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TITLE

LIMB BLOOD FLOW WHILE WEARING AIRCREW CHEMICAL DEFENSE ENSEMBLES IN THE HEAT WITH AND WITHOUT AUXILIARY COOLING

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Limb Blood Flow While Wearing Aircrew Chemical Defense Ensembles in the Heat With and Without Auxiliary Cooling

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The effect of auxiliary air cooling on endurance time and limb blood flow in the heat (37°C, 50% r.h., target time = 150 min) while wearing aircrew chemical defense (CD) ensembles was examined. Eight males were dressed in aircrew CD ensembles with or without an air-cooled vest. After an initial 10 min treadmill walk and 20 min of seated rest, the subjects alternately rested and exercised on a cycle ergometer (10 min rest, 10 min exercise) resulting in an overall metabolic rate of 240 W. Arm and leg blood flow (ABF, LBF), determined by venous occlusion plethysmography, were significantly lower with air cooling (AC) than with no cooling (NC) during the same time period ($p < 0.05$). Endurance time was much greater with AC than with NC (150 min AC vs. 92 ± 0.08 min NC, $p < 0.01$). Arm and calf skin temperatures, rectal temperature and heart rate were all significantly lower with AC than with NC ($p < 0.05$) after the onset of the cycle exercise. The results show that the use of the air-cooled vest under these conditions was able to increase heat tolerance and reduce blood flow to the periphery.

EVEN THOUGH METABOLIC heat production has been shown to be relatively low while flying aircraft, external heat loads and metabolic heat build-up on aircrew can be quite considerable (8). When chemical defense (CD) gear is worn, this heat stress becomes even greater and may cause decrements in aircrew performance. Extreme vasodilatation in the skin that results from this heat stress can effectively remove a great deal of blood volume from the central circulation (23). This can cause venous return to be impaired, thus making aircrew more susceptible to other stresses of flying.

Microclimate cooling devices such as air or water cooled suits have been developed to alleviate heat stress in aircrew. Cooling devices such as liquid-filled suits and air-cooling suits have been used, or at least developed, by both the British and American air forces (7,28). Likely the most well-known example of a liquid-filled suit is the system used in the American space program, especially during the Apollo project, where the suit was used to provide temperature control across the spectrum of cold to hot (15). These suits, however, have been found to be hot and cumbersome when worn on the ground without coolant, as would be the case during walkout to the aircraft and the walkaround checks (7). Recently, a prototype air-cooled vest was designed at our institute to help alleviate heat stress without being as cumbersome. We tested the effectiveness of this vest on peripheral blood flow and heat tolerance in aircrew chemical defense (CD) gear. Although we have previously shown that these vests are capable of relieving some of the heat stress associated with CD gear (25), evidence that they may have a moderating effect on the increase in peripheral blood flow and associated venous pooling resulting from heat stress has not been documented.

One area of flying performance shown to be affected by heat stress is tolerance to headward acceleration ($+G_z$) (5,19,21). The impairment of $+G_z$ is likely caused by the increased peripheral blood pooling associated with the heat exposure, which has the effect of reducing venous return and, therefore, stroke volume and cardiac output; these have been well documented during exercise in the heat (23) and during exposure to $+G_z$ (11,17). Venoconstriction at rest and during supine exercise has also been shown to be attenuated by heat stress in humans (29). It was, therefore, of interest to determine the effect of heat stress on peripheral blood flow in CD gear under conditions of mild to moderate exercise and to determine the effect of an air-cooled vest on peripheral blood flow in the same CD gear.

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METHODS

Eight healthy males participated in the study. Their physical characteristics were as follows (mean ± S.E.M.): age: 30.8 ± 1.5 years; weight: 75.8 ± 2.3 kg; height: 1.80 ± 0.01 m; $\dot{V}o_{2max}$: 50 ± 3 ml • kg^{-1} • min^{-1} (3.77 ± 0.24 L • min^{-1}).

Following the acceptance of the experimental protocol by the Institute's Ethics Committee, subjects were informed of the details and possible risks of the experiment and informed consent was obtained. Subjects were also screened by a physician. They were told that they could withdraw from the experiment at any time without prejudice.

Limb blood flow was estimated by venous occlusion plethysmography using the mercury-in-rubber strain gauge technique (27). Blood flow was sampled at rest with the subjects dressed only in long underwear outside the chamber, immediately after a 10-min walk in the chamber (post walk 1; w1), after 20 min of rest in the chamber, (post walk 2; w2), and immediately after each exercise cycle period (Ex1, Ex2, Ex3 . . . etc.).

Skin temperature was measured using a 12 lead thermistor harness and was calculated using the method of Hody (10). Rectal temperature was measured using a flexible thermistor probe inserted 12 cm beyond the anal sphincter. The probe was held in place using a gauze bandage system configured in the form of a truss.

Maximal oxygen consumption ($\dot{V}o_{2max}$) was determined before and after the six chamber trials using the Bruce treadmill protocol. Expired gases were analyzed by open-circuit spirometry (Sensormedics 4400 metabolic cart, Anaheim, CA). Heart rate was monitored with a cardiotachometer (Sports Tester, Polar Electro, Finland).

Metabolic rate in the environmental chamber was determined during the last 2 min of both the rest and the work periods by open-circuit spirometry (Horizon Metabolic Measurement Cart, Sensormedics, Anaheim, CA).

Subjects reported to the laboratory at the same time each day, having consumed only a light meal. They were required to void before dressing at which time they inserted a rectal probe. After inserting the probe, the subjects reported to the dressing room where they stripped and were weighed nude with the rectal probe. Skin thermistors were taped to the appropriate skin sites and a cardiotachometer electrode/transmitter belt (Sports Tester Polar Electro, Finland) was fastened around the chest. The venous occlusion collecting cuffs were attached and the subject then put on a pair of long underwear bottoms, a turtleneck shirt, and a pair of wool socks. The mercury strain gauges were then affixed to both the forearm and lower leg underneath the clothing at the point of maximum girth of each segment. Care was taken to ensure that the strain gauges would not move during subsequent dressing or movement. This was especially critical for the leg gauge. After the gauges were secured in place, the subject moved to the area used for resting blood flow measurement, sat in a chair and relaxed for 5 min. The subjects' limbs were positioned so that the leg was slightly extended at the knee (i.e., ~120–150°) and the arm was at the side, at or slightly above the level of the heart. Ambient temperature was 22 ± 1.0°C. Resting blood flow measures were taken simultaneously on the arm and leg over a 2-min period. Strain gauge signals were amplified and recorded on a four-channel pen recorder (Beckman, Anaheim, CA). Cuff inflation was controlled manually via a toggle switch connected to an electric solenoid valve that controlled air flow from the air source to the occlusion cuffs and from the cuffs to the environment. This system allowed simultaneous pressurization of the forearm and leg cuffs.

After the resting blood flow measurements were taken, the subjects reported back to the dressing area where they completed the dressing procedure. This involved the donning of the cooling vest, if required, and the Canadian Forces Aircrew Chemical Defence ensemble consisting of a two-layer protective overgarment, gloves (3 layers) and socks, and combat flight boots. All of the above were common to all clothing configurations. Differentiation into the different configurations was based on the rest of the equipment worn. The clothing configurations were defined as follows: H5: AR-5 CD respirator, DH-411 helmet and rubber overboots; H4: AC-4 respirator, DH-411 helmet and rubber overboots; CF: AR-5 respirator, Gentex model 190 helmet, survival vest, anti-G trousers, no rubber overboots. H4 and H5 are helicopter configurations while CF indicates the configuration that would be used in fighter aircraft. The air cooling vest was worn over top of the turtleneck shirt and underneath the CD ensemble. The flow rate through the vest was 280 L • min^{-1} and the inlet temperature was 13°C. Each subject underwent six exposures involving each clothing configuration with or without cooling.

Because all the clothing, with the exception of the long underwear and G-suit, was loose, we did not think it would have an effect on the blood flow measurements. There was some concern, however, that the long underwear and G-suit would cause some measurement error. Initial testing, however, revealed that this was not the case. This was confirmed by the similarity of our resting values to those presented in the literature. We also wanted to be sure that the strain gauge on the calf would not move during the cycle exercise or the walk. We found that by carefully anchoring the strain gauge with tape, taking care not to affect the operation of the gauge, there was no apparent movement of the gauge on the leg. This was confirmed by carefully marking the gauge location, having the subject exercise, and then observing any change in the placement of the gauge. The tape was attached so that the adhesive did not touch the gauge. This was accomplished by placing another piece of tape over the anchor tape with the adhesive sides facing each other so that only the portion of the tape that touched the leg on either side of the gauge adhered to the leg. We also found that the long underwear helped to hold the gauge in place.

Upon completion of the dressing procedure, the subjects were weighed again and then proceeded to the climatic chamber. The environment in the chamber was controlled at 37°C and 50% r.h. Upon entry into the chamber, the subject was connected to the data acquisition unit (Hewlett-Packard, HP 236 + data acquisition unit model 3497 A) and the exhaust port of the respirator was connected to the metabolic cart except for the H4 configuration. In this case, because a proper seal could not be obtained for expired gas measurement, subjects lifted the mask and used a standard mouthpiece and Hans-Rudolph valve. All measurement and recording equipment was outside the chamber. The subject then walked for 10 min at 4 km • h^{-1} on a treadmill to simulate a walk out to the aircraft. Immediately after this, the subject sat in an aircrew seat and the limbs were placed in a position similar to that used during the resting measurements, and the strain gauges and occlusion cuffs were connected to the inflation/measurement apparatus outside the chamber. The first blood flow measurements were taken within 2 min of the subject completing the treadmill walk.

The subject then rested for 20 min at which time another series of blood flow measurements were taken. The subject then began an alternating series of 10 min of cycling on a stationary cycle ergometer and 10 min of rest. Blood flow measurements were taken immediately following each exercise period and, therefore, represent immediate postexercise values and not resting values. The power output for the cycling was 50W. The combination of the work and rest was calculated to achieve an overall work rate of 25W or an overall metabolic rate of about 240W. This represents the approximate metabolic rate seen in the cockpit during normal flying (3,15,18).

Upon termination of the experiment, the subjects undressed and nude body weights were again obtained. The experiment was terminated for any of the following reasons: 1) subjective discomfort, headache, nausea, inability to continue; 2) exercise heart rate greater than 95% maximum for 2 consecutive minutes; 3) rectal temperature of 39.0°C or an increase of greater than 2.0°C over the initial resting value; or 4) maximum time attained (150 min).

Statistical Analysis

The experimental design was a 2 × 3 factorial with two levels of cooling (cooling vs. no cooling) and three clothing configurations (H4, H5, CF) as within subjects factors. The assignment of cooling and clothing combinations was counterbalanced among subjects. The subjects were not aware of which combination they would be wearing prior to the experiment.

The data were analyzed using ANOVA with repeated measures (6). Significance was accepted at the 0.05 level although p values greater than 0.05 and less than 0.1 were considered indicative of trends. Significant differences were clarified using a Neuman-Keuls *post hoc* test for differences between paired means. Statistical significance was again accepted at the 0.05 level.

RESULTS

Since the initial data analysis revealed no difference among clothing configurations, the data were pooled simply as no cooling vs. air cooling.

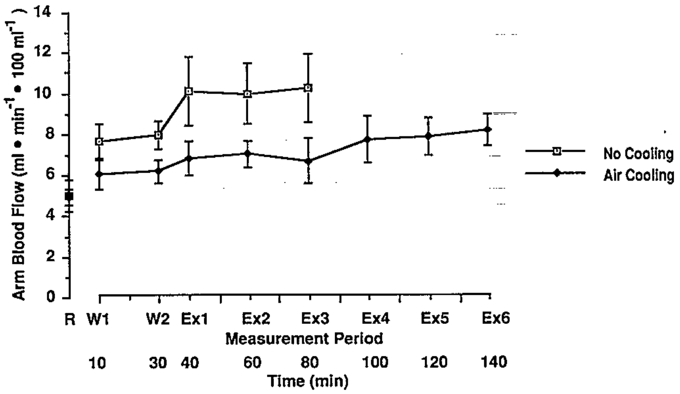

Fig. 1. Effect of cooling on arm blood flow for 8 subjects in aircrew chemical defense ensembles exposed to 37°C air, 50% r.h. R = rest, W1 = immediate post 10 min walk, W2 = after 20 min rest in chamber after walk, Ex1–Ex6 = immediate post cycle exercise values. Mean ± S.E.M.

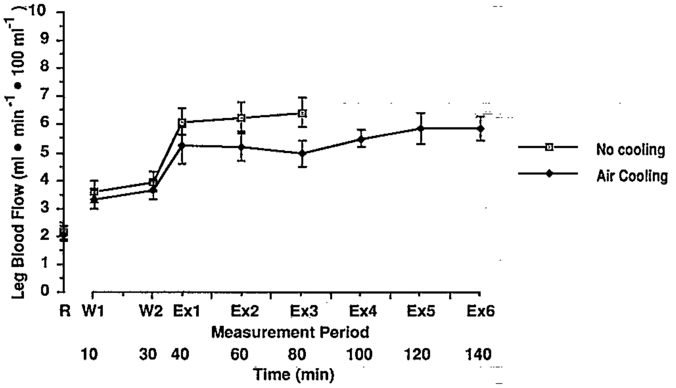

Fig. 2. Effect of cooling on leg blood flow for 8 subjects in aircrew chemical defense ensembles exposed to 37°C air, 50% r.h. Abscissa legend same as Fig. 1. Mean ± S.E.M.

Fig. 1 and 2 show results for arm and leg blood flow, respectively. Resting arm and leg blood flow (ABF, LBF) were 4.97 ± 0.35 and 2.09 ± 0.12 ml • min^{-1} • 100 ml^{-1}, respectively. These values are comparable to other published values (9,24). There were no significant differences in resting values for either ABF or LBF among trials. Arm blood flow was significantly lower with AC from W2 to Ex3 compared with NC values. The blood flow in both limbs was lower from Ex3 to Ex6 during the AC trials than during the NC trials. Blood flow tended to increase to the greatest extent from W2 to Ex1 in both the AC and NC trials. Thereafter arm and leg blood flow values tended to stabilize. There was a significant interaction between cooling and time period for both ABF and LBF ($p < 0.05$). Further analysis showed a significant increase in ABF from Rest to W2 with NC but not with AC. The increase in ABF from Rest to Ex1 was 102% without cooling but only 38% with cooling. Leg blood flow increased significantly by 50.4% and 54.5% from W2 to Ex1 with AC and NC, respectively ($p < 0.05$). There was a significant increase in arm blood flow from W2 to Ex1 when cooling was not used. The pattern for LBF was similar except that there was no difference between cooling and no cooling from Rest to Ex1. The increase in LBF with AC from Ex1 to Ex6 was only 12.6%, indicating that although this was

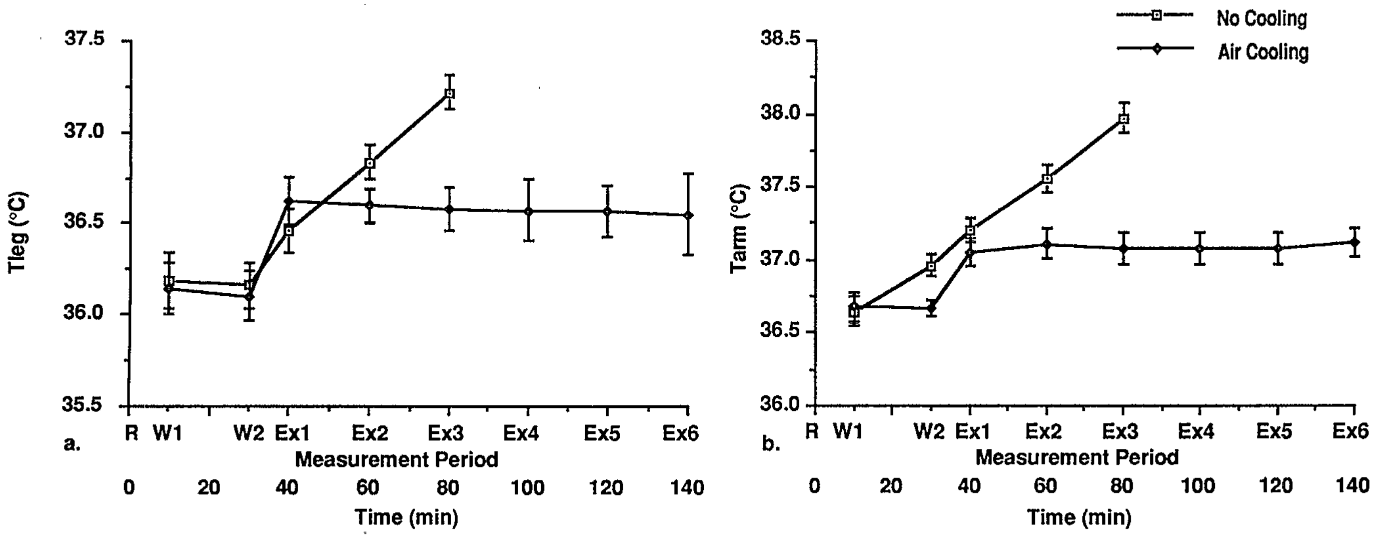

Fig. 3a and b. Effect of cooling on arm and leg skin temperature over time for 8 subjects in aircrew chemical defense ensembles exposed to 37°C air, 50% r.h. Fig. a (left) represents leg values and Fig. 3b (right) represents arm values. Upper abscissa legend same as Fig. 1. Mean ± S.E.M.

almost significant at the 0.05 level ($p = 0.06$) it nonetheless represents a very small increase.

Tolerance time in the heated chamber was markedly increased with air cooling. The mean tolerance time for subjects during the NC trials was 92.0 ± 2.5 min, whereas all subjects were able to complete the full 150 min ($p < 0.01$) when the cooling vest was worn.

Arm and leg skin temperatures (T_{leg}, T_{arm}) were significantly affected by cooling (Fig. 3a and b, respectively). T_{leg} increased by 1.03 ± 0.20°C during NC runs from the initial value at minute 10 to the termination at minute 80. The increase in T_{leg} for the AC run over the same time period was 0.44 ± 0.16°C. Similarly, T_{arm} increased by 1.32 ± 0.09°C during NC runs compared with 0.40 ± 0.07°C during AC runs. AC values were consistently significantly lower than NC ($p < 0.0001$) after about 40 min for the arm and about 50 min for the leg. Both T_{arm} and T_{leg} leveled off immediately after the onset of the cycle exercise during the AC runs. This is in obvious contrast to the NC runs, in which both rose linearly after the onset of bicycle exercise.

Rectal temperature (T_{re}) increased over time ($p < 0.0001$) during both no cooling and air cooling runs, but was significantly higher during NC runs than AC runs after 40 min. T_{re} also began to increase at a significantly faster rate for NC compared with AC at this point (Fig. 4).

Fig. 5 shows the effect of the experimental protocol on heart rate. HR increased significantly over time for both NC and AC runs and was significantly lower during AC runs compared with NC after the onset of exercise. In fact, it can be seen that, toward the end of the NC runs, mean HR was similar at rest to mean exercise HR during the AC runs at the same time period.

DISCUSSION

Previous studies have shown that blood flow in the periphery increases during exercise, heat stress and the combination of these two treatments (12,20,23). The increase in blood flow may be the result of increases to the skin alone, especially in the case of inactive limbs or by increases in both skin and muscle blood flow (20,23).

In the present study peripheral blood flow in the arm

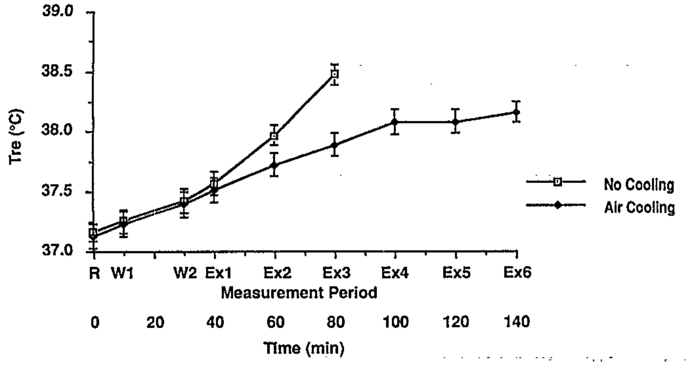

Fig. 4. Effect of cooling on rectal temperature over time for 8 subjects wearing aircrew chemical defence ensembles exposed to 37°C air, 50% r.h. Upper abscissa legend same as Fig. 1. Mean ± S.E.M.

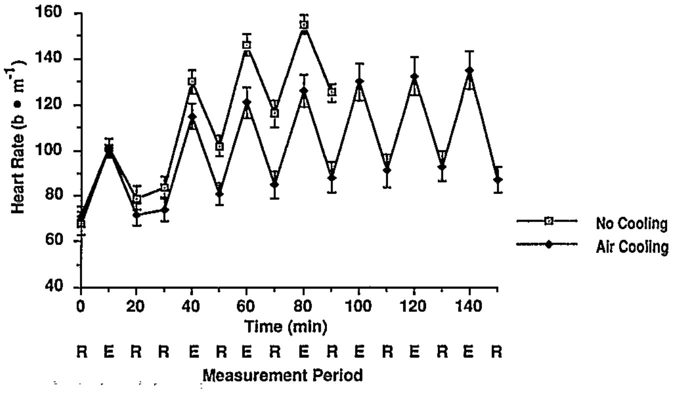

Fig. 5. Effect of cooling on resting and exercise heart rate over time on 8 subjects wearing aircrew chemical defense ensembles exposed to 37°C air, 50% r.h. Mean ± S.E.M. R = Rest, E = Exercise.

and leg increased significantly when subjects were exposed to heat and exercise while dressed in CD gear. The air-cooled vest decreased this response significantly, especially in the arm, thus showing the efficacy of the vest for this purpose.

Explaining the mechanism of the changes in peripheral blood flow due to the heat stress and exercise and the effect of the cooling vest is hampered by the fact that it was not possible to measure arterial pressure (due to logistical considerations). Therefore we were not able to calculate vascular resistance, a parameter which is very important in order to determine vasomotor status. Because of this, it is unclear whether the increase in blood flow to the periphery was due to vasodilatation of vessels of the skin and muscle, or simply the result of the increased heart rate and presumably increased cardiac output. Similarly, it is not clear whether the lower blood flow measured during the cooling trials was the result of a less intense vasodilatation due to lower core and skin temperatures, or again simply due to an overall lower stress on the cardiovascular system, manifested by the lower exercise and resting heart rate. The answer likely involves some combination of the above. The following is a description of the possible sequence of events that might have taken place.

Upon entry into the chamber, blood flow to the periphery began to increase primarily due to an increase in heart rate, as the subjects immediately started walking on the treadmill. Blood flow remained elevated during the subsequent 20-min rest period, even though heart rate returned to near resting levels. This response would suggest that vasodilatation had taken place, probably in the skin. The major increase in blood flow was observed after the start of the exercise-rest cycles. During this time, heart rate and skin temperature had increased considerably, while rectal temperature had not. Therefore, the increase in blood flow most likely reflects the increase in heart rate due to the thermal and exercise stress. However, a further increase in skin blood flow, at least in the forearm, may also have occurred since skin temperature is known to have a strong influence on skin blood flow (4). After this point, blood flow tended to plateau in spite of further increases in both rectal temperature and heart rate. These findings indicate that vasodilatation may have leveled off so that blood flow to the periphery remained relatively constant in spite of an increase in heart rate. Similar results have been obtained by other authors (4,20) who measured forearm blood flow during leg exercise under various conditions. These authors interpreted their results as being representative of changes in vasomotor tone in the skin to help maintain arterial blood pressure despite the increasing demand for muscle blood flow.

Use of the cooling vest markedly reduced peripheral blood flow, especially in the arm. Fig. 1 shows that the magnitude of the average change in blood flow in the arm from W2 to Ex1 was considerably greater during the no cooling trials than during the air cooling trials ($2.16\ ml \cdot min^{-1} \cdot 100\ ml^{-1}$, NC vs. $0.62\ ml \cdot min^{-1} \cdot 100\ ml^{-1}$, AC, $p = 0.05$, paired *t*-test). This cannot be explained by a lower core temperature, as T_{re} was not different during this time period between the two conditions, nor can it be explained by differences in T_{arm} as skin temperature on the arm actually increased at a greater rate during AC compared with NC trials. However, heart rate increased to a greater extent ($p < 0.02$) during the no cooling trials than during the air cooling trials. Thus, it is possible that the greater increase in blood flow in the arm seen during this time period was solely due to the difference in the heart rate response with and without cooling.

Whatever the mechanism, clearly the use of an air cooling vest under the above environmental conditions can significantly improve heat tolerance and reduce blood flow to the periphery. This may have important ramifications in other areas such as $+G_z$ tolerance. It has commonly been assumed that heat stress will reduce tolerance to $+G_z$ because of an increased pooling of blood in the periphery, especially the legs, due to vasodilatation (2) and reduced venous tone (26,29). Indeed, Roberts and Wenger (22) concluded that upright exercise in the heat is accompanied by a shifting of blood to the periphery secondary to veno- and vasodilatation which may reduce cardiac filling pressures, thereby reducing stroke volume. Johnson (13) also suggested that the initial vasoconstriction, which is normally seen in the skin as a response to initiation of exercise, is subsequently reversed as exercise continues and then is largely dependent on thermal status. This is probably more likely with light exercise, in which the metabolic demand of the working muscles is not that great.

That exposure to heat stress can reduce $+G_z$ tolerance has been shown by a number of investigators. Perhaps the most dramatic example however is that of Allen and Crossley (1), who found that passive heating to produce a deep body temperature of 38.5°C, reduced greyout thresholds in a centrifuge by an average of 0.9 G. This, in fact, was the average deep body temperature in our subjects at the end of the NC runs. Air cooling kept deep body temperature at less than 38°C for the same time period. Rectal temperature never rose above about 38.2°C with AC during the entire trial.

If external cooling can reduce heat stress and concomitantly reduce the amount of blood trapped in the periphery, then it could be of significant value in terms of improving cardiac function during heat stress superimposed on normal accelerative forces seen during air combat maneuvering. The effect of cooling on $+G_z$ tolerance, albeit applied differently, has been examined by other authors. For example, Keatinge and Howard (16) were able to demonstrate an average increase in relaxed $+G_z$ tolerance of 0.44 G in subjects whose legs had been cooled, so that skin temperature was 25°C. They attribute this increased tolerance to reduced peripheral pooling of blood. Similarly, Nunneley and Stribley (21) were able to show that tolerance to headward acceleration was reduced when the subjects rode in a centrifuge heated to 38°C compared with 21°C. Their results indicated that mean skin temperature was 1.8°C lower in the cooler environment. Our results, while not quite so dramatic, revealed a difference of 0.75 and 1.0°C between AC and NC trials for T_{leg} and T_{arm}, respectively. Use of a cooling device of the type tested in this experiment appears to be able to make similar modifications to peripheral blood flow and, thus, at least reduce the amount of impairment in $+G_z$ tolerance that would likely occur while wearing CD gear in a hot environment. However, it is apparent that additional direct cooling of the legs would provide even better results.

In conclusion, arm and leg blood flow as measured by mercury-in-rubber strain gauge plethysmography was increased in subjects wearing CD gear in the heat. An air-cooled vest reduced this response to heating considerably but did not eliminate it. These results may have important implications for flying performance under these conditions due to the overall impact on the cardiovascular system.

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