ROLE OF RELATIVE HUMIDITY IN THERMAL EXCHANGE IN AN ACTIVELY COOLED CHEMICAL PROTECTIVE GARMENT

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INTRODUCTION

Heat stress is a major problem associated with use of encapsulating chemical protective garments. Metabolic and radiant heat loads can degrade cognitive and physical performance and prove life-threatening if the heat is not adequately extracted fiom within protective clothing ensembles. Two approaches have historically been used to actively remove heat fiom encapsulating clothing ensembles: (1) vapor-phase cooling, where the heat transfer medium is a vapor, such as air and (2) liquid-phase cooling with water or Freon acting as the heat transfer medium. Personal aircrew cooling systems tend to be vapor-based because of weight considerations and the risk of leaking coolant into the aircraft. In addition, air-cooled systems employing evaporative cooling can theoretically remove greater quantities of heat while using less external energy than liquid-based systems dependent on conductive or convective heat exchange. Mobility for preflight aircraft inspections suggests that man-mounted systems versus tethering to a large cooling system (trailer or aircraft environmental control system) is desirable. Removing heat fiom an untethered system is a particularly vexing problem, however, because supplying the energy necessary for a blower system and pre-conditioning cooling air becomes a significant design problem. This study assesses how ambient relative humidity affects the efficiency of a prototype evaporation-based, untethered personal cooling system—the baseline cooling system for the Helicopter Aircrew Life Support System (HAILSS).

MATERIALS AND METHODS

Seven subjects (1 female, 6 males; 23 to 48 years old) were exposed twice to a 35°C ambient temperature while performing up to 12 repeated, 30-min rest/work cycles (20 min rest/10 min physical work) in a ventilated chemical protective ensemble (HAILSS) with isolated head/eye/respiratory protection. The HAILSS below-the-neck ensemble consisted of a Nomex/butyl coverall with an internal air distribution system to circulate air (110 Lamin-1) over most of the below-neck skin surface. This design closely resembled the previously tested "Dornier" suit (1). A U.S. Navy AR-5 chemical protective hood and respirator provided above-the-neck coverage with an independent blower system providing head ventilation. Physical workloads consisted of pedaling a bicycle ergometer at 40% VO_{2max}. Subjects also performed a series of cognitive tasks lasting roughly 15 min during each rest period. One exposure was at a relative humidity (RH) of 20% while the other occurred at 75% RH. Exposure duration, t, differences between final and initial rectal temperatures, Δt_{re}, the rate of rectal temperature change, **$\Delta t_{re}/t$**, suit cooling air inlet and outlet dry bulb temperatures, T_{db}, suit cooling air outlet wet bulb temperature, T_{wb}, and airflow rate, **V_{suit}**, were determined for each run.

Evaporative heat, Q_E, extracted by the **HAILSS** ventilation system was calculated **fiom** the difference between outlet and inlet airstream enthalpy, h, given by Ah = h_o - h_{in}. Moist air enthalpy can be calculated from the humidity ratio of moist air, W, and dry bulb temperature, T_{db}, by

$$(1) \qquad h = 1.006T_{db} + W(2501 + 1.805T_{db}) \qquad (kJ{\cdot}kg\text{-}1)$$

where W, a function of relative humidity, ϕ, and the humidity ratio of saturated air, W_s, at a given temperature and pressure is

$$(2) \qquad W = \phi W_s/[1+(1-\phi)W_s/0.62198]$$

and $\phi = f(T_{db}, T_{wb})$ (2). Given the ventilation mass flow rate, M_{air}, Q_E can be determined after calculating h_{out} and h_{in}, from

$$(3) \qquad Q_E = M_{air}\,\Delta h$$

Experimental results were also compared to predicted exposure durations that defined the time required for ventilation to remove sufficient metabolically generated heat for a user to sustain $\Delta t_{re} < 2°C$. This metabolic heat burden can be divided into a resting component and excess heat fiom mechanical work. An imposed physical workload can be divided into the energy required to perform mechanical work and energy providing additional heat to the body. The average maximum oxygen consumption (a measure of fitness) for a 25-year-old, 70 kg male is approximately 3.5 $L{\cdot}min^{-1}$ (3). Pedaling a bicycle ergometer at 45% VO_{2max} means that this average 25-year-old male experiences an approximate workload of 1.58 $L{\cdot}min^{-1}$ or 101W (6.1 $kJ{\cdot}min^{-1}$) based on the relationship

$$(4) \qquad VO_2 = 5.8wb + 151 + 10.1\,lw \qquad (ml{\cdot}min^{-1})$$

where wb = body weight (kg) and lw = workload (4). Because the mechanical efficiency of bicycle pedaling is roughly 30% (4), this work contributes an additional 4.9 $kJ{\cdot}min^{-1}$ of heat to a basal metabolic rate of **84** W (5.0 $kJ{\cdot}min^{-1}$) so that thermal homeostasis requires total removal of 9.9 $kJ{\cdot}min^{-1}$.

If ventilation system cannot totally remove 9.9 **$kJ{\cdot}min^{-1}$**, excess metabolic heat will increase body heat storage in the two body compartments: core and skin. **Assuming** total body heat storage (**S_{body}** = $(mCp/AD)(dT_{body}/dt)$) is divided between core (90%) and skin **(10%)** compartments then heat storage per hour in each compartment for a 70 kg individual with body surface area = 1.8 m^2 equals

$$(5) \qquad S_{core} = .034\ \Delta T_{re} = S_{body} -.004\ \Delta T_{sk} (kJ \cdot sec^{-1} \cdot m^{-2})$$

Since

$$(6) \qquad S_{body} = M - H_{removed}$$

where M = metabolic rate (9.9 kJ·min^{-1}) and $H_{removed}$ = heat removed by ventilation, then estimates of exposure times for given changes in T_{re} and T_{sk} can be obtained fiom equation **5**.

Statistical Analysis. The Wilcoxin matched pairs test was used to determine whether significant differences existed for Q_E, t, Δt_{re}, $\Delta t_{re}/t$, and V_{suit}, between 20% RH and 75% RH. Correlation between t and Q_E, Δt_{re}, and V_{suit} was also assessed. Values are reported as mean SEM with differences considered significant at the $\alpha < 0.05$ level.

RESULTS

Mean exposure durations significantly declined by 78% ($P < 0.01$) when RH rose from 20% (174.3 ± 16.24 min) to 75% (97.9 ± **9.4** min). Q_E also exhibited a significant decrease (149%) as RH increased from 20% (8.36 ± .53 kJ·min^{-1}) to 75% (3.36 ± .17 kJ·min^{-1}) ($P < 0.0001$). RH **did** not significantly

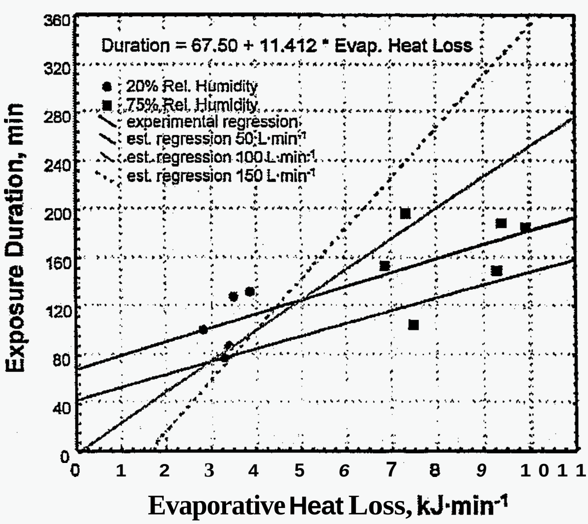

Figure 1. Correlation between active HAILSS ensemble evaporative heat extraction and exposure duration. r = 7.63, ***P* < 0.01**

affect Δt_{re} (1.46 ± .12°C) or V_{suit} (106.8 ± 5.0 L·min⁻¹) but $\Delta t_{re}/t$ rose significantly fiom .0085 °C·min⁻¹ to .0159 °C·min⁻¹ as RH increased fiom 20% to 75% ($P < 0.01$). Figure 1 shows significant correlation observed between t and Q_E ($P < 0.01$). Note how the regression line corresponding to actual heat losses at a mean flow rate of 110 L·min⁻¹ falls between theoretical regressions for flow rates between 50 and 100 L·min⁻¹. Normalizing heat loss for body surface area or weight did not appreciatively affect this correlation. No significant correlation was observed between t and either Δt_{re} or V_{suit}.

DISCUSSION

The ability or willingness to tolerate exposure to hot humid conditions depends on physiological as well as psychological factors. Previous studies have identified the importance of heat extraction to extend exposure times and both air- and liquid-cooled have been explored (5,6,7). Unlike prior studies, however, this study directly quantified evaporative heat extraction rather than inferring it fiom physiological measurements. Results fiom this study suggest that the ability to tolerate hot environments while wearing an air-cooled encapsulating garment depends, to a considerable extent, on inlet RH. In addition, overall tolerance cannot be reliably predicted fiom a simple thermodynamic model of heat extraction. Given that approximately 58% of variation in t is attributable to QE, deviations fiom thermodynamic predictions appear attributable to other factors such as convective heat losses, individual fitness and garment fit.

CONCLUSIONS

Performance of the proposed cooling system is degraded when operated in a high humidity environment system. This suggests that ancillary inlet air cooling is necessary when used in high temperature/humidity conditions common during temperate or tropical summers.

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