

# OPTIMIZATION OF LIQUID MICROCLIMATE COOLING SYSTEMS: IMPORTANCE OF SKIN TEMPERATURE

*Samuel N. Cheuvront, Scott J. Montain, Lou A. Stephenson, Michael N. Sawka*

*U.S. Army Research Institute of Environmental Medicine, Natick, MA 01760*

**Contact person:** samuel.n.cheuvront@us.army.mil

## INTRODUCTION

Personal protective equipment (PPE) markedly increases heat strain, reduces work performance, and increases the incidence of heat casualties. Microclimate cooling (MCC) technologies have been successfully used to alleviate heat strain and sustain performance (Pandolf et al., 1995) (Figure 1) in mounted soldiers, but cooling limitations, power and weight restrictions do not currently make this technology applicable to dismounted soldiers. Not only does the provision of substantial MCC require a large power supply, but conventional (i.e., continuous) MCC approaches can result in constriction of the cutaneous vasculature. Overcooling increases tissue insulation ( $I_t$ ), decreases convective heat transfer from the body core, and reduces the MCC garment – to – skin ( $T_{sk}$ ) gradient, thus theoretically reducing MCC operating efficiency (Cheuvront et al., 2003). This is particularly true when the thermal demands of the wearer are not constant. Automated control of MCC garments using various biofeedback signals have been investigated (Nyberg et al., 2001) for their potential to improve the practicality of MCC relative to changing needs in real-time, but no comparison of an automated approach to simpler and more conventional solutions for reducing heat strain had been attempted.

A series of studies (Cheuvront et al., 2003; Xu et al., 2004; Stephenson et al., 2007; Vernieuw et al., 2007) were undertaken to compare the bio-thermal responses to automated and non-automated MCC solutions for reducing heat strain. Particular interest was in understanding the potential for automated MCC to reduce the combined power and size of MCC systems for the dismounted soldier. The purposes of this research were to 1) use a variety of intermittent cooling paradigms in humans combined with modelling simulations to determine the optimal  $T_{sk}$  for maximizing thermoregulatory efficiency, and 2) examine the potential power savings associated with using biofeedback to maintain an optimal  $T_{sk}$  temperature range.

## METHODS

Two human studies were conducted using the same facilities and test equipment. In study one (Cheuvront et al., 2003), 5 male soldiers exercised moderately (~500W) in a warm environment (30°C, 30%rh) while wearing PPE (clo: 2.1;  $i_m/clo$ : .32) over a water-perfused (21°C) liquid MCC garment covering the head, chest, back, and legs (72% of body surface area, BSA). All four body regions were independently controlled. A matrix of six randomized trials was conducted in which conventional MCC (continuous perfusion, CP), no MCC (NC), or 4 trials of

intermittent and regional (IR<sub>1-4</sub>) MCC was provided. IR<sub>1-4</sub> was time-activated and on:off cooling ratios and the % BSA cooled were systematically varied. Additional metabolic rates and inlet water temperatures were later modelled for additional insight (Xu et al., 2004). In study two (Stephenson et al., 207; Vernieuw et al., 2007), 8 male soldiers were subjected to the same conditions as study one, but only three trials were performed to include CP, IR<sub>2</sub> (2 min on: 2 min off, 72% BSA), and skin temperature feedback (STF, 72% BSA) using a T<sub>sk</sub> range of 33 – 35°C. Heart rate (HR), body core (T<sub>c</sub>), mean T<sub>sk</sub>, and ratings of thermal comfort (TC) were measured at regular intervals.

## RESULTS

In study one, all IR<sub>1-4</sub> paradigms significantly reduced physiological strain compared with NC (P<0.05) and were similar to CP (P>0.05). In CP, T<sub>sk</sub> was lowered to ~32°C and tissue insulation (I<sub>t</sub>) increased (Figure 2A). In NC, T<sub>sk</sub> rose quickly to 36°C and HR increased exponentially (Figure 2B). In IR<sub>1-4</sub>, T<sub>sk</sub> fluctuated between 33 – 35°C (Figure 3), which improved theoretical thermoregulatory efficiency (> 100%) by maintaining heat flux similar to CP over a smaller average BSA (Cheuvront et al., 2003) (Figure 2A). The variety of time activated on:off ratios made little difference to the results and suggested an optimal T<sub>sk</sub> range of 33 – 35°C (Figure 2A/B). Modelling different options for metabolic rate and coolant inlet temperature (Xu et al., 2004), it became clear that the complexity of situational cooling needs would require a bio-engineering feedback approach. In study two, IR<sub>2</sub> and STF again reduced physiological strain (Stephenson et al., 2007) and TC (Vernieuw et al., 2007) similar to CP (P>0.05), but the power required for STF was lowest (122±18 W), followed by IR<sub>2</sub> (169±16 W), and CP (224±15 W) (P<0.05, successive) (Figure 4) (Stephenson et al., 2007).

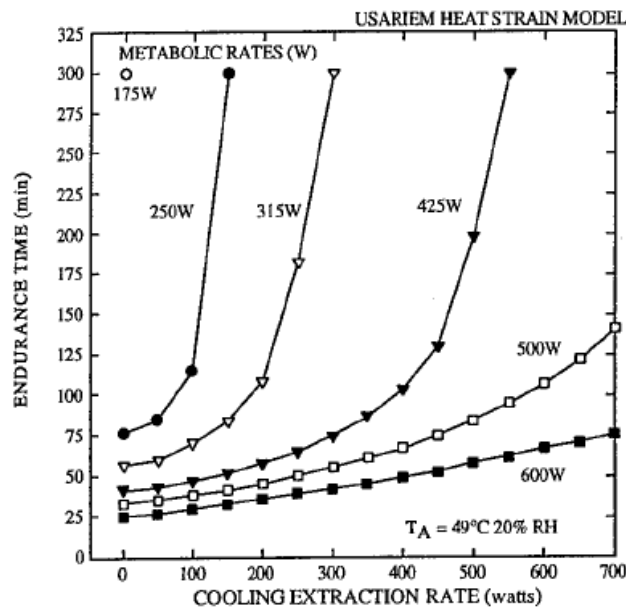


Figure 1. Relationship between MCC and endurance times at selected metabolic rates and wearing NBC protective clothing in a desert environment. From: Pandolf et al., 1995.

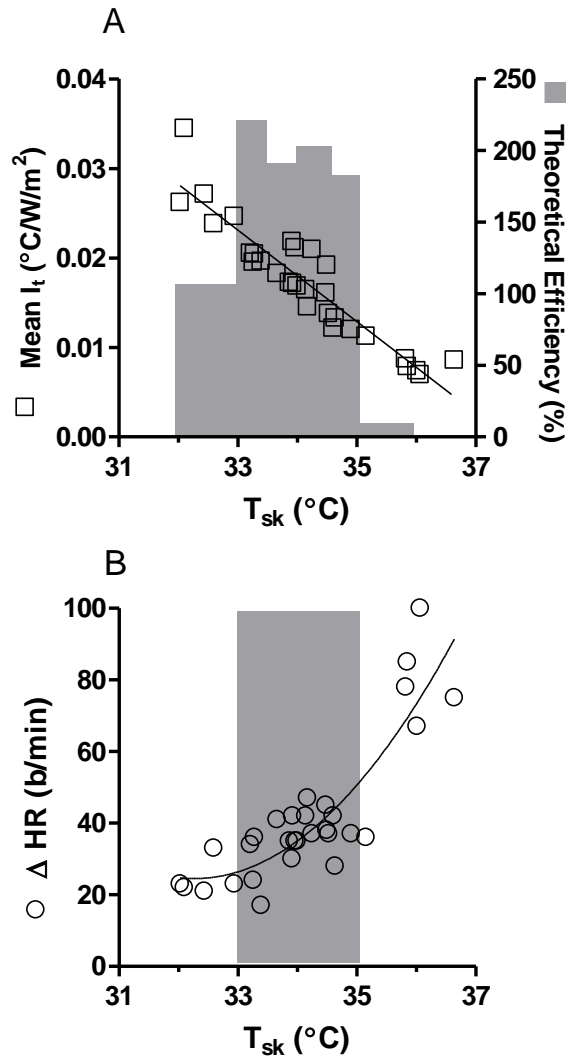


Figure 2. (A) Mean tissue insulation ( $I_t$ ) and theoretical cooling efficiency shown as a function of mean skin temperature. (B) Curvilinear relationship between  $\Delta HR$  and  $T_{sk}$ . Shaded region represents optimal  $T_{sk}$  range for reducing cardiovascular strain while maximizing cooling efficiency. Adapted from Chevront et al., 2003.

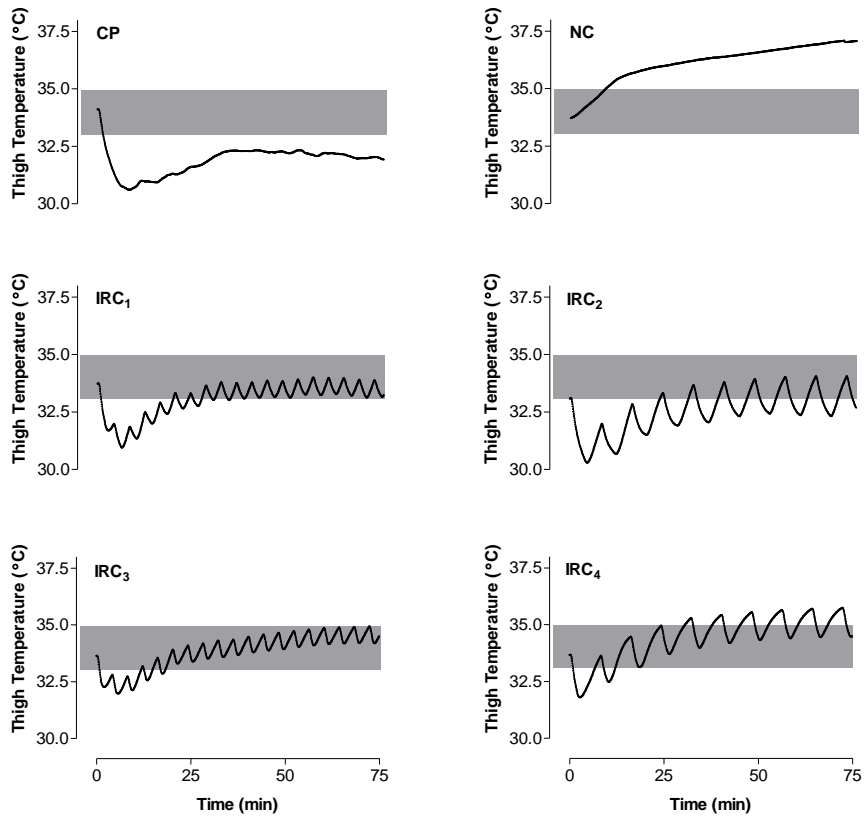


Figure 3. Effect of cooling paradigms on variability of local thigh temperature. Data represent the mean for all subjects measured continuously. Shaded region represents optimal  $T_{sk}$  range for reducing cardiovascular strain while maximizing cooling efficiency. From: Chevront et al., 2003.

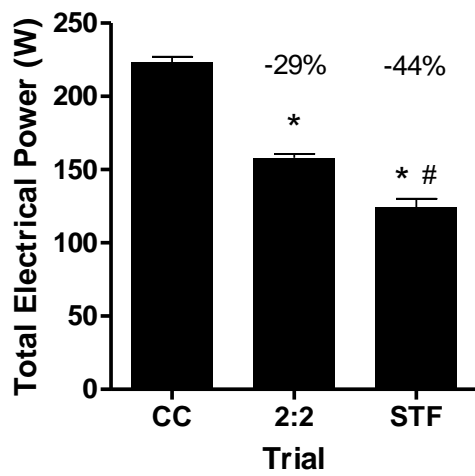


Figure 4. Electrical power consumption using conventional constant cooling (CC), intermittent regional cooling (programmed for 2-min on: 2-min off), and skin temperature feedback (STF) to maintain  $T_{sk}$  at 33–35°C. Adapted from Stephenson et al., 2007.

## CONCLUSIONS

STF as a methodology for maintaining  $T_{sk}$  within the narrow range of 33 – 35°C (European Patent no.: 1708586; U.S. Patent Pending) reduces heat strain similarly to constant cooling paradigms, improves thermoregulatory efficiency, and decreases MCC power requirements. The vasomotor response to a  $T_{sk}$  range 33 – 35°C appears optimal for simultaneously minimizing physiological strain while maximizing power efficiency at the MCC –  $T_{sk}$  interface. This potential breakthrough has direct application for the dismounted soldier, Objective Force Warrior, and Homeland Defense.

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