems or improved cockpit air conditioning systems appear as two viable solutions to this problem. With protective clothing, however, the cooling effect of the air conditioning system is markedly reduced due to the thick layers of insulation of the IPE (4,7). Many studies have demonstrated that the cooling effect is greater whenever the cooling system is close to the body, as with individual microclimate cooling systems (4,7,20,22). Air-cooled (AC) and liquid-cooled (LC) systems for aircrew members have been studied for many years (7, 20,24,25). The effectiveness and the mechanisms of heat transfer of an AC and a LC prototype for the CF have not been examined in detail, particularly with respect to their interaction with CD-IPE.

The goals of this study were: first, to determine how much heat strain is encountered by wearing the CF-CD-IPE under simulated hot cockpit conditions; and second, to evaluate the extent that heat intolerance can be improved by using a LC or AC vest in combination with the IPE, and by which mechanisms or avenues of

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From the Biosciences and Medical Life Support Divisions, Defence and Civil Institute of Environmental Medicine, North York, Ont., Canada.

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Address reprint requests to DCIEM, P.O. Box 2000, 1133 Sheppard Ave. W., North York, Ont., Canada M3M 3B9. This is DCIEM publication no. 90-P-XX. Dr. Vallerand is a Defence Scientist at DCIEM, Adjunct Professor of Human Biology at the University of Guelph, Ont., and is presently on foreign exchange at the Unite de Thermophysiologie at the Centre de Recherches du Service des Santé des Armées, in Grenoble, France.

heat exchange this is effected. The latter was achieved by partitional calorimetry using the heat balance equation.

METHODS

Subjects

Seven healthy young male volunteers participated in the present study. Their standard physical characteristics were (mean ± S.E.M.): 30.8 ± 1.5 years old, 1.80 ± 0.01 m in height, 75 ± 7 kg body mass, 1.93 ± 0.04 m^2 body surface area, 51.0 ± 3.1 mL $O_2 \cdot kg^{-1} \cdot min^{-1}$ maximal aerobic power ($\dot{V}O_{2max}$; Bruce protocol), and 12.0 ± 1.1% body fat (underwater weighing technique). A physician examined each subject and approved his participation in the study. The nature, purpose and possible risks of the study were carefully explained to each subject before he gave his consent to participate. The protocol was reviewed and approved by the institutional human ethics committee. Subjects were informed that they could withdraw from the study at any time without bias. They also knew that any test would be terminated if their rectal temperature (T_{re}) reached 39.0°C (or a 2.0°C rise), if their heart rate was maintained for 2 min continuously at 95% of the previously determined maximal level, if a maximal subjective rating of thermal discomfort or perceived exertion were given (see below), or when the subject requested that the test be aborted. Prior to any experimental testing, subjects were familiarized with the protocol, the clothing, and the heat stress test (for 1 h).

Experimental Protocol

Three heat exposures (150 min, 37.0 ± 0.5°C T_{db}, 50 ± 5% r.h., and 42°C T_g at the helmet) 1 week apart were performed on each subject wearing a CF helicopter aircrew CD-IPE supplemented with an AC or LC vest, or without cooling (NC). The ambient conditions were selected to be representative of the environmental stress that can be encountered in the cockpit. The order of the tests was randomized. The clothing ensembles can be briefly described as follows: cotton longjohns (with turtleneck-style top), semipermeable charcoal-impregnated CD foam liner, CD coverall, survival/flotation vest, impermeable ventilated AR-5 mask, DH-411 helmet, wool and CD socks, combat and rubber boots, and wool, rubber and leather gloves.

Before dressing, subjects were instrumented with a rectal temperature thermistor (Sherigan, Argyle, NY; inserted 12 cm beyond the anal sphincter), 12 skin thermistors for the assessment of mean skin temperature, and a heart rate recorder (Sport Tester, Polar Electro, Finland). Subjects then attempted the following protocol: 10 min walk on the treadmill (4 km/h, 0% grade) to simulate the walk-out to the aircraft, 20 min rest, then alternate periods of 10 min ergocycle (50 W of mechanical power output) and 10 min rest, for a target time of 150 min at an average time-weighted metabolic rate of about 240 W, exactly as illustrated in Fig. 1. This work/rest schedule was selected to simulate the periodic nature of physical exertion during the flying of helicopters (i.e., periods of evasive flying maneuvers followed by periods of straight flying). Cooling, if any, was applied after the simulated walk-out (Fig. 1).

Nude body weights were measured (±10g; Setra Scale, Los Angeles, CA) before and after the experiment to determine overall sweat rate, which was corrected for respiratory water losses (15; no fluid intake was permitted during the tests). The change in pre vs. post dressed body weight, also corrected for respiratory water losses, was used to determine sweat evaporation rate. The evaporative efficiency index (% of sweat produced that evaporated) was also calculated (2). Subjects were asked every 5 min to rate their thermal comfort (scale: 7 = comfortable, 10 = hot, 13 = maximal) and perceived exertion (18; scale: 0 = no exertion, 2 = light, 5 = heavy, 10 = maximal).

Cooling Systems

Both the LC and AC vests were worn over the underwear, and thus close to the skin but under the CD liner. The LC can be described as a closed-loop system which comprised a vest and a refrigeration unit to cool the torso area of the subject (Life Support Systems Inc., Los Angeles, CA; vest surface area of 0.27 m^2) (7). The coolant was a 50% mixture of propylene glycol and water. Heat is transferred from the body to the coolant in the vest strictly by conduction (K), which is thus dependent upon good contact between the vest and torso. Flow and inlet temperature were maintained at 300 ml/min and 13°C, respectively. The AC system was open-loop and, similarly to the LC system, comprised a vest and an air-chiller set-up (DCIEM-developed; vest sur-

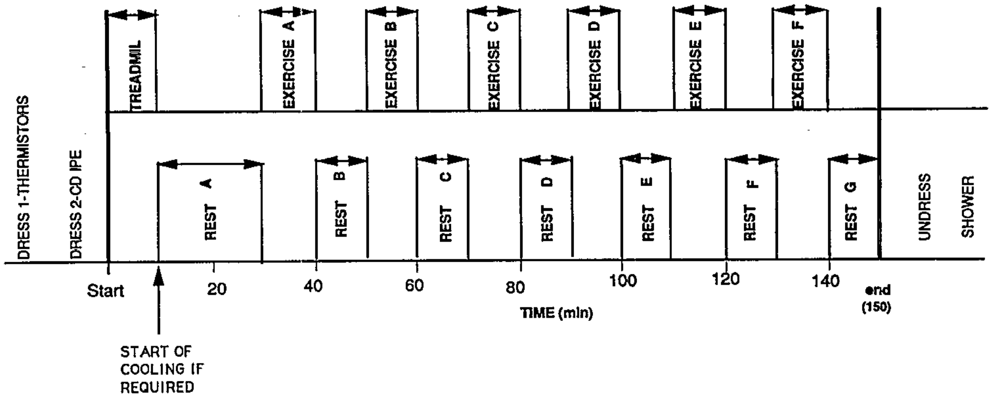

Fig. 1. Protocol: Subjects were wearing Canadian Forces chemical defence individual protection ensemble for aircrew and were exposed to a target of 150 min at 37°C T_{db}, 50% r.h., 42°C T_g at an approximate time-weighted metabolic rate of 240 W on three occasions: with no cooling, with a liquid-cooled vest, and with an air-cooled vest.

face area of 0.25 m^2). The vest incorporated an inner spacer fabric design to ensure uniform distribution of air over the entire surface of the torso covered by the vest (J. Frim, DCIEM, unpublished results). Air is directed across the permeable underwear, thus close to the skin surface, so that it acquires heat both by evaporation of sweat (E) and by convection (C_{VEST}) and then vents at the vest periphery through the clothing to the surrounding environment. Flow and inlet temperatures were maintained at 280 L/min (10 scfm) and 13°C (dew point 8°C), respectively.

The theoretical maximal dry convective cooling capacity of the air vest (C_{VEST} = 123 W) was calculated as the product of air flow rate, air density and specific heat, and the gradient between air temperature and an assumed skin temperature of 35°C, as described elsewhere (17). The theoretical maximal evaporative cooling capacity (E = 364 W) was calculated as the product of the air flow rate, the latent heat of evaporation of water at 35°C, and the gradient between moisture content of inlet air and air saturated at an assumed skin temperature of 35°C. The theoretical total air cooling capacity (C_{VEST} + E) was therefore 487 W. The theoretical maximal conductive cooling capacity of the liquid vest (K = 459 W) was estimated by the product of the coolant flow rate, coolant density, coolant specific heat, and change in coolant temperature from a 13°C inlet to a 35°C outlet temperature, assuming a final skin temperature of 35°C. Thus, at the settings described above, these two vests have relatively similar total theoretical cooling capacities, albeit with different mechanisms of heat transfer.

Respiratory Gas Exchange Measurements

Oxygen consumption and carbon dioxide production (converted to STPD values) were measured for 3 min of every 10 min rest/exercise session (Beckman Horizon Metabolic Cart, Anaheim, CA). Analyzers were regularly checked for proper calibration during the tests. Metabolic rate was calculated from the tables of Lusk (14), as described elsewhere (27).

Thermal Measurements and Heat Balance Analysis

All thermal data were continuously monitored, averaged and recorded every min using a computer-controlled data acquisition system described in detail elsewhere (Hewlett-Packard 236 computer and 3497A data acquisition unit; 28). A standard 12-point system of skin temperature measurement was used in the present study (26,28). However, because the four standard torso sites were heavily influenced by the cooling vests during the cooling conditions, they were deemed more representative of only the vest area covering the body (0.27, 0.25, and 0.26 m^2 or, 14, 13, and 13.5% of the BSA for LC, AC, and NC, respectively) rather than the entire torso area (about 0.69 m^2 or 35% of the BSA). Accordingly, mean skin temperatures for the whole body, vest and non-vest areas of the body ($\bar{T}_{sk(WB)}$, $\bar{T}_{sk(V)}$ and $\bar{T}_{sk(NV)}$, respectively) were calculated using modifications of the standard weighting factors. Specifically, $\bar{T}_{sk(V)}$ was defined as the area-weighted mean temperature of the four torso sites adjusted to exclude the non-vest area of the torso, while $\bar{T}_{sk(NV)}$ was taken as the area-weighted mean temperature of the non-torso skin temperatures adjusted to exclude the vest area of the torso. $\bar{T}_{sk(WB)}$ was then calculated as the area-weighted sum of $\bar{T}_{sk(V)}$ and $\bar{T}_{sk(NV)}$. Mean body temperature ($\bar{T}_b$) was calculated as $0.8T_{re} \pm 0.2\ \bar{T}_{sk(WB)}$ (23), where T_{re} is the rectal temperature. Body heat storage (watts) was calculated according to Burton (6):

$$S = (3.48 \times \text{body mass} \times \text{rise in } \bar{T}_b/\text{h})/3.6 \qquad \text{Eq. 1}$$

where 3.48 is the specific heat of the body tissues (kJ • kg^{-1} • $°C^{-1}$) and 3.6 is the conversion factor from kJ/h to J/s, or watts.

The dry heat exchange with the ambient environment by radiation and convection (R + C_{amb} in watts) was assessed as follows (3,13):

$$R + C_{amb} = [BSA \times 6.45 \times \bar{T}_{sk} - \bar{T}_{amb})]/I \qquad \text{Eq. 2}$$

where BSA is either the whole body or non-vest surface area (no cooling or cooling configurations, respectively), 6.45 is the heat transfer coefficient when the clothing insulation I is in clo units (2.5 clo for the CF-CD-IPE), $\bar{T}_{sk}$ is either the final $\bar{T}_{sk(WB)}$ or $\bar{T}_{sk(NV)}$ (no cooling or cooling configurations, respectively) corresponding to the above BSA, and T_{amb} is the ambient environmental temperature (37°C). Other heat losses, or the combination of E, K from LC, and C_{VEST} from AC (K and C_{VEST} were assumed negligible with the AC and LC vests, respectively) were lumped into one term (H_{EKC}) that was calculated by resolving the heat balance equation (all units are in watts):

$$M - W - L - S - R - C - K - E = O \qquad \text{Eq. 3}$$

or,

$$M - W - L - S - (R + C_{amb}) - E - K - C_{VEST} = 0 \qquad \text{Eq. 4}$$

then,

$$H_{EKC} = M - W - L - S - (R + C_{amb}) \qquad \text{Eq. 5}$$

where M is the average metabolic rate between rest and exercise, W is the average external work (8), L is the respiratory heat losses through evaporation and convection (8% of M) (5), S is the rate of heat storage (Eq. 1) and R + C_{amb} is the dry heat exchange (Eq. 2). Note that all components of Eq. 5 except H_{EKC}, were either measured directly, or were easily derived from direct measurements. In addition, they represent the final readings available under each test condition. Because of some missing metabolic data, and because some NC tests were terminated before a last metabolic measurement, we have considered that, on some occasions, an average metabolic rate of the last two rest and exercise sessions would still provide a reasonable and reliable metabolic assessment.

Statistics

The effects of the cooling configuration (NC, LC, AC) were analyzed using a one-way analysis of variance with repeated measures (Biomedical Computer, Programs, BMDP-89, Los Angeles, CA). Paired *t*-tests, adjusted for multiple comparisons by the Bonferroni method were used to locate significant differences. Results are mean ± SEM.

RESULTS

Tolerance time or heat exposure time is depicted in Fig. 2. Subjects could only tolerate 95 ± 5 min of the heat stress test with the NC configuration, whereas all subjects were able to complete the 150 min test with either AC or LC ($p < 0.01$). After 1 h in the chamber, significant differences in T_{re} were observed between NC and both LC and AC (Fig. 3A). The average rate of increase in T_{re} (pre- and posttest values divided by the heat exposure time) for NC was 1.00 ± 0.05°C/h. This rate was reduced 51% by LC ($p < 0.01$) and 63% with AC, the latter being significantly lower than that of LC ($P < 0.01$; Fig. 3B).

The changes in $\overline{T}_{sk(WB)}$ were quite revealing. Fig. 4A shows that $\overline{T}_{sk(WB)}$ increased by almost 4°C with NC, whereas it was increased by less than 2°C with either cooling vest. How this was achieved is demonstrated by comparing $\overline{T}_{sk(V)}$ and $\overline{T}_{sk(NV)}$ for all three configurations (Fig. 4B and 4C). Whereas $\overline{T}_{sk(V)}$ increased by 3.4 ± 0.1°C with NC, it did not increase but dropped by 5.4 ± 0.9°C and by 5.6 ± 7.0°C with LC and AC, respectively ($p < 0.01$). $\overline{T}_{sk(NV)}$ increased by 4.0 ± 0.1°C with NC, whereas it only increased by 2.9 ± 0.2 and 3.0 ± 0.1°C with LC and AC, respectively ($p < 0.01$). In addition to producing much lower absolute levels of $\overline{T}_b$ (Fig. 5), the LC and AC cooling vests entailed a 59% (0.53 ± 0.04°C/h) and a 66% (0.45 ± 0.04°C/h) reduction in the rate of $\overline{T}_b$ increase in comparison to NC (1.30 ± 0.04°C/h; $p < 0.01$).

Fig. 6 summarizes sweat rate, sweat evaporation rate and evaporative efficiency index data. NC was associated with almost 1 kg/h of sweat rate, or a dehydration of about 2% of body weight for the average 95-min exposure. This sweat rate was reduced by 38% with LC and 51% with AC ($p < 0.01$). The AC sweat rate was also significantly lower than that of LC ($p < 0.01$; Fig. 6A). The sweat evaporation rate data presented a different picture. LC reduced it by 21% whereas AC increased it by 19%, in comparison to NC ($p < 0.05$; Fig. 6B). In terms of the evaporation efficiency index, Fig. 6C clearly shows that only 23% of the NC sweat produced had evaporated. Surprisingly, LC fared only slightly better than NC (n.s.); in contrast, AC displayed a much higher evaporative efficiency index than the two other conditions ($p < 0.01$).

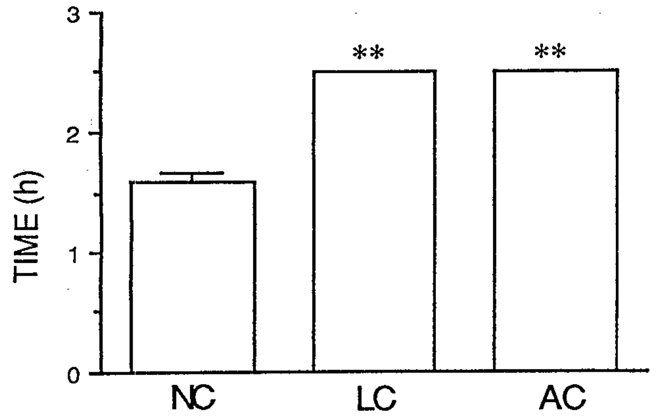

Fig. 2. Influence of liquid-cooling (LC) and air-cooling (AC) on heat exposure time. There was no SEM with either cooling vests since all subjects were able to complete the 150 min test. Significant differences from the no cooling (NC) configuration are indicated by ** = P < 0.01.

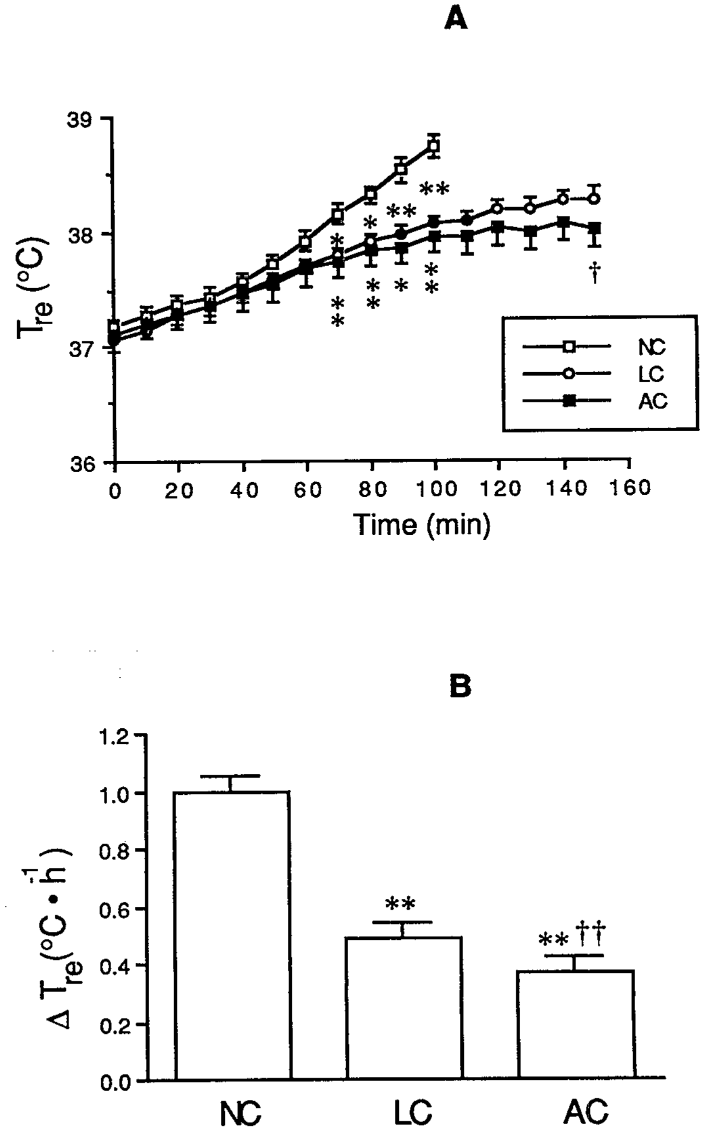

Fig. 3. Influence of liquid-cooling (LC) and air-cooling (AC) on core temperature (T_{re}) profile over time (Fig. 3A) and on the rate of change in T_{re} (pre and post divided by exposure time, in °C/h; Fig. 3B). Significant differences from the no cooling configuration (NC) are indicated by either one (* = P < 0.05) or two symbols (= P < 0.01), whereas the significant differences from LC are indicated by either one († = P < 0.05) or two symbols (†† = P < 0.01).**

Table I shows the heat balance data which comprises the results of metabolic heat production (M), external work rate (W), respiratory heat losses (L), heat storage (S), dry heat exchange with the environment (R + C_{amb}), and other heat losses (H_{EKC}). Although M, W, and L were similar between the three tests (n.s.), S was 59% and 66% lower with the LC and AC vest in comparison to NC, respectively ($p < 0.01$). R + C_{amb} corresponded to practically no dry heat exchange with the ambient

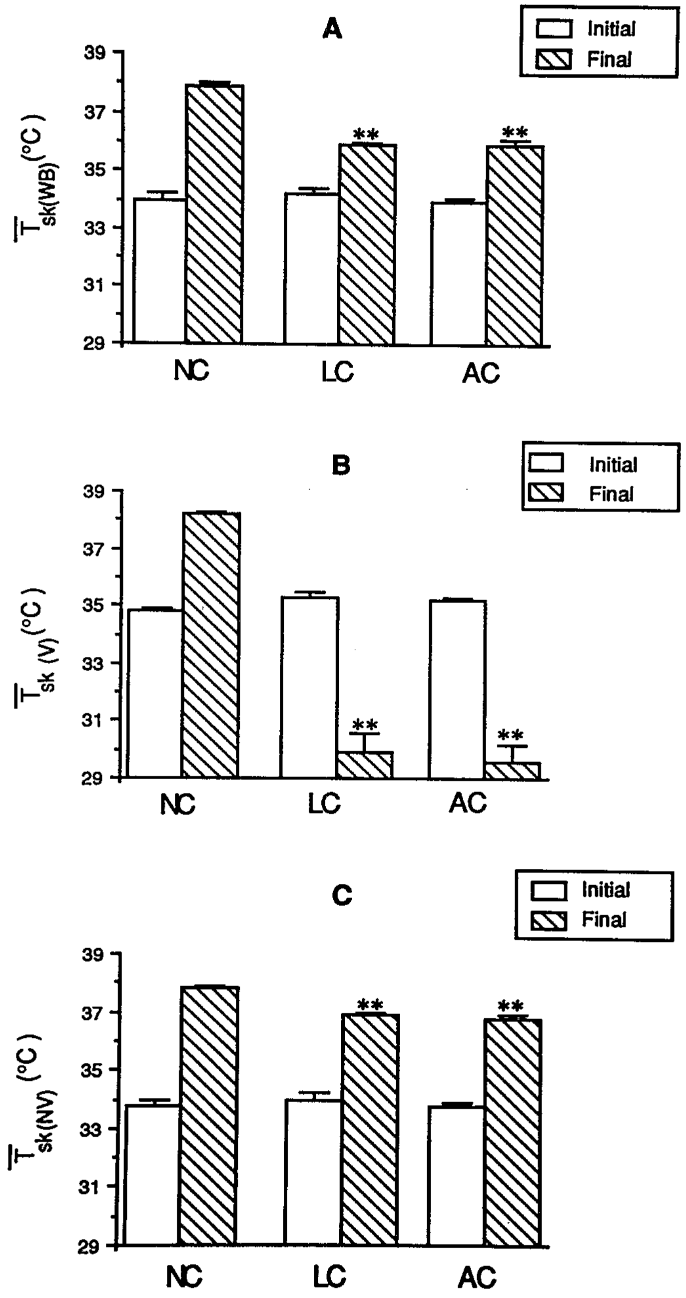

Fig. 4. Influence of liquid-cooling (LC) and air-cooling (AC) on mean skin temperatures for the whole body (Fig. 4A), vest (Fig. 4B) and non-vest areas (Fig. 4C) of the body ($\bar{T}_{sk(WB)}$, $\bar{T}_{sk(V)}$ and $\bar{T}_{sk(NV)}$, respectively). $\bar{T}_{sk(V)}$ was defined as the area-weighted mean temperature of the four torso sites only covering the vest area, while $\bar{T}_{sk(NV)}$ was defined as the area-weighted mean temperature of the non-torso skin temperatures including the non-vest area of the torso. $\bar{T}_{sk(WB)}$ was calculated as the area-weighted sum of $\bar{T}_{sk(V)}$ and $\bar{T}_{sk(NV)}$, as described in Methods. Symbols for statistical differences are as in Fig. 3.

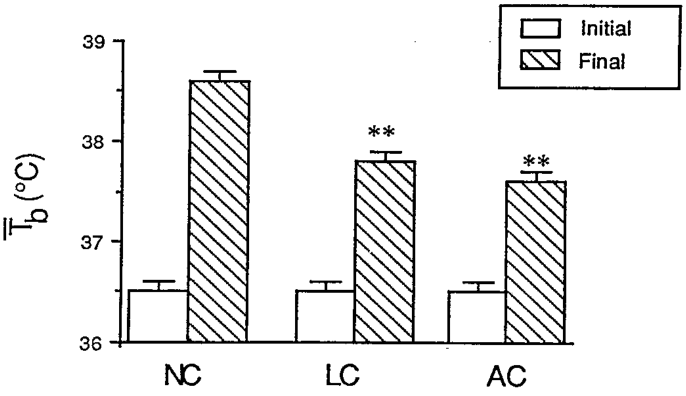

Fig. 5. Influence of liquid-cooling (LC) and air-cooling (AC) on mean body temperature ($\bar{T}_b$), which was calculated as $0.8 T_{re} \pm 0.2 \bar{T}_{sk(WB)}$, as described in Methods. Symbols for statistical differences are as in Fig. 3.

environment when either cooling vest was used, whereas it amounted to a very small heat loss with NC ($p < 0.05$, Table I). HEKC of LC and AC were therefore 32% and 46% higher than that of NC, respectively ($p < 0.01$). Interestingly, AC's HEKC was slightly higher than LC, although it did not reach significance (Table I).

Heart rate data was analyzed using averages of both the initial and final values during both the rest (initial rest was between min 10–30; see Fig. 1) and exercise sessions (Fig. 7A) Briefly, the data shows that both cooling systems decreased initial and final heart rates during both rest and exercise sessions. It is important to note that final exercise heart rate with AC was significantly lower than that observed with LC ($p < 0.05$). Exactly the same pattern of response and differences was observed with the subjective ratings of thermal comfort (Fig. 7B). The rate of perceived exertion was, however, barely altered with the use of either cooling vests, with the exception of the final ratings at rest, which were significantly lower with AC in comparison to NC ($p < 0.05$; Fig. 7C).

DISCUSSION

The results of the present study demonstrate that subjects wearing the Canadian Forces aircrew chemical defence individual protection ensemble (CF-CD-IPE) under simulated hot cockpit conditions experience significant heat stress and can only complete 95 min of the 150-min heat exposure. This reduced tolerance time was accompanied by high rates of T_{re} increase, sweat output, and body heat storage (Fig. 2, 3, and 6; Table I). The present results also confirm and extend previous findings which showed that liquid-cooled garments are an effective means of alleviating heat stress for aircrew (7), even when wearing CD ensembles in the heat. Indeed, changes in T_{re}, sweat rate and S were all significantly improved with the use of LC (Fig. 2, 3, and 6; Table I). The results also demonstrate that the present prototype AC vest was even slightly better than the present LC vest in reducing the heat strain, as shown by the significant improvements in T_{re}, sweat rate, evaporative efficiency index, subjective rating of thermal comfort and heart rate (Fig. 2, 6, 7). It is suggested that these differences between LC and AC result from a slightly greater total cooling (sum of HEKC and R + C_{amb}), and a very high evaporative cooling (Table I).

Air-Cooled Vest

Although both vests were found to provide relatively similar theoretical maximal cooling capacities, the actual cooling that was achieved was slightly different (Ta-

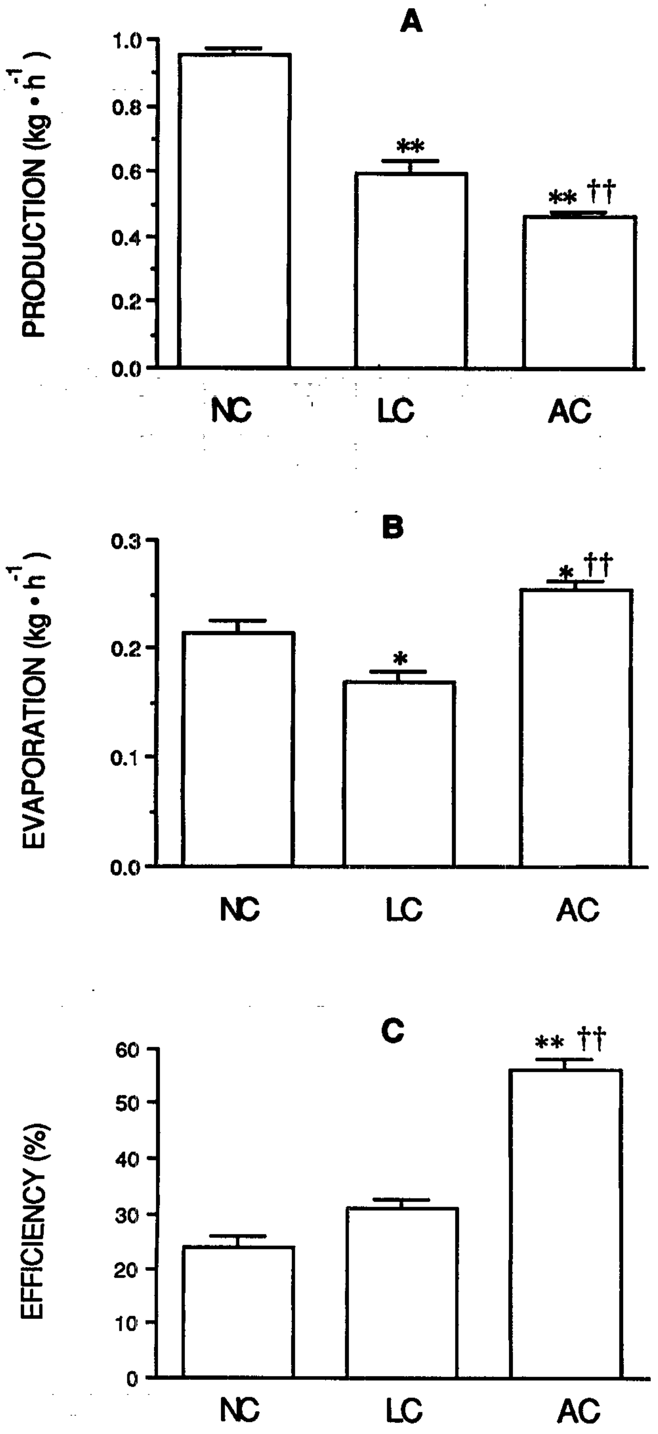

Fig. 6. Influence of liquid-cooling (LC) and air-cooling (AC) on sweat rate (Fig. 6A), sweat evaporation rate (Fig. 6B) and evaporative efficiency index (Fig. 6C). Symbols for statistical differences are as in Fig. 3.

TABLE I. INFLUENCE OF LIQUID- OR AIR-COOLING ON HEAT BALANCE.

	M	W	L	S	R + C_{amb}	H_{EKC}
No cooling	268	25	21	93	4	124
	±9	±0	±0	±4	±0	±9
Liquid	247	25	20	38**	0*	164**
cooling	±8	±0	±1	±3	±0	±7
Air	257	25	20	32**	−1*	181**
cooling	±12	±0	±1	±2	±1	±9

Values in the heat balance equation during the heat stress test while wearing no cooling (NC), a liquid-cooled (LC) vest and an air-cooled (AC) vest with CF protective clothing. M average metabolic rate, W external work rate, L respiratory heat losses, S rate of heat storage, R + C_{amb} whole body or non-vest dry heat exchange with the ambient environment for the no cooling and cooling tests, respectively, and H_{EKC} the combination of other heat losses through evaporation (E), conduction (K from LC) and convection (C_{VEST} from AC). These parameters were measured or estimated exactly as described in Methods. All units are in watts. Results are mean ± SEM. The symbol * refers to a significant difference from the NC configuration ($P < 0.05$), whereas two symbols ** = $P < 0.01$.

ble I), and it occurred via quite different mechanisms. The present prototype AC vest was estimated to have a maximal C_{VEST} of 123 W, and a maximal E of 364 W, for a total theoretical capacity of 487 W (see Methods). H_{EKC}, which represents the heat losses by E, K (assumed negligible with the exception of LC), and C_{VEST} that are unaccounted for by the R + C_{amb} heat losses, amounted to 181 W (Table I). This would indicate that the vest was, at best, operating at 37% of the maximum theoretical capacity. Unfortunately, we could not directly measure the vest's true efficiency by monitoring outlet air conditions as it left the IPE.

To estimate the proportion of heat loss through E and C_{VEST} in the AC vest configuration, we assumed that E was high since both the subjects and the clothing appeared almost entirely dry at the end of each AC test. Assuming that an arbitrary 80% of the heat necessary to evaporate sweat came from the skin (the rest would have to come from the underwear), then the AC sweat evaporation rate of 0.255 kg/h (Fig. 6B) would correspond to a maximal E of 137 W. This would leave an AC C_{VEST} component that would amount to only 44 W (181 − 137 W). Consequently, 76% of the high total cooling in the AC configuration would thus be derived from E, AC's predominant mechanism of heat transfer. This percentage would only increase to 82% if we had assumed the same fraction of sweat evaporation at the skin (87%) used in NC (see below). The above data would thus be in line with the low sweat rate, high sweat evaporation rate, high evaporative efficiency, low heart rate and low discomfort found with AC, compared to the other conditions (Fig. 6 and 7), although they would need confirmation from future studies.

This study confirms other findings which have shown that AC systems are as effective in alleviating heat stress as LC systems (20,21) and provide drier skin conditions, thereby increasing the level of comfort (22). This study also extends the above findings by showing that AC garments can be physiologically superior to LC garments of similar coverage design (Fig. 2, 6, and 7; Table I). Unfortunately, while the heat balance data are consistent with this concept, they do not explain how it was possible with AC to observe a lower T_{re} than with LC, in the presence of relatively similar $\overline{T}_{sk(WB)}$, $\overline{T}_{sk(V)}$, and $\overline{T}_{sk(NV)}$ (Fig. 3 and 4). One possible explanation is that air cooling occurs throughout a greater body surface area than the vest area (monitored by four thermistors). Recent *post hoc* tests performed with additional thermistors positioned at locations outside of the vest supported our suggestion that LC cools only the area it

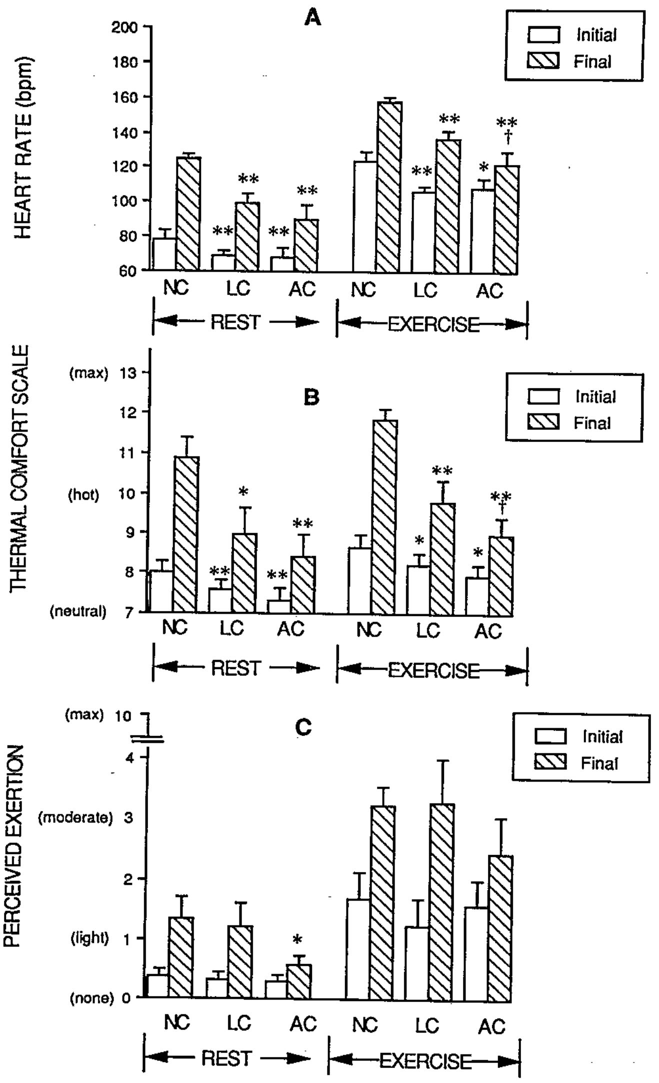

Fig. 7. Influence of liquid-cooling (LC) and air-cooling (AC) during rest and exercise on heart rate (Fig. 7A), subjective ratings of thermal comfort (Fig. 7B), and subjective ratings of perceived exertion (Fig. 7C). Symbols for statistical differences are as in Fig. 3.

covers, whereas with AC, cooling spreads to a greater area which includes not only the vest area but also the neck and the non-vest areas of the torso; i.e.: areas not directly represented by the present four torso thermistors, thereby resulting in an overestimation of the absolute value of $\overline{T}_{sk(WB)}$ and $\overline{T}_{sk(NV)}$ (Vallerand & Michas, DCIEM, unpublished results). Further studies are nevertheless requried to confirm these suggestions.

Liquid-Cooled Vest

The present LC vest was estimated to have a theoretical maximal cooling capacity of 459 W (see Methods). It is also known that the actual cooling was lower than the estimated maximum since preliminary tests had indicated that outlet temperatures were approximately 19°C, corresponding to a K of 125 W (calculated as in Methods). This level of cooling corresponds to a 27% efficiency when compared to the above theoretical maximal value. Since we have determined in Table I that other heat losses (H_{EKC}) in LC were 164 W, then E would be 39 W (164 − 125 W). With the sweat evaporation rate (0.169 kg/h; Fig. 6) corresponding to a potential E of 113 W, it appears that only 35% of the heat required for sweat evaporation came from body and the rest from the environment. It must be noted that the estimation of E of LC is about one third of that of NC (see below), even though LC's evaporative efficiency index was slightly higher than that of NC (Fig. 6C). This clearly indicates that this index is strictly related to sweat and its evaporation and is not indicative of changes in evaporative cooling (Fig. 6, Table I).

Besides increasing the surface area of the garment, which could eventually interfere with aircrew gear, inlet temperatures can be varied to increase cooling. However, previous studies have established that coolant inlet temperatures less than 10°C are unacceptable to the wearer (22). Furthermore, as water has a high heat capacity, LC has been considered well suited for microclimate cooling where heat loads greater than 465 W need to be removed (22). Conversely, if the cooling requirements are lower, the wearer can become chilled. Since AC depends mainly on E, excessive cooling would be unlikely because sweating would stop, thus sharply restricting the cooling to the smaller C_{VEST} component. This is in contrast to LC which may develop uncomfortable cold spots on the body when cooling exceeds requirements. The essential differences between AC and LC are the slightly greater total cooling achieved with AC (181 vs 164 W), and the different mechanism of heat transfer employed. It is suggested that the combination of these two differences are directly related to the AC-induced improvements in T_{re}, sweat rate, evaporative efficiency index, thermal comfort and heart rate (Fig. 3, 6, 7). LC depends on K (76% of total cooling) while AC depends on E to be effective (76% of total cooling). In addition, E of AC was estimated to be 3.5 times E of LC.

No Cooling

The estimation of the proportion of heat loss derived from E in H_{EKC} was fairly straightforward with the NC configuration. Since there was no K (from LC) or C_{VEST} (from AC), then H_{EKC} equals E (124 W, Table I). It is, therefore, very interesting to note that a sweat rate of almost 1 kg/h resulted in a sweat evaporation of only 0.214 kg/h, which corresponds to a potential E of 143 W. This would indicate that up to 87% (124/143 W) of the sweat evaporation occurred at the skin level with this configuration. The reason this percentage is higher than that of LC (35%), and the reason E (124 W) is estimated to be three times as high as with LC (39 W) are not clear. One possible explanation is that NC provided markedly warmer $\overline{T}_{sk(WB)}$ (by about 2°C) than LC, thus facilitating E (Fig. 4).

Another possible explanation is that the LC vest acts as an impermeable layer of insulation covering an important portion of the torso area which prevented evaporation of sweat underneath it. In addition, as ambient humidity increases (within the cool LC microclimate) sweat evaporation becomes increasingly ineffective so that more sweat is wasted, or wicked into the clothing (outside vest perimeter) and evaporation takes place at sites more removed from the skin. On the one hand, individuals wearing CD gear may find it sweat-permeable but they frequently receive less than the full cooling benefit of sweat evaporation (10). On the other hand, it would appear from the present data that the cooling effect of sweat evaporation is even further reduced by the cool LC microclimate. This suggestion would deserve further investigation. Nevertheless, the predominant mechanism of heat loss in NC is E (97% of total). However, it comes at the high cost of possible dehydration. Indeed, subjects produced sweat at a high rate because only 23% of that amount was evaporated. Even then, they only benefited from 87% of the cooling effect of E at the skin. It should be noted that this was also associated with the lowest evaporative efficiency index (Fig. 6C). As stated earlier, this index seems a poor indicator of evaporative cooling.

The present data thus confirm previous CD studies which have shown that tolerance time in the heat is more dependent on heat dissipation than ambient load (9–11,17,22). We have also shown that the low rates of heat loss and the high rates of body heat storage with NC were significantly improved with either cooling garment (Table I), although the AC vest was slightly but significantly better in several aspects. Each of the subjects wearing LC or AC was able to complete the full duration of the test without difficulty, particularly with AC. All subjects agreed unanimously, on a written questionnaire completed at the end of the study, that a cooling system is required to complete this strenuous test and that the AC was substantially more comfortable than the LC.

Microclimate cooling systems also have limitations. It is difficult to provide conditioned air outside the aircraft, and the cooling capacity of ambient air systems depends on ambient environmental conditions. Liquid systems can impose a weight penalty on individuals, and some LC systems have even been shown to deteriorate heat tolerance (12). Finally, tethered systems limit the user's freedom of movement. However, it has been demonstrated that a 1°C rise in T_{re} can decrease aircrew performance and that a 1–3% body weight dehydration impairs G-tolerance (4,19). The present 1.5°C increase in T_{re} and 2% of dehydration with NC are certainly indicative of heat strain beyond the limit of acceptance for aircrew (1,16). Under the present test conditions, the use of a microclimate cooling system, particularly AC, would be recommended to prevent degradation of thermal comfort, aircrew performance, G-tolerance, and safety.

In conclusion, the results of this study have demonstrated that subjects wearing the Canadian Forces aircrew chemical defence individual protection ensemble under simulated hot cockpit conditions could tolerate only 95 min of the 150-min test, and experienced significant heat strain. This heat strain was, however, significantly alleviated by either AC or LC vest. E and K accounted for 76% of the total cooling with AC and LC, respectively, whereas 97% of the total cooling in NC was achieved by E. Compared to LC, greater improvements in T_{re}, sweat rate, evaporative efficiency index, heart rate, and subjective comfort were observed with the AC vest, possibly as a result of its slightly higher total cooling and greatly enhanced evaporative cooling.

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