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Liquid cooling garments (LCG) absorb heat from both the human body and the environment. The cooling efficiency is influenced by the configurations of the LCG and clothing ensembles worn over the LCG (outer clothing, e.g. personal protective equipment), and environmental conditions. Thermal manikins (TM) have been used to evaluate the performance of LCG systems and to determine the amount of heat that a LCG can extract from a TM. However, effects of the outer clothing's insulation on cooling efficiency have not been investigated. The purpose of this study was to use a TM to investigate the relationship between LCG efficiency, insulation of the outer clothing, and water inlet temperature (Tin).

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EVALUATION OF THE EFFICIENCY OF LIQUID COOLING GARMENTS USING A THERMAL MANIKIN

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Introduction

Liquid cooling garments (LCG) absorb heat from both the human body and the environment. The cooling efficiency is influenced by the configurations of the LCG and clothing ensembles worn over the LCG (outer clothing, e.g. personal protective equipment), and environmental conditions. Thermal manikins (TM) have been used to evaluate the performance of LCG systems and to determine the amount of heat that a LCG can extract from a TM (1-4). However, effects of the outer clothing's insulation on cooling efficiency have not been investigated. The purpose of this study was to use a TM to investigate the relationship between LCG efficiency, insulation of the outer clothing, and water inlet temperature (T_{in}).

Methods

Three ensembles consisting of a cooling vest (CV) only, CV plus battle dress uniform (CVB), and CVB plus battle dress overgarment (CVBO), were tested on a sweating thermal manikin. The TM has 18 independently heated thermal zones plus an additional heated guard zone at the neck mounting plate. Sixteen of the zones are wet zones with an integrated sweating dispenser. The setpoints for water flow in each zone are adjusted to keep the TM skin saturated. The TM is covered with a cotton skin layer to distribute water over the zone surface. The ThermDAC software (Measurement Technology Northwest, Seattle, WA) controls, records data, and displays real time numerical and graphical plots of section temperatures. The software also calculates thermal resistances and evaporative resistances.

TM tests were run dry (i.e. no sweating) and wet (i.e. manikin sweating). The TM surface temperature was maintained at 33°C during all tests and the environment in the climatic chamber was 30 ± 0.5°C, and 50 ± 5% rh. After the clothing ensemble was placed on the TM, baseline values were measured without any perfusate flow through the LCG. The cooling system was then turned on to circulate cool perfusate. The perfusate inlet temperatures (T_{in}) were 15, 20 and 25°C respectively, and the flow rate was 0.5 liter/min. The LCG heat removal from the TM (Q_{tm}) was calculated using the difference between the power input to the TM with and without the perfusate flow. The fluid side heat gain (FSHG) was calculated from the flow rate and the temperature rise of perfusate flow. LCG heat removal from the environment (Q_{en}) was calculated by subtracting Q_{tm} from FSHG. The cooling efficiency (CEF) was defined as:

$$CEF = \frac{Q_{tm}}{FSHG} = \frac{Q_{tm}}{Q_{tm} + Q_{en}} \qquad (1)$$

Results and Discussion

Table 1 represents the thermal and evaporative resistances of the three clothing ensembles with and without perfusate. Thermal resistances were reduced by 10-15% when perfusate filled the CV, as the perfusate inside the tubes increased heat conduction from the TM to the environment. Evaporative resistances were only measured with no perfusate, as perfusate inside tubes does not affect vapor transfer from the TM surface to the environment.

Table 1 Heat transfer properties of the LCG ensembles as measured on the TM

	thermal resistance ($m^2°C/W$)		evaporative resistance (m^2Pa/W)
	no perfusate	with perfusate	no perfusate
CV	0.28	0.24	43.11
CVB	0.39	0.35	65.25
CVBO	0.60	0.51	101.45

Table 2 shows LCG cooling efficiency measured in dry and wet experiments with different water inlet temperatures. As expected, thermal resistances of outer clothing affected the cooling efficiency. Insulated outer clothing (i.e. higher thermal resistance) increased heat removal from the TM and decreased the heat removal from the environment, and consequently the cooling efficiency increased. The cooling efficiency was increased from ~0.45 with no outer clothing to ~0.70 with the added insulation of outer clothing (i.e. CVBO). Reducing T_{in} from 25 to 15°C increased both the heat removal from the TM and the heat removal from the environment, but the cooling efficiency remained nearly constant. A similar phenomenon was also observed by Dionne and his colleagues (1).

Table 2 Cooling efficiency during dry and wet experiments

	dry manikin			wet manikin		
	T_{in} 15°C	T_{in} 20°C	T_{in} 25°C	T_{in} 15°C	T_{in} 20°C	T_{in} 25°C
CV	0.45	0.44	0.46	0.50	0.53	0.56
CVB	0.62	0.58	0.52	0.63	0.64	0.63
CVBO	0.71	0.66	0.73	0.77	0.77	0.82

Cooling efficiency for wet experiments are higher than for dry experiments, and LCG heat removal from the TM in wet experiments was about 2 times as much as in dry experiments. There are two mechanisms which contribute to this increase: (1) the cooling vest fabric was absorbing “sweat” in wet tests, thus enhancing heat conduction from the TM surface to flowing perfusate; (2) water vapor from the TM skin condensed onto the perfusate tubes, then evaporated and diffused into the clothing and the environment.

Dionne and his colleagues used TMs to compare the performance of various personal cooling garments (1). The outer clothing in their studies had thermal resistances similar to our CVBO ensemble. They observed efficiencies of ~0.9, which were higher than our values. The TM skin temperature in their study was 2°C higher than the TM skin temperature in our study. Given that the heat removal from the TM increases when the TM surface temperature increases(1), cooling efficiency would also be expected to improve.

Understanding the impact of outer clothing on cooling efficiency serves several purposes: (1) the cooling efficiency relationship can be used to improve mathematical simulation of human responses with LCG/outer clothing combinations; (2) in physiological studies, by estimating the LCG heat removal from human by the fluid side heat gain, knowledge of the cooling efficiency equation components can improve heat balance analyses; and (3) the information on cooling efficiency can help personal protective system design engineers convert the physiological cooling requirements into requirements for cooling unit performance.

In this study, tests were conducted with one set of environmental conditions (i.e., constant values for temperature, humidity, and wind speed) without any adjustment for solar radiation. The addition of a solar component could significantly impact the efficiency of LCG system. Further tests and theoretical analysis would be required to investigate how this might affect the cooling efficiency in an operational scenario.

Conclusion

This study used a sweating thermal manikin to systematically investigate the impacts of outer clothing and water inlet temperature on LCG efficiency. The insulation of an outer clothing ensemble reduces

LCG heat removal from the environment and thus increases the LCG efficiency. The water inlet temperature had minimal influence on the cooling efficiency of the LCG.

Disclaimer

We thank Mr. Gary N. Proulx for his technical assistance in setting up the cooling system. The views, opinions, and/or findings contained in this report are those of the authors and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other official documentation. Citation of commercial organizations and trade names in this report do not constitute an official Department of the Army endorsement or approval of the products or service of the organizations. Approved for public release; distribution is unlimited.

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