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Cooling Individuals Using Encapsulating Protective Clothing in a Hot Humid Environment

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ABSTRACT

Introduction: Persons responsible for removing extremely hazardous chemical agents or responding to chemical incidents typically wear fully encapsulating chemical protective ensembles (Level A) during field operations. Level A ensembles are currently used without any ancillary cooling system thereby greatly increasing the risk of thermal injury. The present study evaluated 4 candidate cooling systems intended to mitigate thermal stress experienced by Level A ensemble users in hot humid conditions. **Methods:** Four current members (males, ages = 22-24) of a military chemical response unit served as subjects in this study. Participants wore operationally configured Level A ensembles with a closed circuit soda-lime based re-breather system while performing repeated rest (5 minutes)/work cycles (25 minutes: alternating treadmill walking (4.8 km hr^{-1}, 5% grade) and level walking while carrying 22.7 kg) designed to simulate tasks and workloads associated with actual missions for up to 2 hours. Air temperature was maintained at 37°C with relative humidity = 75% throughout exposures. Tested cooling systems were: 1) liquid cooled vest with hood (ice cooling source); 2) phase change vest; 3) wetted vest; and 4) liquid cooled whole body garment (super critical air cooling source). The non-cooled Level A configuration served as the experimental control. **Results**: No significant differences were observed between control and cooling runs. Subjects were unable to complete more than 2 rest work cycles (mean ± S.D. = 47.9 ± 8.5 minutes) while experiencing changes in rectal temperature = 1.4 ± .4 °C and maximum heart rates = 167 ± 11beats min^{-1}. Runs terminated either because of breathing difficulties, high heart rates, or subject exhaustion. **Conclusions**: None of the cooling systems proved effective in overcoming the severe heat stress imposed on subjects. Hot breathing gas coming off the re-breather was originally thought to be a major factor contributing to the thermal burden but this proved incorrect. Conventional cooling methods appear entirely inadequate to address the combined stressors of high ambient temperature and humidity coupled with demanding physical workload.

Paper presented at the RTO HFM Symposium on "Blowing Hot and Cold: Protecting Against Climatic Extremes", held in Dresden, Germany, 8-10 October 2001, and published in RTO-MP-076.

BACKGROUND

Impermeable or semi-permeable garments providing protection against chemical and biological warfare agent (CBW) threats can retain large quantities of body heat. Body heat trapped within these encapsulating garments needs to be removed if the garment user is to adequately perform required tasks, especially when users are physically active. Otherwise, trapped heat leads to hyperthermia, a potentially dangerous condition that can severely degrade mission performance, cause injury, and in extreme cases, result in death.

The U.S. Marine Corps (USMC) Chemical Biological Incident Response Force (CBIRF) routinely employs encapsulating CBW protective garments in all environmental conditions while performing a variety of demanding physical tasks. CBIRF personnel experience performance degradation and reduced endurance while wearing these garments during training and actual missions. They are currently investigating a number of advanced cooling concepts that can theoretically address this problem. The present study was intended to evaluate four advanced cooling methodologies (hydro-weave suit (HW), liquid cooled vest (LCV), phase change vest (PCV), and Super Critical Air Mobility Pack (SCAMP)) in combination with compatible chemical protective outer garments (CPOGs) ensembles.

METHODS

The purpose of this study was to identify cooling systems which maximize an individual's tolerance time in hot/humid environments by mitigating heat related degradation of physical endurance and strength experienced while wearing a fully encapsulating CBIRF CPOG during simulated operational tasks.

Subjects: The experimental protocol was approved by the Naval Air Warfare Center Aircraft Division (NAWCAD) Institutional Review Board in accordance with Department of Defense and U.S. Navy requirements. Four healthy male Marines currently assigned to CBIRF volunteered to particpate after being fully informed of the details of the experiment protocol and associated risks. These four subjects routinely perform rigourous physical tasks in CPOGs under a wide variety of environmental conditions. Consequently, study conditions were judged to reflect conditions these individuals would experience during normal operations (i.e., training or actual operations). Table 1 lists the physical characterisitics of the subjects. Body surface area was calculated from the height and weight of each subject (5) and % body fat was calculated from skinfod measurements (6, 19).

Table 1. Physical characteristics of subjects.

Subject	Age	Height (cm)	Weight (kg)	Surface Area (m^2)	% Body Fat
A	23	168	72.8	1.82	16.7
B	23	188	83.4	2.10	13.9
C	22	180	80.6	2.00	17.0
D	24	175	81.9	1.98	11.9
Mean ± std. dev.	23 ± .8	1.78 ± .08	79.7 ± 4.7	1.98 ± .12	14.9 ± 2.4

Cooling Systems (Table 2): Five distinct cooling systems were employed in this study. Two of these systems also provided breathing air (SCAMP, APACS) while the others (HW, LCV, PCV) relied upon an external breathing source in this study.

Liquid cooled ***vest (LCV)***: Two systems (LCV, SCAMP) employed liquid-filled tube garments to extract heat from the body surface. The LCV tube garment consisted of a water-filled tubed shirt and hood worn directly over the skin. Conduction (and some convection) transferred heat from the skin to the circulating fluid. Water passed from the tubing through an ice filled bottle and then recirculated through the tubing via a pump directly attached to the ice bottle. A tubing pass-through enabled cooled water to enter and exit the tubing garment without compromising LA garment integrity. Mounting the LCV cooling unit onto LA was accomplished by a hook mounted onto a reinforced point on the LA surface. A strap system mounted opposite the supporting hook was intended to transfer the ice bottle/pump weight onto the weight bearing straps from the breathing system.

Table 2. Cooling systems evaluated in present study.

Item	Study Notation	System Weight (kg)	Cooling Technology	Primary Heat Transfer Mechanism
1	LCV	6.0	Liquid cooled tube suit (water/ice)	Conduction
2	PCV	2.9	Phase change beads (hydrocarbon wax)	Conduction
3	HW	1.4	Water-soaked vest	Evaporation
4	SCAMP		Liquid cooled tube suit Cooled breathing gas	Conduction Respiratory evaporation

Phase change vest (PCV): An open-weave mesh vest containing hundreds of small plastic coated wax beads comprised the PCV. Convection extracted heat from the skin and melted the wax. PCV vests were worn over a tee shirt to prevent chaffing and covered both the entire torso and upper shoulders.The open weave mesh permitted air flow through the vest during use.

*Hydroweave vest (**HW**)*: The HW was prepared by soaking the lightweight porous fabric vest containing a hydrophilic inner lining in water and wringing it out. Cooling occurred when heat released from the skin evaporated the trapped water. The vest was worn over a tee shirt to prevent chaffing and covered most of the torso.

Table 3. Components of the test clothing ensembles.

ENSEMBLE	SYMBOL	System Wt. (kg)	COMPONENTS
CBIRF Level A CPOG	LA	22.3	• Fully encapsulating Tyvek outer garment with plastic face shield and integral booties • Litpac II soda-lime rebreather (LA-L) -or- Compressed air self-contained breathing apparatus (LA-S) • Cotton blend shirt & trousers, underwear, socks • Chemical-resistant boots

Supercritical air cooling package (SCAMP): A full coverage (arms, legs, torso) tubing suit worn next to the skin was used to extract heat from the skin. Polyethylene glycol passing through the tubing transferred heat to a heat exchanger through which supercritical air (-193°C) passed as part of the breathing loop. The supercritical air removed heat from the circulating propylene glycol and was consequently warmed to an acceptable breathing temperature. A Dewar bottle chilled with liquid nitrogen retained the supercritical air under low pressure (750 psi) for both body cooling and as breathing gas.

CPOG (Table 3): ***Level A (LA)***: A single-piece, impermeable, and totally encapsulating garment completely seals the user from the external environment. A supplemental breathing source worn inside the LA supplies oxygen to the user. LA was used with either a soda-lime based LITPAC rebreather (approx. fully charged wt. = 18.2 kg) (LA-L) or self-contained breathing apparatus (approx. fully charged wt. = 17.3 kg) (LA-S) in this study.

Experimental Design: The study was designed to expose each test subject to five experimental trials (Table 4). The study intended to identify the most effective of four cooling systems (HW, LCV, PCV, SCAMP) by measuring work endurance in a hot/humid environment while wearing LA. The current operational configuration (LA-L with no supplemental cooling) was used as the experimental control. Short exposure durations in the earlier runs led to adding additional runs to assess the effect of breathing system (self-contained rebreather (LITPAC) vs. pressurized air bottles (SCBA)) on exposure tolerance.

Experimental Conditions: Environmental conditions were selected to reflect some of the more extreme environments CBIRF personnel are exposed to during training and operations. Air temperature (T_{air}) = 37°C and relative humidity (RH)=75% were chosen to reflect hot summer days in Southeastern United States or the Persian Gulf. Workloads were imposed to reflect the physical tasks performed by CBIRF personnel in the field. CBIRF personnel perform many of their field tasks while wearing CPOGs including walking from vehicles to a contaminated site, carrying equipment into and about the site, and dragging injured individuals from the site. To simulate these activities, subjects attempted to complete 4 consecutive rest/work cycles comprised of five minutes of rest (R period) followed by 25 minutes of light to moderate work (Figure 1). These work periods were comprised of three 5 minute bouts of treadmill walking (4 – 5.6 km hr^{-1} (2.5 to 3.5 mph) at 5% grade) (T period) interspersed with two 5 minute periods of carrying weights (two 11.3 kg (25 lbs) barbells) repeatedly across the chamber (W period). Subjects carried weights across the chamber only on alternating walks during W periods because of excessive strain on their hands and forearms. Brisk walking to and fro across the chamber (a total distance of approx. 15 m) replaced treadmill exercise in 8 of 23 runs because of treadmill failure.

Table 4. Experimental design to assess cooling techniques

Condition #	CPOG	Cooling Systems
1	LA-L	PCV
2	LA-L	HW
3	LA-L	LCS
4	LA-L	SCAMP
5*	LA-L	none

* - experimental control, current USMC CBIRF configuration

Instrumentation: Two temperature probes (model 4491E, Yellow Spring Instr., Yellow Springs, OH) inserted 10 cm anterior to the anal sphincter measured rectal temperatures (T_{re}) during exposures. Four skin surface temperature probes (model 4499E, Yellow Spring Instr., Yellow Springs, OH) measured upper left chest (T_{chest}), upper right arm (T_{arm}), anterior thigh (T_{thigh}), and lateral shin (T_{shin}) temperatures. Temperature probes were interfaced with VitalSense temperature telemetry systems (Mini Mitter Co., Sunriver, OR). In addition, inlet and outlet airstream temperatures and air temperatures just behind the visor were measured within the LITPAC and SCBA masks with 36 AWG (.05 mm dia.) type T thermocouples. Thermocouple signals were collected and processed with a thermocouple data logger (model SmartReader Plus 6, ACR Systems, Surrey, BC, Canada). The temperature measurement system was calibrated at 2 points with a constant temperature (29.7718°C) Gallium cell (model 17402, Yellow Springs Instruments, Yellow Springs, OH) and a zero-point (0°C) cell (model K140-4, Kaye Instruments, Bedford, MA). Heart rate was displayed on an ECG monitor (model Visa II, Datascope, Inc., Paramus, NJ) and recorded with a heart rate monitor (model Xtrainer Plus, Polar Electro, Kempele, Finland). Clothed and nude body weights were measured with an electronic scale accurate to ± 50 g (model FV-150K, A&D Ltd., Tokyo, Japan).

Subjects were asked to subjectively rate their comfort, sweating, and fatigue, and temperature (comfort scores) on a seven point scale every 15 minutes. Comfort, sweating, and fatigue were reported using a scale of increasing distress (e.g., for fatigue: 1 = very rested, to 7 = extremely exhausted) and temperature was reported as 1 = very cold, 4 = neutral, to 7 = very hot.

Experimental exposures: Each subject generally reported to the laboratory at roughly the same time (early (7-9 AM) or late (10–12 AM) morning) each day they participated. A brief physical exam and medical history was conducted when subjects entered the laboratory dressing area to begin each trial. Mean ambient air temperatures maintained inside this preparation area = 22.5° ± .2°C. Initial comfort scores were obtained prior to obtaining semi-nude weight (with underwear and rectal probes) ($m_{i,nude}$) after subjects inserted their rectal probes. Four ECG electrodes attached to the upper torso were adjusted to obtain the clearest signal and skin thermocouples were taped to the subject (Transpore tape, 3-M, Minneapolis, MN). A Polar heart rate transmitter was placed on the chest after moistening the contact surface with water. The subject was then dressed in the remaining clothing items and the cooling and breathing systems mounted on the subject. Telemetry transmitters (i.e., VitalSense (temperature), Datascope (ECG)) were affixed to the breathing apparatus (LITPAC, SCBA, SCAMP). The ACR datalogger for collecting respiratory mask temperatures was mounted on the top of the LA breathing apparatus at this time. The Polar wrist receiver was affixed to a chest strap just prior to sealing the CPOG. Computer data collection began roughly after the skin temperature probes were affixed to the skin but useful data collection (i.e., stable reliable data) generally began at approximately the t = -5 minute mark. Clothed weight ($m_{i,clothed}$) was obtained immediately after garments were sealed and then subjects entered the chamber to begin experimental exposures.

Subjects entered the environmental chamber at t = 0 and began a series of up to four consecutive rest/work cycles. Chamber conditions for all runs were fixed at T_{air} = 37.0 ± 0.2°C and RH = 75 ± .7%. Subjects seated at a small table completed questionnaires and provided comfort scores (estimated metabolic rate =195 W assuming metabolic output for writing (11) given a mean clothed weight = 99.6 ± 8.2 kg) during the initial R period. At the end of five minutes, subjects began the first T period (estimated metabolic rate = 637 (13) -710 W (22)). Subjects were instructed to walk briskly across the chamber on those occasions when a treadmill was malfunctioning (estimated metabolic rate = 562-683 W at 4 mph (13, 22)). This represented a 4% decrease in workload with walking versus treadmill. Two alternating W (estimated metabolic rate = 746 W (3)) and T periods completed the first rest/work cycle. These rest/work patterns produced an mean estimated time-weighted metabolic rate of 572-636 W (assuming treadmill use) and represent a heavy (12) or continuous (13) workload while bearing 20 kg. Estimated metabolic rates for lighter garments (10kg) were approximately 10% less (11). The third R period was designated the time for replacing breathing apparatus or bottles. In practice, however, breathing system replacements often occurred prior to the third R period due to unanticipated high breathing rates. Ice bottles (LCV runs) were replaced when requested. Subjects were not provided water or food during exposures because drinking or eating are not provided for in the LA design and would require removing the CPOG. This is consistant with field conditions; drinking occurs prior to doning a LA CPOG or subsequent to its removal but not while wearing it.

Chamber exposures terminated when (a) subjects completed 4 rest/work cycles, (b) they requested removal, (c) T_{re} increased to 39°C, (d) a subject's sustained heart rate (HR) reached 90% of estimated maximum safe heart rate for age (220 - age in years), or e) critical equipment failure occurred. Clothed weight ($m_{f,clothed}$) was obtained immediately upon exiting the chamber. Subjects were then seated and rested for approximately 15 minutes while their T_{re} was monitored. Subjects were released to remove their rectal probes and take a shower once T_{re} dropped below 38°C. Final semi-nude weight ($m_{f,\ nude}$) was measured after the shower and then subjects were medically cleared to leave the laboratory.

Physiological Indicies: Physiological temperatures were analyzed as differences (e.g., $\Delta T_{re} = T_{re, final} - T_{re, initial}$) over an exposure period because within-subject initial temperatures varied between exposures. Mean weighted skin temperatures were calculated using the method of Ramanathan (15):

$$T_{sk} = 0.3(T_{chest} + T_{arm}) + 0.2(T_{thigh} + T_{shin}) \quad [1]$$

Total sweat losses, SWL, including evaporation and dripping, was

$$SWL = m_{i,\,nude} - m_{f,\,nude} + \text{water consumed} \quad [2]$$

and the amount of sweat absorbed by the clothing was calculated by

$$\Delta GW = (m_{f,clothed} - m_{f,\,nude}) - (m_{i,clothed} - m_{i,\,nude}). \quad [3]$$

Figure 1. Planned rest and work periods for an individual trial. Each rest or exercise period (R, W, or T) had a 5 minute duration and total exposure times were intended to last up to 240 minutes. Subjects entered the environmental chamber at the start of rest period #1. Exchanging depleted breathing systems was intended to occur during rest period #3. R = rest periods, T = treadmill (or brisk walking), W = walking with two 25 kg weights across the chamber

	Work Cycle						Work Cycle						Work Cycle						Work Cycle				
R	T	W	T	W	T	R	T	W	T	W	T	R	T	W	T	W	T	R	T	W	T	W	T
Duration of rest/work cycles (minutes)																							
5	25					5	25					5	25					5	25				

Data Analysis:

The central hypothesis of this study was that at least one cooling system would generally enable users to tolerate exposures of greater than 60 minutes. Exposure tolerance was broadly defined as retaining the volition or physical ability to continue performing physical and mental tasks while exposed to experimental conditions. Independent variables were defined as the protective ensemble and cooling system. Dependent variables were rectal temperature (T_{re}), skin temperatures, heart rate (HR), sweat loss, salivary amylase concentration, and subjective stress assessments.

A sample size of 4 was chosen as a compromise between statistical power and study cost and duration. This sample size provides a statistical power, $1\text{-}\beta$, of 0.873 when using an analysis of variance to compare mean final T_{core} between 4 individuals exposed four times (once per clothing configuration) assuming the study detects T_{core} differences = 0.3°C with a standard deviation = 0.1°C. Reducing the sample size to 3 subjects drops the statistical power of the paired-t test to $1\text{-}\beta = 0.745$. The intent was to have a balanced experimental design for subsequent statistical analysis.

Nearly all experimental conditions had an n = 4; subject illness limited LA-L/HW runs to an n=3. Final values were tested for between-subject variability with a non-parametric Kruskal-Wallis analysis of variance (ANOVA). One goal in analyzing study data was to use each subject as their own control and eliminate between-subject variability. A non-parametric Friedman ANOVA was employed to analyze within-subject variability. When the ANOVA detected significant differences among configurations, a Newman-Keuls post hoc test was used to identify those configurations which differed significantly from the others. Linear correlation analysis was used to assess relationships between variables. Data are reported as mean value ± standard deviation. Differences were considered significant at the $\alpha = .05$ level.

RESULTS

In general, study conditions did not identify any of the tested cooling systems as significantly more effective in mitigating the thermal stresses imposed by environmental conditions and physical workloads. Physical and mental tolerance, measured by exposure duration, and physiological responses to the thermal stresses were statistically indistinguishable by most measures with three factors causing the majority of run terminations: HR, fatigue, and breathing difficulties. In general, however, cooling systems did not significantly affect exposure durations (Figure 2) as observed in both between- and within-subject analyses.

Though breathing gas temperatures in LA-L runs were deemed hot and many runs terminated for subjective intolerance to breathing hot air, any breathing system effects were not determined to be statistically significant. Initially, subjects subjectively attributed short LA-L exposures to breathing heated air generated by the LITPAC rebreather. Soda lime contained in the LITPAC removes CO2 from the exhaled airstream but the chemical reaction generates heat. This increases LITPAC temperature and the inhalation gases coming out of the unit. In contrast, SCBA consists of compressed air bottles; expanding breathing gas cools as it exits the bottles. There are no exothermic chemical reactions to generate heat in the SCBA breathing system. Comparison between LITPAC and SCBA mask inlet temperatures, however, indicated that breathing gas temperature was independent of breathing system while wearing a LA. Strong correlation of inlet mask temperature with ambient temperature (Figure 3, $r^2 = 0.91$ (LITPAC), $r^2 = 0.81$ (SCBA)) demonstrated that mask inlet temperature was primarily a function of the interior LA air temperature. In addition, no significant differences in exposure duration, ΔT_{re}, total sweat loss, or sweat rate between LITPAC and SCBA runs were observed. Consequently, use of either the LITPAC or SCBA did not significantly affect exposure durations due to breathing gas temperature.

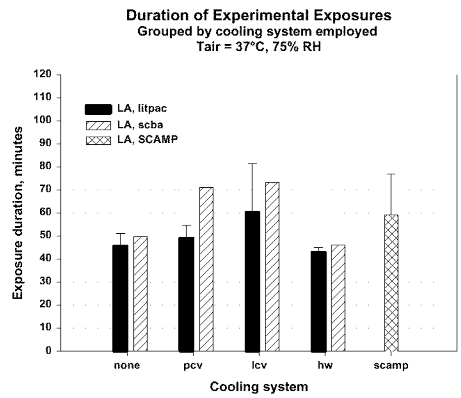

Figure 2. Exposure durations observed as a function of cooling system.

PHYSIOLOGY: A strong positive linear correlation existed between exercise duration and T_{re} ($r = .795$; $p < .001$). Overall, between-subject analysis demonstrated no significant ΔT_{re} differences between configurations (Figure 4). Within-subject analysis, however, showed cooling systems effects were inconsistent with different systems producing the smallest ΔT_{re} depending on the subject. LA-L/LCV produced the smallest ΔT_{re} in subjects A (along with LA-L/PCV) and B. LA/SCAMP produced the smallest ΔT_{re} in subject C while LA-L/control and LA-S/HW generated the smallest ΔT_{re} in subject D.

Maximum HR did not vary significantly between configurations in between- or within-subject comparison. HR variation over the course of an exposure also did not differ significantly (Figure 5). Not surprisingly, T_{re} correlated to heart rate ($r = .495$; $p = .003$).

Sweat losses did not vary significantly between CPOG/cooling system configurations when analyzed as either total sweat losses, % body weight loss, or sweat rate (Table 5). Analysis of sweat loss was not able to differentiate between evaporation and liquid sweat as much of the sweat loss occurred post-exposure during removal of the LA CPOG.

Mean skin temperatures were significantly lower during LA/LCV and SCAMP than LA-L/control across all subjects and generally lower than other configurations though these results were inconsistant among subjects. SCAMP generally maintained significantly lower ΔT_{thigh}, ΔT_{shin}, ΔT_{chest}, and ΔT_{arm} than other cooling systems (except LCV) in all subjects ($p<0.01$ in most cases). LCV also provided significantly better than other cooling systems in minimizing ΔT_{chest} and ΔT_{arm} (generally $p < 0.01$) but results for ΔT_{thigh} and ΔT_{shin} were equivocal. HW consistantly produced significantly higher skin temepratures than the other runs ($P < 0.05$) while PCV results were inconclusive and more dependent on individual subject variations. Using either the LITPAC or SCBA did not significantly affect skin temperature changes. JSL runs produced significantly greater temperature increases in most runs

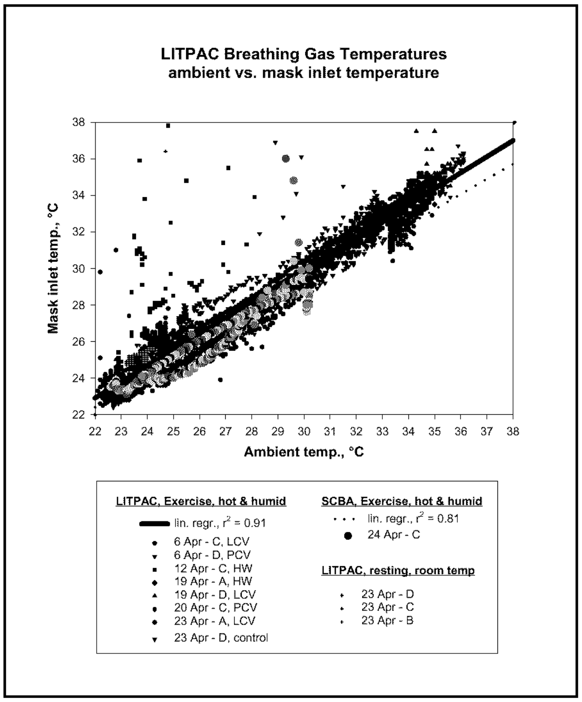

Figure 3. Relationship between breathing gas temperature and ambient temperature as a function of breathing system.

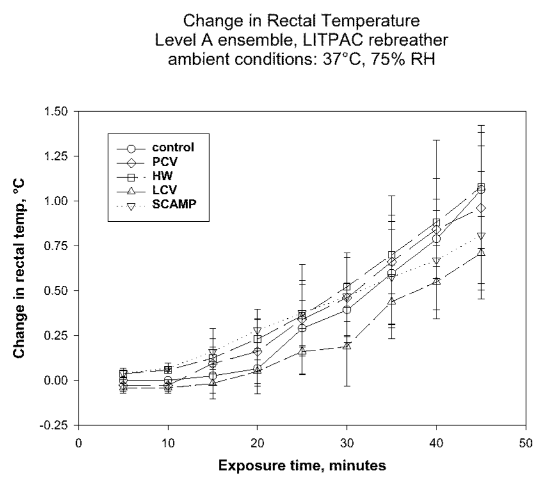

Figure 4. Rectal Temperature changes over time as a function of cooling system. Data is given as mean ± standard deviation.

Table 5. Observed subject tolerance and physiological temperature changes during experimental exposures.													
		Duration (minutes)			*Total Sweat Loss (kg)*				*% Weight Loss*				
	n	*mean*	*max*	*min*	*mean*	*max*	*min*	*SD*	*mean*	*max*	*min*	*SD*	
LA-L/control	4	**45.8**	51	39	**0.87**	1.1	0.58	0.21	**1.1**	1.3	0.7	0.3	
LA-L /HW	3	**43.1**	45	41	**4.78**	0.59	2.32	2.19	**2.8**	5.7	0.8	2.5	
LA-L /LCV	4	**60.4**	87	40	**1.04**	1.49	0.69	0.39	**1.3**	1.8	0.9	0.5	
LA-L /PCV	4	**49.2**	56	45	**0.56**	0.99	0.71	0.12	**1.1**	1.2	1.0	0.1	
LA /SCAMP	4	**59.4**	72	33	**0.89**	0	1.46	0.71	**1.2**	2.0	0	0.9	

compared to other configurations.HAILSS produced significantly lower ΔT_{chest} and ΔT_{arm} than most other configurations but essentially equivalent ΔT_{thigh} and ΔT_{shin} in the single individual tested.

SUBJECTIVE RESPONSES: No significant differences in comfort score sums were observed between configurations during the pre-exposure period or at the first rest period. A subjective ranking of cooling systems merit is given in Table 6. These responses reflect retrospective subjective assessments provided by the subjects at the end of the study and are not based on any quantitative analysis.

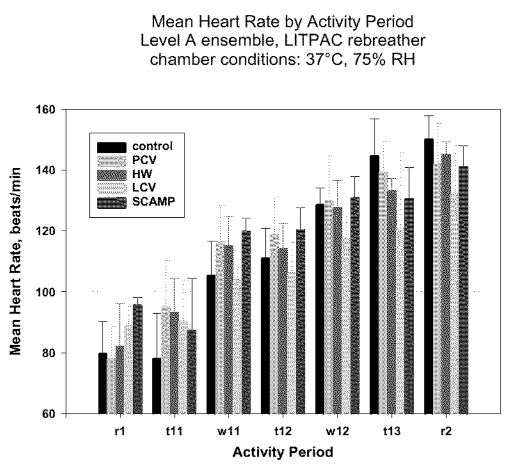

Figure 5. Mean heart rates measured at the end of each activity period as a function of cooling system (LA runs only). Data given as mean ± standard deviation.

EQUIPMENT: A number of equipment limitations and problems were detected during the course of the study. Most of these related to LCV and SCAMP hardware; HW and PCV were passive systems employing relatively simple technology. Both LCV and SCAMP cooling media provided for shorter exposure durations than initially anticipated. LCV ice containers typically lasted between 30-45 minutes before cooling became undetectable and needed replacement. In addition, one of the pump outlet hoses leaked after only 1-2 runs.

SCAMP bottles typically lasted approximately 30 minutes before requiring replacement, 50% less than an anticipated 60-minute duration. Furthermore, there were significant problems with initially charging the SCAMP bottle; leakage in the charging unit caused excessive use of liquid nitrogen and compressed air bottles. Even when repaired, the SCAMP recharging unit required a minimum of one "K" bottle of compressed medical grade air per SCAMP bottle.

Other problems encountered during SCAMP runs included a malfunctioning SCAMP monitoring meter. This meter generally posed a problem even prior to failure because the meaning of meter output was not well defined. A SCAMP air bottle inlet coupling also failed, leading to rapid depletion of available breathing gas and requiring a rapid swapping of bottles. Poor garment fit led to crimping in the inlet tubing of the SCAMP lower extremity tube suit and diminished leg cooling during that run.

A common problem was the extreme discomfort associated with the LITPAC and SCAMP support straps. Narrow straps and the attachment points on the units caused the straps to dig into a user's shoulders. In addition, subjects complained of the awkward position of the LITPAC weight on the back.

Table 6. Subjective cooling system ranking and overall comments following completion of study.

	Subject			
	A	B	C	D
Best	SCAMP	LCV	LCV	LCV
Worst	HW	HW	HW	HW
Subject comments	Given logistic considerations would prefer PCV	SCAMP worked best but not logistically feasible	Better training needed before using some systems	

DISCUSSION

None of the cooling systems tested in this study provided significantly greater protection in terms of extending exposure tolerance or minimizing the risk of heat injury. Physiological stress, as reflected in HR and salivary amylase data, also appeared unaffected by cooling system. Even overall comfort scores were unable to differentiate between cooling systems. HR and fatigue do reflect, however, the physical strain imposed by environmental conditions, physical tasks performed by subjects, and the burden of wearing heavy, bulky garments with additional weight imposed by cooling systems.

These equivocal results may reflect the severity of test conditions; wearing a LA in a hot/humid environment while exercising may overwhelm the cooling capacity of any of these systems. The intent of the study, however, was to identify cooling systems which might alleviate heat stress under the most dangerous environmental conditions by exposing subjects to extreme conditions. Dry bulb temperatures often exceed 37°C in much of the U.S. (e.g., approximately 5% of August days in Meridian, MS exceed 38°C (9)) so air temperatures used in the study are relatively conservative for a worst case scenario. The temperature/humidty combination used in this study is high (heat index (HI) = 144 (1)); only selected international geographic regions approach these combined high temperature/high RH on a regular, albeit uncommon, basis (e.g., Manama, Bahrain; Gwalior, India (2)). Humidity levels and consequently HI in the U.S. are typically lower but excursions approaching these levels can occur. This extreme hot/humid environment seems to reflect extreme but realistic conditions for CBIRF personnel wearing chemical protection and are the very conditions in which a cooling system becomes essential.

Humidity, however, should only affect heat exchange in vapor permeable garments; thermal conditions within the LA should be unaffected by ambient humidity because evaporation cannot occur across the impermeable material. Consequently, HI values are meaningless in assessing potential heat stress in individuals wearing impermeable clothing. This suggests a need for a new heat stress/strain index and exposure guidelines for users of impermeable clothing in hot environments.

Use of the LITPAC rebreather was feared to bias results because breathing gas gradually warms after repeatedly traversing the soda lime bed to extract CO_2. Using relatively cooler SCBA compressed air, however, did not mitigate T_{re} increases. It seems likely that heat transfer occurs as breathing gases travel from the gas source (LITPAC, SCBA) to the breathing mask because the gas is cooler than the surrounding atmosphere. Breathing gas warms as atmospheric heat is transferred to the tubing connecting the gas source and mask as noted in Figure 3. Inhaling this warm gas limits respiratory heat exchange and diminishes a potentially significant source of body cooling. Insulating SCBA tubing might mitage this problem by allowing cooler breathing gas to reach the respirator mask and improve overall body cooling. SCAMP potentially provides cooler air to the respirator though mask temperatures were not The large number of runs terminated due to breathing related complaints suggests that breathing system improvements may provide tremendous benefits in extending tolerance of hot/humid environments.

A major goal of this study was to impose workloads and conditions which mirror field conditions. Subjects noted that the study workloads (treadmill walking, weight bearing) provided a reasonable approximation of field workload demands but dragging a heavier weight (approximately 50-100 kg) rather than bearing weights upright would better reflect field conditions. In addition, subjects noted that temperature and humidity were high but not unrealistic.

Liquid cooled systems (LCV, SCAMP) appeared to reduce skin surface temperatures but did not appreciably retard rising core temperatures. The general sense of approval given to LCV and SCAMP indicated in Table 8 probably reflects greater comfort due to lower skin temperatures. It was therefore surprising that comfort scores did not reflect these results and did not differentiate between configurations. These results do suggest that benefits from liquid cooling are generally independent of the source of cooling. SCAMP tended to produce somewhat cooler skin temperatures than LCV but generally their performance was similar. It is unclear whether the increased complexity of the SCAMP system is merited until a more detailed assessment of respiratory heat exchange is made. In contrast, passive cooling systems (PCV, HW) did not provide a noted improvement over the control condition of no cooling with regard to rectal or skin temperatures, HR, or comfort scores.

Sweat loss was also indistinguishable between cooling systems. Given similar thermal burdens represented by equivalent ΔT_{re}, sweat output would likely be equivalent. Cooling efficiency would improve if some of this sweat can evaporate. Unfortunately, none of the non-APACS cooling systems have any mechanism to actively extract water vapor from the microenvironment within a CPOG. Consequently, sweat loss during exposures depended entirely on diffusion which was impossible in the impermeable LA. Improving evaporative cooling in an impermeable CPOG has limited potential, however, because LCV, PCV, SCAMP, and HW depend on conduction as their primary heat exchange mechanism. While HW does employ evaporation, it is not evaporating sweat but using conductive heat exchange with the skin to evaporate water trapped in HW fibers.

One positive aspect of impermeable material was the insulation it apparently provided for roughly the first 20 minutes of exposure. Subjects had relatively low HR and ΔT_{re} at the first rest period during LA-L/control runs, probably reflecting relatively cool air trapped within the LA during dressing. This may suggest development of a variably permeable CPOG which can trap relatively cool air and passively extend exposure times.

CONCLUSIONS

1) None of the cooling systems provided a distinct advantage in the hot/humid environment with an imposed exercise regime. Consequently, individuals wearing impermeable garments in high heat/humidity conditions appear vulnerable to heat injury even when using one of the tested cooling systems. Defining heat exposure limits, therefore, appears necessary to provide some degree of protection against heat exhaustion and heat stroke for personnel wearing impermeable garments.

2) Passive cooling systems provide no apparent benefit over no cooling when used with an impermeable garment in extremely hot/humid environments. Liquid cooled systems may provide some benefit over no cooling but equivocal results suggest further study.

3) Breathing plays a major role in determine tolerance to hot/humid exposures. Choice of LA breathing system (LITPAC, SCBA), however, did not appear to affect outcome though the SCBA sample was very small.

4) Clear instructions and adequate training are required to avoid improper use of cooling systems. Inadequate quality control can hamper cooling system effectiveness.

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Inclusion of cooling systems in this study does not imply official or unofficial endorsement of these products in any way. The opinions expressed in this document reflect only the author's viewpoint and do not constitute an official position by the U.S. Navy, U.S. Marine Corps, Department of Defense, or other U.S. government agency.

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