HEAT ACCLIMATISATION AND ACTIVE BODY COOLING STRATEGIES TO MITIGATE HEAT STRESS FOR OPERATIONS INVOLVING BULLET PROOF VESTS

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ABSTRACT

Heat acclimatization (HA) and personal body-cooling are effective methods of heat stress mitigation. HA involves conditioning the body to function under hot conditions by exposing the individual to an incremental level of heat stress daily over 10 to 14 days. Although HA improves thermoregulation during heat exposure, effective physical heat exchange between the body and environment must still take place. Operating with body armour may limit the benefits of HA due to the increased physical workload and greater coverage of body surface. In terms of personal cooling, substantial amount of research has shown that a significant amount of body heat can be removed with the use of a personal body cooling system. **Aim:** The study aims to quantify the magnitude of heat strain when marching with bullet proof vests in hot and humid conditions, and to evaluate the effectiveness of heat acclimatisation and active body-cooling as heat stress mitigating strategies in these conditions. **Methods:** Thirty-three trained male volunteers were randomly assigned to the Bullet Proof Vest (BPV) (n= 15) or Bullet Proof Vest and Full Battle Order (BPV+FBO) (n=18) groups. Participants were involved in three heat stress tests each, before (pre-HA) and after (post-HA) heat acclimatisation and with active body cooling (A-cooling). These tests were conducted in an environmental chamber programmed to simulate 36 °C ambient heat, 65% relative humidity and 800 W/m^2 of simulated solar radiation. During the trials, participants walked at 4 km/h for two 60 min cycles. The exercise cycles were shortened if core temperature (Tc) reached 39.5 °C for 1 min before 60 min or volitional fatigue, whichever occurred earlier. Participants then rested for 30 min or until Tc decreased to 38 °C, whichever occurred first, at the end of each exercise cycle. **Results:** Marching with the BPV induced Tc to increase at a rate of 0.28°C/min and adding the FBO to the BPV increased the rate of rise of Tc to 0.034°C/min and 0.037°C/min, respectively. HA was not effective in suppressing the rate of rise in Tc, but was effective in increasing work duration by lowering the resting Tc and by increasing work tolerance. Active body cooling was the most effective strategy in mitigating heat strain and increasing work tolerance. Work tolerance was limited by symptoms of physical exhaustion and discomfort resulting from the BPV in 70% to 80% of the participants, whereas 20% to 30% of the participants interrupted their trials because of high Tc. **Conclusion:** Heat acclimatisation was effective in improving work duration and tolerance by inducing a significant decrease in resting core temperature and by increasing physical fitness in both the BPV and BPV+FBO conditions. Active body cooling effectively decreased the rate of rise of body temperature and provided an alternative avenue for heat dissipation through conduction, resulting in a significant increase in work tolerance. **Conclusion:** HA should be a part of the overall training strategy whilst active body cooling devices should be considered as part of the technology-driven solutions that will allow the BPV to provide the required ballistic protection with minimal burden on the physiology of the soldier.

1. INTRODUCTION

The donning of a bullet-proof vest (BPV) places an additional burden on human thermoregulation, especially when operating with combat load in warm and humid environments. The potential burden of the BPV on soldiers may be learnt from events in the 12th century, when King Richard and his crusaders, clad in metal harnesses, lost their final battle for the Holy Land against the well-acclimatised Arab horsemen because of heat illness and fever (Prawer, 1984 and Shibolet et al., 1976). Ironically, after centuries of absence from the military environment, "metal harnesses" are being introduced back into military operations in the form of the BPV. The threat of ballistic wounds appears to have overridden the threat of heat injury in modern warfare.

The implementation of the BPV in military forces around the world highlights a common dilemma in equipping the soldier, which is the delicate balance between protection and the physiological costs of the equipment that provides the protection. The BPV protects the soldier from ballistic threats, but increases the burden on thermoregulation and risks of heat injury. The higher priority given to ballistic protection over protection from heat injury is likely due to the more eminent ballistic threats versus the consequences of heat stress and heat injury in hostile environments. The consequences of the lack of ballistic protection and hyperthermia are, however, equally disastrous. The impediment of the BPV on the movement of the soldier also needs to be considered when evaluating the cost-benefit of the BPV on soldier performance and safety.

The aims of the present study were to quantify the magnitude of heat strain when marching with the BPV,

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with and without full-battle load (skeletal battle load with backpack, FBO) at a speed of 4 km/h in a hot and humid condition, and to evaluate the effectiveness of heat acclimatisation and active body-cooling in mitigating heat strain in these conditions.

2. METHODS

2.1 Participants

The study involved 33 male volunteers from the Singapore Armed Forces (SAF), each with more than 1 year of military training. The volunteers were from the same battalion and have been training and living under the same conditions since their enlistment. Following an explanation of all procedures, risks, and benefits of the study, each volunteer gave his informed consent to participate in this study. The procedures of this study were approved by the Defence Medical and Environmental Research Institute Institutional Review Board (Singapore), the Joint Medical Committee for Research (Headquarters Medical Corps, SAF, Singapore) and the Army Conference (SAF, Singapore). Parental consent was required for participants < 21 yr of age. The mean age, height and weight of the volunteers were 20.8 (SD 1.1) yr, 171.1 (SD 5.0) cm and 68.3 (SD 9.8) kg. All the soldiers were medically certified for combat duty. They were healthy and had no symptoms of any illness during the trial. In addition to the informed-consent, all participants were asked to confirm their consent again and to declare their state of health before each trial. Those who declared that they were unwell had their trials rescheduled to another day or were excluded from the study.

2.2 Experimental Procedures

The participants were randomly assigned to the BPV (n= 15) or BPV+FBO (n=18) groups. Each participant completed a total of three heat stress tests, which were conducted in an environmental chamber (Haraeus, Balingen, Germany) that was programmed to 36 °C ambient heat, 65 % relative humidity and 800 W/m^2 of simulated solar radiation. The three heat stress tests were conducted before (pre-HA) and after (post-HA) exposure to a 14-day heat acclimatisation programme; and with active cooling (A-cooling) using the Micro-Evaporative and Conductive Cooling System (MEVACCS), which is a prototype system developed in-house. HA was conducted at the parent military base for 14 days, and included daily incremental exposure of exercising in the heat with the BPV. Although conducting the heat acclimatisation programme in the field will not allow the control of environmental conditions, it provides a closer reflection of the actual implementation of a heat acclimatisation programme in the military setting.

The heat stress tests required participants to walk on the treadmill at a speed of 4 km/h for two 60 min cycles. The exercise cycles were shortened if Tc reached 39.5 °C for 1 min before the end of the 60 min cycle or volitional fatigue, whichever occurred earlier. The participants rested for 30 min or until Tc decreased to 38 °C, whichever occurred first, at the end of each exercise cycle. Participants in the BPV group performed the heat stress tests wearing his camouflage uniform and helmet, and carried his Skeletal Battle Order items, dummy rifle, 8 dummy magazines, 2 dummy fragmentation and smoke grenades, 2 filled water bottles, and the BPV with hard plates (~25 kg). Participants in the FBO group carried the same items plus a standard full-pack (~36 kg).

All participants refrained from strenuous exercise, consumed their regular diet, and were advised to be well-hydrated and well rested with > 8h of sleep the day before the trial. Participants also ingested the temperature-sensing capsule (Coretemp, HQI Inc, Palmetto, FL) the night before the trial to ensure that the temperature-sensing capsule had sufficient time to move further into the gastrointestinal tract by the next morning so that its readings were not influenced by the temperature of fluid ingested during the trial.

On the day of the trial, participants had their routine meal > 2 h before the heat stress test. Upon reporting to the laboratory, participants cleared their bowels and bladders before having their nude body weights measured with an electronic digital scale (Mettler-Toledo Gmbh, Giessen, Germany). They were then fitted with a heart rate monitor (Polar Vantage, Polar, Kempele, Finland) and sat passively for 5 min, before pre-exercise blood samples were drawn (5 mL) by venipuncture and stored in EDTA tubes. Participants then proceeded to the climatic chamber and sat in the chamber for 10 minutes to allow resting heart rates to be recorded. The exercise protocol commenced following the prescribed rest, with participants walking on the treadmill at the required speed until cessation criteria was achieved. A*d libitum* fluid ingestion was adopted during the heat stress tests and the amounts of water ingested were recorded. Blood samples were taken at each rest interval and after exercise in a seated position. Nude body weights were measured after the exercise.

2. 3 Measurements

Heart rates (HR) were measured with a telemetric HR meter (Polar, Kempele, Sweden) and Tc was measured with an ingestible temperature sensor capsule (HQI Inc. FL). Ratings of perceived exertion (RPE) were recorded every 15 min during the exercise, using the Borg (6 to 20) scale. Sweat rates were determined through differences in body weight, after taking fluid intake and urine output into account.

2.4 Statistics

All data were analysed with the Statistical Package for Social Sciences (SPSS) version 15, and results are presented in mean (SD). Mean difference between the three heat stress tests with each group was analysed with the repeated measure analysis of variance (ANOVA). Pair-wise difference was performed using the dependent *T*-test if the ANOVA analysis was observed to be significant. Mean difference between the BPV and BPV+FBO group at each heat stress test was analysed using the independent *T*-test. Significance level was set at $P < 0.05$.

3. RESULTS

3.1 Thermoregulation

Thermoregulation was evaluated by analysing the rate of rise (RORtc) and decrease (RODtc) in Tc under each trial condition. Using the RORtc and RODtc controls for the effect of trial duration without influencing the effect of temperature response.

<u>BPV Group</u>. Core temperature increased at a mean rate of 0.028 °C/min in both exercise cycles before and after heat acclimatisation in the BPV group (Figure 1). Undergoing a period of heat acclimatisation did not have a significant impact on temperature response during exercise in the heat with the BPV. However, active body cooling with the MEVACCS mitigated the increase in Tc significantly by 43%, to 0.016 °C /min in the first exercise cycle ($P < 0.001$) and to 0.15 °C/min in the second exercise cycle in the BPV trials. The RORtc at the A-cooling trials was significantly lower than those observed before and after the HA. The rate of decrease in Tc (RODtc) during the rest intervals ranged from 0.01 °C/min to 0.02 °C/min across all conditions in the BPV group, and were not found to be significantly different between the trial conditions.

<u>BPV+FBO Group</u> Adding the FBO to the BPV increased the RORtc by 28% ($P < 0.05$) in the pre-HA trial and by 14% ($P < 0.05$) in the post-HA trial (Figure 1). Heat acclimatisation narrowed the difference in RORtc between the BPV and BPV+FBO groups by decreasing the RORtc in the BPV+FBO group, but not in the BPV group. With the BPV+FBO, mean RORtc ranged between 0.034 °C/min and 0.037 °C/min in both exercise cycles before and after heat acclimatisation, and these were not significantly different.

Similar to the BPV group, heat acclimatisation also did not have a significant effect on Tc response during exercise in the heat with the BPV+FBO, but active body cooling with the MEVACCS mitigated the RORtc by 40% to 45% ($P < 0.01$) in the BPV+FBO trials.

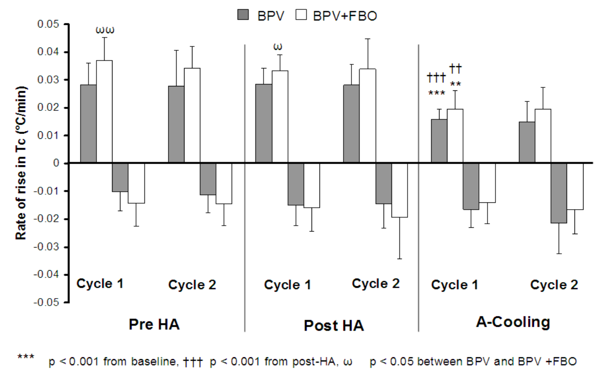


Figure 1. Mean (SD) rate of rise (positive bars) and decrease (negative bars) in core temperature

3.2 Predicted Core Temperature Profile

The mean resting Tc and the RORtc and RODtc data in each condition were used to plot the predicted Tc profile in the context of the heat stress test. Using a Tc of 39.5 °C as a guide for safety limit, the Tc profile at pre-HA would achieve the safety limit after 15 min of work in the second exercise cycle for the BPV+FBO group and after the 30 min of work in the second exercise cycle for the BPV group (Figure 2A). Following heat acclimatisation, work duration within the safety limit is extended by 15 min in the BPV+FBO (30 min, 20%) and BPV (45 min, 17%) groups (Figure 2B).

Although heat acclimatisation did not decrease the RORtc or increase the RODtc significantly, it increased the predicted work duration by 17% to 20% in both groups and this is due to the lower resting Tc after heat acclimatisation. Resting Tc decreased from 37.5 °C pre-HA to 37.3 °C post-HA ($P < 0.05$) in the BPV group and from 37.4 pre-HA to 37.1 °C post-HA ($P < 0.01$) in the BPV+FBO group. Heat acclimatisation thus promotes heat strain mitigation during exercise in the heat by inducing a lower baseline temperature and not by directly influencing temperature response during exercise.

The predicted work duration is further improved with the use of active body cooling. The predicted Tc profile in both groups remained below 39 °C at the end of both work cycles, which is much lower than the safety limit. The predicted Tc profile achieved with active body cooling indicates that work could be extended for another 45 min (120%) in the BPV+FBO and another 60 min (> 200%) in the BPV groups from post-HA in a third exercise cycle (Figure 2C). The predicted peak Tc remained below 39.5 °C at the end of the third exercise cycle. The slower RORtc with active body cooling translates into a 120% (BPV+FBO) and > 200% (BPV) improvement in work duration when operating with the BPV in hot conditions. These results indicate that active body cooling can significantly extend work duration by suppressing the rate of increase in Tc through conductive heat loss.

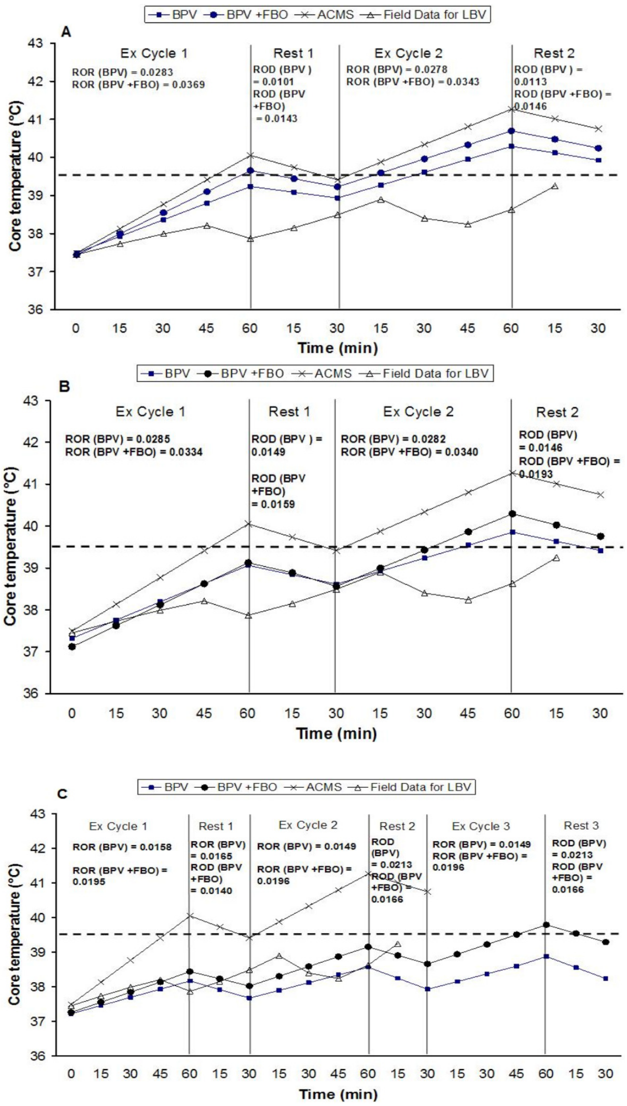
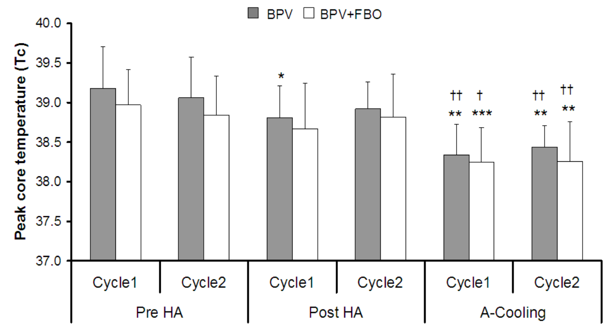


Figure 2. Predicted core temperature (Tc) profile based on rate of rise and decrease in Tc at pre-HA (A) and post-HA (B) and A-cooling (C)

3.3 Peak Core Temperature

<u>BPV Group.</u> Before heat acclimatisation, the BPV group achieved a mean Peak Tc of 39.2 °C in the first exercise cycle and 39.1 °C in the second exercise (Figure 3). The highest individual peak Tc achieved were 39.7 °C in both exercise cycles. Heat acclimatisation decreased the mean peak Tc significantly to 38.8 °C ($P < 0.05$) in the first exercise cycle. Mean peak Tc was also lower (38.8 °C) in the second than in the first exercise cycle after heat acclimatisation, but was not significant. The highest individual peak Tc achieved was 39.6 °C for both exercise cycles post-HA. It should be highlighted that the peak Tc in the second exercise cycle of the pre-HA and post-HA trials are not a good reflection of the true condition because of shorter exercise duration due to high incidences of early trial termination (Figure 4). Physical exhaustion occurred before a true peak Tc could be achieved.



*** p < 0.001 from baseline, ††† p < 0.001 from post-HA.

Figure 3. Mean (SD) peak core temperature

Active body cooling with the MEVACCS resulted in significantly lower peak Tc in both exercise cycles than the pre-HA ($P < 0.001$) and post-HA ($P < 0.01$) trials. The peak Tc achieved with active body cooling in the BPV condition are 39.2 °C (pre-HA) and 38.8 °C (post-HA). These data indicate that Tc in majority (70%) of the soldiers operating with the BPV is within the physiological in the first exercise cycle, and that work performance in the second exercise cycle is limited by work tolerance. Work termination occurred before Tc reaches a level where heat injury can occur (> 40 ^{o}C) in 70% (BPV) to 83% (BPV+FBO) of the participants. These are the percentage of participants who terminated their trials prematurely because their Tc reaches 39.5 ^{o}C before the 60th min.

<u>BPV+FBO Group.</u> The mean peak Tc in the BPV+FBO group ranged between 38.7 °C to 39 °C before and after heat acclimatisation (Figure 3). Active body cooling significantly decreased the mean peak Tc to 38.2 °C in the first exercise cycle ($P < 0.05$, pre-HA and $P < 0.001$, post-HA) and to 38.3 °C in the second exercise cycle ($P < 0.01$). However, these Tc data are not representative of the true heat strain because only 11% (pre-HA) and 28% (post-HA) of the participants completed the first exercise and none of the participants completed the second exercise cycle in these trials (Figure 4). Although active cooling increased the number of completed trials in the first (50%) but not in the second exercise cycle (6%), these data of peak Tc would also not be representative of the true condition. These data indicate that work tolerance will be impeded by other factors before heat can stress can reach a level of concern when the FBO is added onto the BPV.

3.4 Work Tolerance

BPV Group Before heat acclimatisation, the mean duration of work in the BPV group was 53.3 min in the first cycle and 20.4 min in the second exercise cycle (Figure 4). Heat acclimatisation increased work durations in both the first (55.6 min) and second (25 min) exercise cycles, but these increments were not statistically significant. Active body cooling increased the work duration in the first exercise cycle to a mean of 59.7 min, which is significantly longer than work durations in the pre-HA ($P < 0.01$) and post-HA ($P < 0.001$) trials. Work duration with active body cooling in the second exercise cycle (50.6 min) is also significantly higher than the pre-HA and post-HA trials ($P < 0.01$).

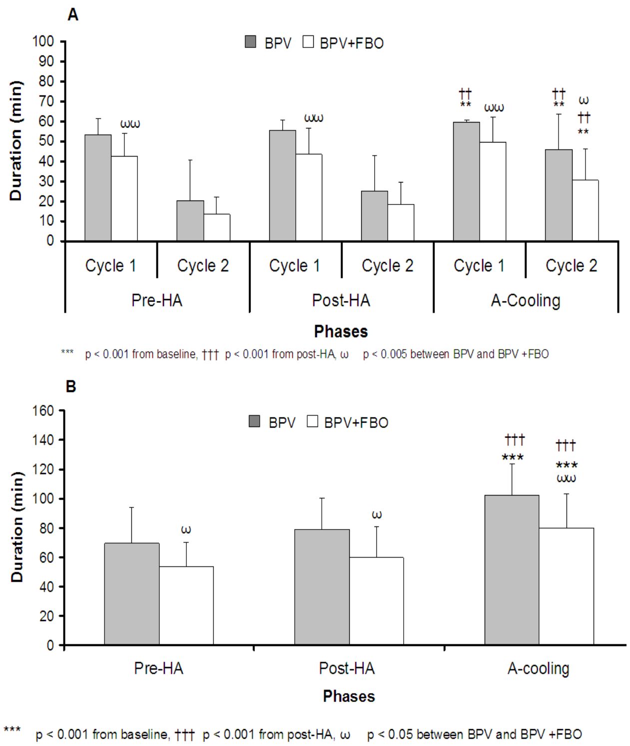


Figure 4. Mean (SD) duration of work in each exercise cycle (A) and both cycles combined (B)

BPV+FBO Group The number of incomplete trials in the BPV+FBO group is 1.5- to 7-fold higher than that in the BPV group. Adding the FBO to the BPV decreased the work tolerance of the participants significantly. In the pre-HA trial, 11% of the participants completed the trials, and this was increased to 28% (2.6-fold) after heat acclimatisation and to 50% with active body cooling (Figure 4). None of the participants completed the second exercise cycle in the pre- and post-HA trials and one subject completed the second exercise with active body cooling. Symptoms of physical exhaustion (50%) and discomfort (21% to 37%) rather than heat stress (11% to 23%) were the key contributors to poor work tolerance before and after heat acclimatisation as determined through a subjective survey. With active body cooling, numbness, breathlessness, fatigue and discomfort were the key reasons cited for the inability to tolerate the work.

In the first exercise cycle, the mean work duration in the BPV+FBO group is 42.4 min at pre-HA, 43.4 min at post-HA and 55.7 min with active body cooling. The work duration in the second exercise cycle is much lower, averaging 13.5 min before heat acclimatisation. Heat acclimatisation extended the work duration to a mean of 18.5 min, which did not improve much even with active body cooling (18.9 min). It appears that heat acclimatisation had a positive effect on work duration, although the improvements observed in this study were not statistically significant at $P < 0.05$.

3.5 Fluid Cost of the BPV

The fluid cost of the BPV, with and without the FBO, is determined by evaluating the sweat rate during the experiment. Participants lost an average of 0.85 L/h sweat when marching with the BPV before and after heat acclimatisation (Figure 5). The consistency in sweat rate in the pre- and post-HA trials suggests a saturation in sweating response and reiterates the earlier suggestion that heat dissipation in the pre- and post-HA trials is limited by the impediment of evaporative heat loss due to the BPV vest. Sweat rate decreased significantly to 0.6L/h (29%) in the A-cooling trials, which is significantly lower than the pre-HA ($P < 0.01$) and post-HA ($P < 0.01$) trials (Figure 5).

Adding the FBO to the BPV did not increase sweat rate (0.89 L/h) significantly from BPV alone before heat acclimatisation (Figure 5). Compared with pre-HA sweat rate in the BPV+FBO group decreased significantly at post-HA to 0.75 L/h ($P < 0.05$) and was decreased further to 0.67 L/h ($P < 0.001$) with A-cooling. The lower sweat rate observed in the BPV+FBO trials may be influenced by the much shorter exercise duration in the BPV+FBO trials.

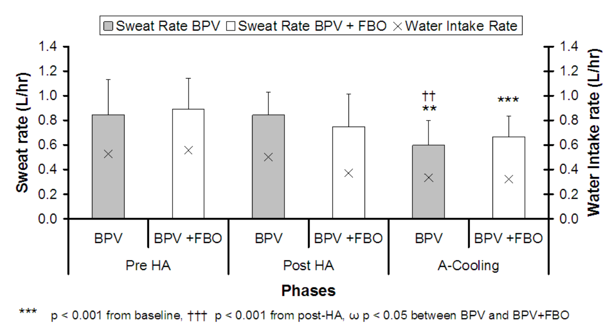


Figure 5. Mean (SD) sweat rate and mean corresponding water intake rate

The volume of fluid intake was about 50% to 60% of sweat output (Figure 6). This negative fluid balance resulting from the imbalance did not induce a significant state of dehydration because there is no significant change in plasma osmolality in all the trial conditions. The baseline plasma osmolality of ~300 Mosm/kg bordered between euhydration and early dehydration, and this level was found to be maintained consistently at the end of each exercise cycle (Figure 7).

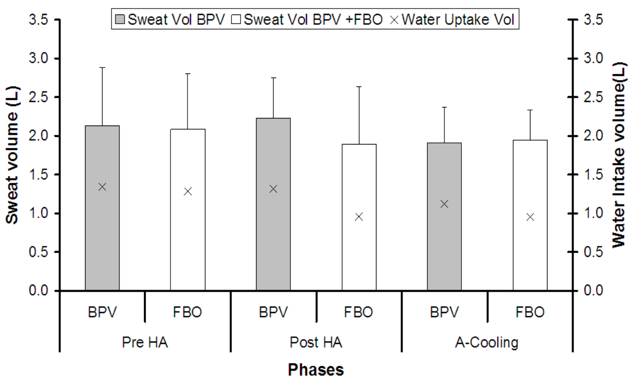


Figure 6. Mean (SD) sweat and fluid intake volumes

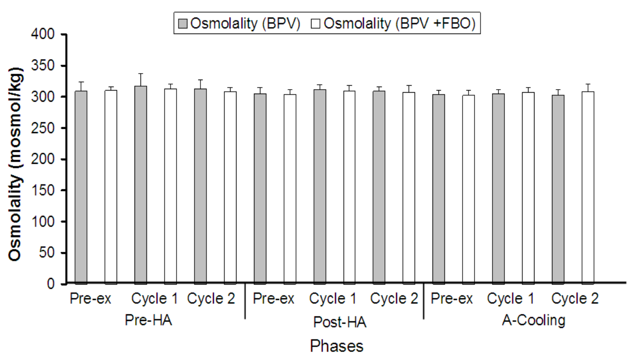


Figure 7. Mean (SD) plasma osmolality

4. DISCUSSION

The effects of heat acclimatisation and active body cooling appear to be consistent when using the BPV, with or without the FBO, alluding to the suggestion that the physics of heat transfer is not changed by adding the FBO to the BPV. The limited effects of heat acclimatisation is likely due to the impediment of evaporative heat loss with the BPV (physical property of heat transfer), which explains the effectiveness of active cooling because it promotes heat loss through conduction. An increase in sweat rate is one of the advantageous adaptations resulting from heat acclimatisation. However, the increase in sweat rate can only improve temperature regulation if the sweat produced can be readily evaporated. The effects of HA is not effective in with BPV because of the tight fit of the BPV vest and uniform against the skin impeded evaporation of the sweat and evaporative heat loss.

The results on Peak Tc and work tolerance indicate that heat stress is not the major limitation to work performance in the BPV, even when the FBO is added onto the BPV. Physical exhaustion and discomfort were found to limit work performance before Tc increased too high in about 70% to 80% of the participants. Based on RORtc, we estimate that 20% to 30% of the participants would have breached the trial safety limit for Tc (39.5 ^{o}C) if they were to complete both cycles of the exercise.

Most of the participants that terminated their trials prematurely cited “breathlessness,” “numbness” and “discomfort” as the key contraindicative factors with the BPV. These sensations are likely due to the physical constraints of the BPV on the rib cage. The sensations of “discomfort” and “numbness” in the upper body were key complaints with the BPV+FBO. Numbness in the upper body is likely due to the effects of the load, which can impede blood flow through an increase in peripheral resistance or direct compression of blood vessels. This is a common problem with the carriage of heavy load, which can lead to acute load palsy, a condition associated with loss of blood supply to the brain.

Although heat acclimatisation did not have a significant impact in increasing the number of complete trials, heat acclimatisation significantly decreased peak Tc in the first exercise cycle. Exercise duration in both groups also increased with heat acclimatisation, but is not statistically significant. The increase in physical fitness resulting from the heat acclimatisation programme contributed to the longer work duration. Heat acclimatisation should hence continue to be used as a strategy to enhance work tolerance.

The benefits of active body cooling in moderating peak Tc and improving work tolerance was clearly demonstrated in this study. The MEVACCS improved work duration significantly even in the BPV+FBO group. Active body cooling was thus found to be an effective solution to protect against work intolerance and stress strain when operating with the BPV.

In terms of fluid costs, the volume of water ingested during the trials may be indicative of the volume that is well-tolerated during exercise as excessive volume of fluid intake leads to other consequences e.g., bloated and nausea. These results do not suggest that a higher volume of fluid needs to be consumed during exercise because it is usually not possible to completely replace sweat loss during exercise. Moreover, the body is able to defend a fluid deficit of up to 2% of body weight loss without significant physiological consequences. Nevertheless, the deficit in fluid exchange must still be compensated by fluid intake post-exercise.

5. CONCLUSION

In conclusion, the study observed that heat acclimatisation was not effective in suppressing the rate of rise in Tc, but was effective in increasing work duration by lowering the resting Tc and by increase work tolerance (fitness). Active body cooling is the most effective strategy in mitigating heat strain and increasing work tolerance. As such, heat acclimatisation should be a part of the overall training strategy whilst active body cooling devices should be considered as part of the technology-driven solutions that will all the BPC to provide the required ballistic protection with minimal burden on the physiology of the solider.

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