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Cooling and Thermal Control Strategies in the Space Suit for Routine and Emergency Situations

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ABSTRACT

A series of demonstration studies were conducted with the aim of better understanding how to regulate body heat and thus enhance thermal comfort of astronauts during EVA requiring intensive physical exertion. The first study evaluated body zone heat transfer under different cooling temperatures in a liquid cooling garment (LCG), confirming the effectiveness of areas with high density tissue. The second study evaluated different configurations of hoods and neck scarves to maximize heat extraction from these key areas for heat release. The third study explored the possibility of regulating body heat by control of the water temperature circulating through selected body zones in the LCG, or blocking heat dissipation from particular body areas. The potential of heat insertion/removal from the head, hands, and feet to stabilize body comfort was evaluated in terms of the ability to advance this heat current "highway" from the core. These strategies for achieving heat regulation show potential for further more comprehensive study.

INTRODUCTION

While a significant amount of effort has been made to advance the space suit design for EVA, there is still need for improvement, particularly when considering the challenge of lunar and Mars missions. Of the currently emerging issues, a strategy for regulating body heat in routine and emergency situations is particularly critical. This problem needs to be addressed more intensively to protect the astronaut from thermal stress and to enhance work efficiency during EVA. As a component of this issue, attention also needs to be paid to controlling body temperature by cooling the head. Assessment of different configurations of garment hoods and scarves was carried out in an effort to identify the most effective design.

In this paper, the authors consider some of the strategies for better heat regulation of the body during different space activities, relying on the principles of biological tissue heat transfer, which the Laboratory for Health and Human Performance in Extreme Environments (LHHPEE) has actively conducted research on over the last decade. Regulation of heat release through major heat current "highways" between the core of the body and the head, hands, and feet, and regulation through heat flux/temperature on the periphery of the finger as an integrative index reflecting thermal status of the core were studied. Three different approaches are presented to obtain comprehensive information for improving the process of heat transfer from different body areas and thus stabilizing comfort in a liquid cooling garment (LCG).

1. ZONAL TISSUE HEAT TRANSFER UNDER DIFFERENT WATER TEMPERATURES

Based on the most recent findings from research conducted at LHHPEE, efforts were directed at measuring heat extraction from different body zones to evaluate their effectiveness to transfer heat. Inlet and outlet temperatures of water circulating through sections of the garment tubing were calculated to obtain measures of heat flow (kcal/min), heat flux (kcal/min/meter) and heat flux (kcal/min/meter/liter) by body region. Different water temperatures were circulated through each of the garment sections to obtain a comprehensive assessment of heat extraction.

Method

The environmental chamber was maintained at an air temperature of 24±1^{o}C and relative humidity at 24±2%. During each session, the subject was dressed in a sport shirt and shorts and seated in an armchair for a 20min period of thermal stabilization. Subsequently, the subject wore different sections of a multi-compartment garment connected to a water bath, placed on different body areas. These areas were cooled by water circulating through the tubing of the garment section. The body areas assessed in sequential order were the head/neck (hood), upper torso (vest), both hands (gloves), both forearms (low arm sleeves), upper arms (short sleeves), lower torso (shorts), both calves (leggings) and both feet (socks). For each body area, the inlet water temperature regime was as follows: 25°C (20min), 15°C (20min), 20°C (20min) and 10°C (20min). Between each temperature application, there was a 5-10min rest interval with no cooling for recovery of blood circulation and comfort in the previously cooled zones. Inlet/outlet water temperatures were continuously measured; temperature data were recorded by the Labview data acquisition system. The primary assessment index was inlet/outlet water temperature to calculate heat extraction according to the formula: Heat flow (kcal/min) = m_w C_w (T_{in}-T_{out}) where, m_w, water flow rate (l·min^{-1}); C_w, specific heat of water, 1kcal·kg^{-1}·℃$^{-1}$; T_{in}, inlet temperature (℃); T_{out}, outlet temperature (℃)(Fig. 1-3).

Results

Using a single subject example, Figures 1-3 present the effectiveness of high density tissues to transfer heat in and out of different body areas, at different inlet water temperature conditions, evaluating heat flow (kcal/min), heat flux (kcal/min/meter), and heat flux (kcal/min/meter/liter).

These dynamic profiles demonstrate the possibility of heat extraction (kcal) in terms of duration (Fig. 1); duration by length of tubes (Fig. 2); duration, length of tubes, and flow rate (Fig. 3). Figure 2 provides the best summary of heat release depending on the factor of tissue conductivity, zonal dependence, and the influence of the temperature of the circulating water and flow rate. Heat flux calculated according to meter of tubing showed the greatest effectiveness in the upper arm and calf areas. If heat flux is calculated according to the index of kcal/min/meter/liter (Figure 3), then the zones most effective for heat release are the head, neck, hands, and feet. These data can be highly informative for the individualized design of a cooling/warming garment.

Figure 4 shows that local heat extraction differs according to different zonal tissue structure, flow rate differences, and tube length. Heat extraction through these multi-local areas was more effective than the heat extraction capability of the total garment with a common manifold. In the total garment, at the lower water temperature of 10°C, the heat extraction capability was two times lower than the combination of the individual local body areas with separate inlet/outlet water distribution.

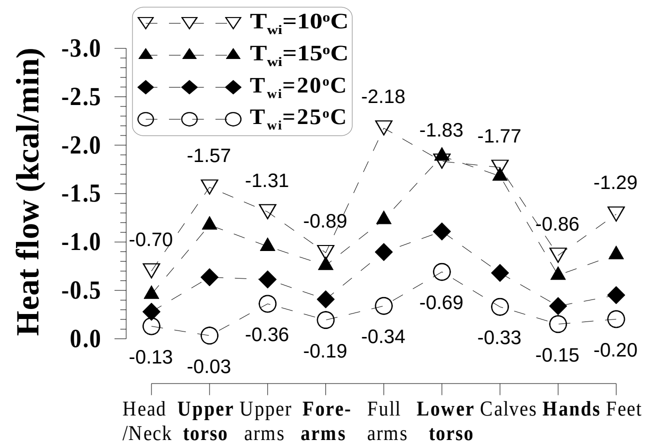


Figure 1. Heat flow (kcal/min) by body region and water inlet temperature in rest conditions. Male subject, Age 25, Height 183.5cm, Weight 85.4kg, BSA 2.12m^2, BMI 25.4, Body Fat 7.7%.

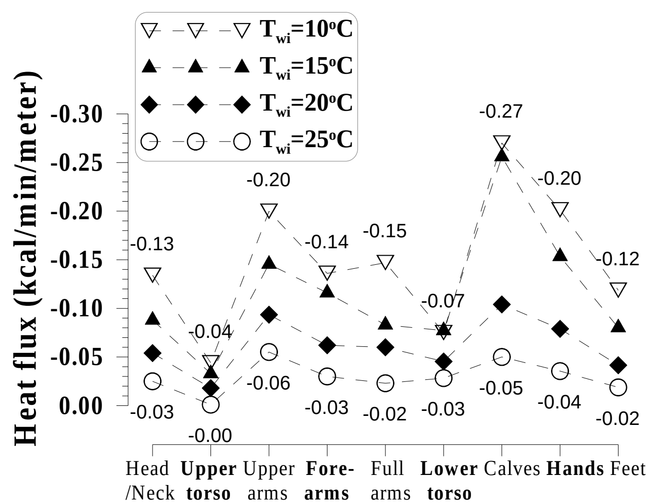


Figure 2. Heat flux (kcal/min/meter) by body region and water inlet temperature in rest conditions. Male subject, Age 25, Height 183.5cm, Weight 85.4kg, BSA 2.12m^2, BMI 25.4, Body Fat 7.7%.

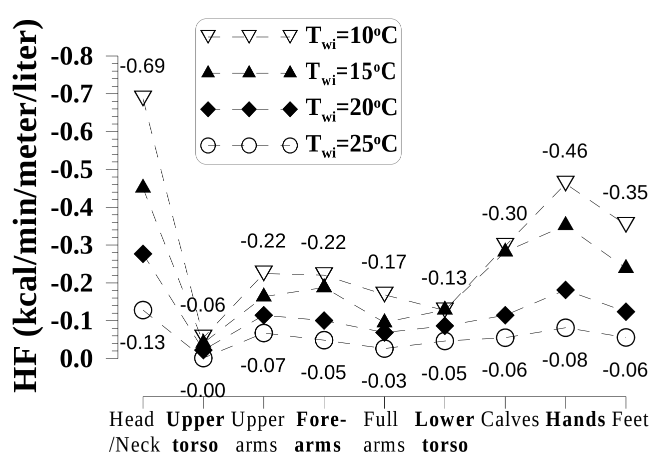


Figure 3. Heat flux (kcal/min/meter/liter) by body region and water inlet temperature in rest conditions. Male subject, Age 25, Height 183.5cm, Weight 85.4kg, BSA 2.12m^2, BMI 25.4, Body Fat 7.7%.

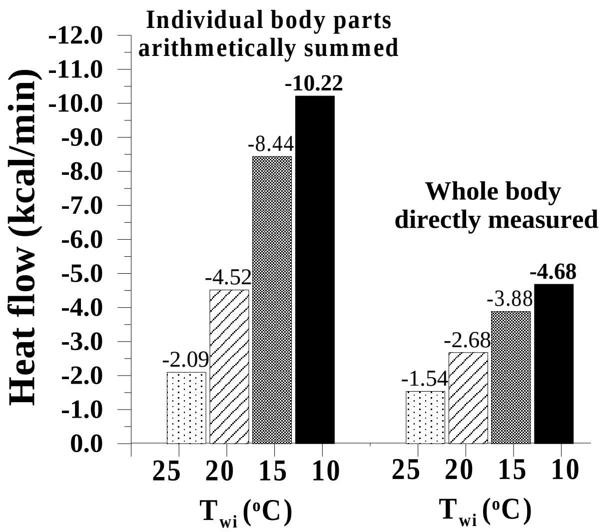


Figure 4. Heat extraction through individual body parts and the whole body - arithmetically summed values vs. directly measured values. Male subject, Age 25, Height 183.5cm, Weight 85.4kg, BSA 2.12m^2, BMI 25.4, Body Fat 7.7%.

2. MAXIMIZATION OF HEAT EXTRACTION THROUGH THE USE OF A COOLING HOOD OR NECK SCARF

Further refinement of the MACS-Delphi cooling/warming garment developed at the LHHPEE (patent number 7,089,995) was conducted to improve the head/neck capability to extract a greater amount of heat. Various tubing configurations placed on the head and neck (areas with high thermal conductivity and minimal vasoconstriction) were evaluated for effectiveness in enhancing heat extraction and lowering water temperature in the designated physiological range.

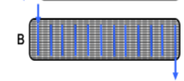
Method

Experimental liquid cooling hoods and scarves

Four different configurations of tubing cooling hoods and two types of cooling neck scarves through which water circulated were designed for this research. The characteristics of each of the hoods and scarves are presented in Table 1.

Subjects were tested in an environmental chamber maintained at an air temperature of 24±1°C and relative humidity of 24±2%. During each session, the subject was donned in a cotton leisure garment and one of the experimental hoods or scarves, and seated in an armchair. The procedure consisted of 20min of thermal stabilization with inlet water temperature in the hood or scarf at 33°C, followed by local cooling of the head or neck area with inlet water temperature at 10°C for 15 min, followed by 20 min of recovery with water temperature at 33°C. To calculate the heat removal rate of each hood and scarf, heat flow was calculated by the following formula: Heat flow (kcal/min) = m_w C_w (T_{in}-T_{out}), where, m_w, water flow rate (l·min^{-1}); C_w, specific heat of water, 1kcal·kg^{-1}·℃$^{-1}$; T_{in} , inlet temperature (℃); T_{out} , outlet temperature (℃).

Table 1. Characteristics of the Liquid Cooling Hoods and Scarves.

	Hood A	Hood B	Hood C	Hood D	Scarf A	Scarf B
						
Tubing direction	Vertical	Spiral	No tubing on top	Spiral	Horizontal	Vertical
Tubing length (m)	5.22	6.23	4.06	6.23	1.72	1.72
Water flow rate (l/min)	0.195	0.143	0.196	0.233	0.408	0.402
Tubing diameter(mm)	ID 2.4 OD 4.0	ID 2.4 OD 4.0	ID 2.4 OD 4.0	ID 2.8 OD 4.5	ID 2.8 OD 4.5	ID 2.8 OD 4.5
Material	PE Spandex	PE Spandex mesh	PE Spandex/ Mesh top	PE Spandex mesh	PE Spandex mesh	PE Spandex mesh

Results

As shown in Table 1, the characteristics (diameter, water flow rate, etc.) of the hoods are very close to each other in terms of the length of tubes, which are between 4-6m. However, in spite of similar characteristics, there were some differences in the ability to extract heat related to the different configuration of the tubing placement on the head. Hoods B and C and Scarf B were most effective in heat extraction (Figures 5-7).

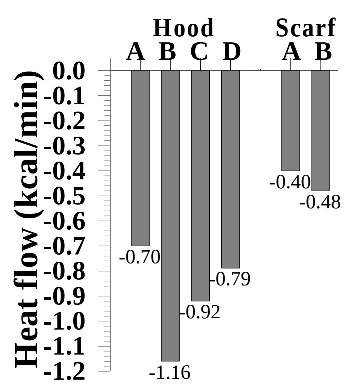


Figure 5. Heat flow (kcal/min) through the head and neck through different configurations of liquid cooling hoods and scarves. Male subject, Age 25, Height 183.5cm, Weight 85.4kg, BSA 2.12m^2, BMI 25.4, Body Fat 7.7%.

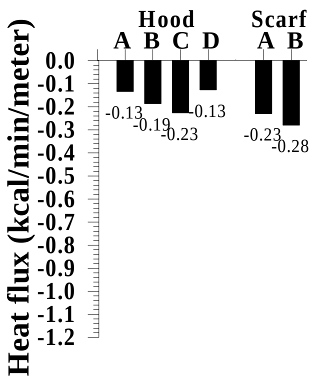


Figure 6. Heat flux (kcal/min/meter) through the head and neck through different configurations of liquid cooling hoods and scarves. Male subject, Age 25, Height 183.5cm, Weight 85.4kg, BSA 2.12m^2, BMI 25.4, Body Fat 7.7%.

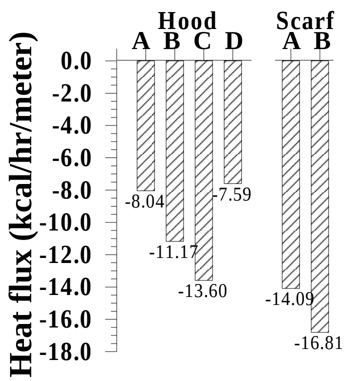


Figure 7. Heat flux (kcal/hr/meter) through the head and neck through different configurations of liquid cooling hoods and scarves. Male subject, Age 25, Height 183.5cm, weight 85.4kg, BSA 2.12m^2, BMI 25.4, Body Fat 7.7%.

3. HEAT REGULATION

The head, hands, and feet are highly effective zones for heat release/intake because these areas are highly vascularized and contain high density tissues for heat transfer[1]. One third of heat dissipates through the head and neck part of the body core[2,3]. The partial blocking of heat release from the head or neck has the potential to notably change the thermal status of the entire body. The strategy of the following experiments was to find a key to regulate the heat current in and out of the body to support human heat balance in thermal extremes.

The possibility of regulating body heat through cooling/warming different body zones or combinations of zones was studied. Two experimental paradigms were employed to receive the quantitative amount of heat extraction through each zone by (1) turning on/off cooling to three different body zone combinations, each assessed in a separate experiment (3.1); (2) regulating heat release by blocking heat outflow from combinations of the head, lower, and upper extremities - body areas where the heat current is highest (3.2). In the latter series of experiments, the possibility of achieving a certain level of regulation of heat outflow from the body by allowing zonal heat dissipation from different body areas was assessed. The possibility of regulating heat release through the head and distal part of extremities was the driving principle of these studies.

3.1- Regulation of heat extraction/insertion through selection of MACS-Delphi cooling/warming garment zones with maximal capability to accept heat

Method

The zone combinations studied were 1. head/chest/back; 2. head/torso/forearms, 3. head/torso/forearms/thighs (multi-compartment garment). Each combination was studied in a separate experiment. The experimental protocol was as follows: thermal stabilization, 20min treadmill exercise at 80%VO_{2max} / 20min rest; the exercise/rest sequence was repeated three times. Cooled water (15^{o}C) was circulated to the particular zone combination studied. Table 2 presents information on the cooling capacity of the MACS-Delphi during each of the three different cooling zone combinations, based on location, tubing length, flow rate, and exercise activity.

Table 2. Cooling Capacity of Different Body Zone Combinations During Physical Exertion

MACS-Delphi Cooling Area		Combination 1 (Head, Chest, Back)	Combination 2 (Head, Torso, Forearms)	Multi-Compartment Garment
				
Tubing Length (m)		14.9	32.7	55.1
Flow Rate (ℓ/min)		0.25	0.40	0.58
Cooling Capacity (Watts)	During exercise	78	126	209
	Exercise /rest	70	114	193

The findings indicated that as a general principal, regulating the process of heat extraction through different body areas was effective in maintaining core temperature during physical exertion. Within a certain quantitative range, regulation of a combination of different zones to reach a certain level of cooling appears promising in the support of different levels of work intensity, especially in cases of emergency.

3.2 Regulation of heat outflow through blocking the heat release process from the head/hands/feet: Pre-design and development of an Automatic Feedback System (AFS).

The potential of heat insertion/removal from the head, hands, and feet to stabilize body comfort was evaluated in terms of their role in blocking or advancing the heat highway from the core. Through combining zonal warming/cooling, the possibility of regulating heat release through the head and distal part of extremities was evaluated. To study the changes in thermal dynamics, a hood, gloves, and socks were designed with the capability to support a local temperature regime close to a core temperature of 37°C. Through maintaining this temperature, heat outflow was regulated or totally blocked on the periphery of the body.

Method

Experimental garment

A plastic tubing liquid cooling garment with a tubing net on the hood, long gloves and socks was designed for this research. The hood and gloves were composed of spandex mesh fabric. The tubing diameter was ID 2.8mm and OD 4.5mm (TYGON R TUBING AAC02641-CP, Cole-Parmer, IL). The total tubing length was 6.23, 9.60, and 10.85 meters for the hood, long gloves and socks, respectively. The garment was connected to a water bath to provide warmed water at 37°C.

Procedure

The experimental design consisted of four conditions: (a) Head/Hands/Feet warming (heat release through the major heat release zones are blocked); (b) Hands/Feet warming, Head open (major heat outflow is through the head); (c) Head/Feet warming, Hands open (major portion of heat is through the hands); (d). Head/Hands warming, Feet open (major heat outflow is through the feet). To provide such regimes a hood, gloves and socks were used during all stages. In each condition, each body zone combination was connected separately to a water bath to provide different heat outflow or total blocking of heat release when the water temperature was close to the core/local skin temperature (36.6-37°C).

The experimental procedure was as follows: thermal stabilization, running, rest, running and rest. During the exercise stage, the subjects ran on a treadmill at the level of a pre-determined 80% heart rate for 20 min; treadmill speeds were adjusted in the range of 5.5 to 6.0 mph. After the treadmill run, subjects were seated in an armchair for 10 min rest, and then repeated the exercise and rest stages.

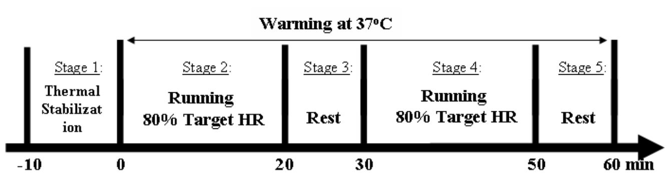


Figure. 8. Experimental protocol.

Results

As shown in Figure 9(a-d), the dynamic of the temperature of the core and the distal part of the fingers showed interesting findings in this series of experiments. T_{re} was highly elevated and Tfing was lower when the head was open (no heat imposed) (9b); T_{re} was lower and Tfing higher when heat was imposed on the head; thus blocking heat release from the head while the hands were open for free heat release (9c). These findings indicate a significant potential of using the hands for regulating heat release as compared to the head, which is already recognized as a highly effective regulation tool.

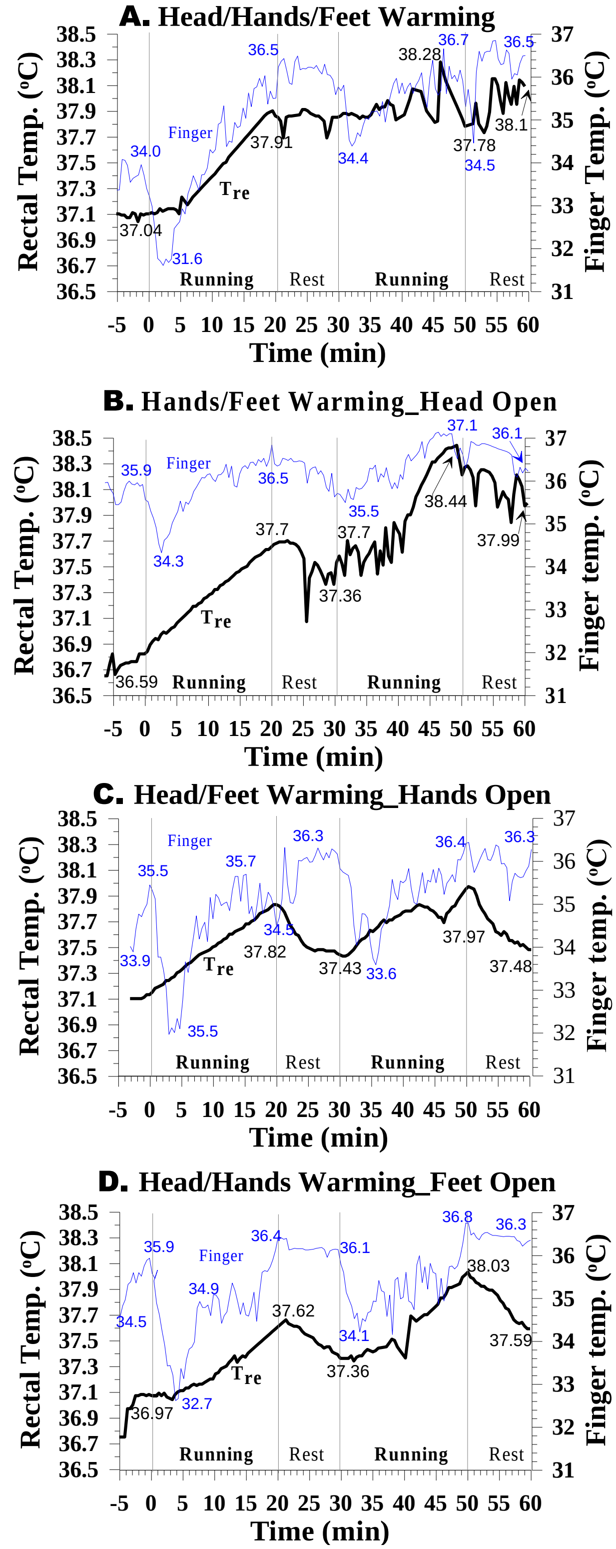


Figure 9. Rectal and finger temperatures under different open zones for heat release. A. Head/Hands/Feet warming (no zonal heat release); B. Hands/Feet warming, Head open (heat release through head); C. Head/Feet warming, Hands open (heat release through hands); D. Head/Hands warming, Feet open (heat release through

feet). Male subject, age 22yrs, Height 163.5cm, Body mass 68.6kg, BSA 1.78m^2, BMI 25.7, Body Fat 8.3%.

DISCUSSION

Several options to regulate heat release from the body were demonstrated as potential tools, one relying on imposing cooling to selected body areas intensively impregnated by heat during physical exertion, the other regulating heat content in the body through blocking heat release through different major thermal "highways" of heat release, that is, the head, hands and feet. Even though the head is a primary area for intensive heat release, the head is capable of releasing less heat than the hands. The vascular extension in the head is much more limited in regulating heat current than the surface of the hands and the fingertips. The anatomy and morphology of the hands are more adapted for maximizing heat release than the head, which has a stable heat outflow because there are no vessels to regulate cold/heat. The finger temperature profiles found in this research together with our previous investigations demonstrate high accuracy and stability in using T_{fing} to inform about the thermal status of the core[4]. Therefore, together with the principles of heat regulation demonstrated in the current studies, the next step is to examine more closely the heat regulation process in the body in terms of the heat flux/temperature index on the finger. The latter may be a prime candidate for practical use in developing an automatic thermal feedback system.

CONCLUSIONS

Three different protocols (Studies 1-3) were carried out to inform on how to improve the capability of the cooling system of a LCG. These studies have contributed additions to our knowledge about heat transfer processes through different body tissues, and how to regulate these processes. A significant improvement in extracting more heat through the entire system can occur through the following: 1. zonal tubing distribution in highly effective heat transfer zones; 2. short-looping the cooling tubes of the net together with the principle connection to a manifold, 3. cooling processes on the head using an optimal configuration of the tubing net on the head/neck surfaces.

Zonal regulation is effective for certain levels of activity. The areas studied for regulation can support thermal comfort if the total heat storage does not exceed 210 Watts. The combination of head/torso/forearms showed particular promise. The pilot test examining the blocking of heat release indicated that this strategy also was effective in heat regulation. However, this method will require detailed exploration in terms of how to apply this methodology in a practical way.

The appropriate regulation of heat release makes the garment system more physiologically applicable to the human body, and prevents any spikes of sharp cold water in the process of body surface cooling, thus avoiding unpleasant and distracting subjective sensations. Zonal regulation between the distal periphery of the hands and the core are of prime interest to specialists working on improving the garment cooling system, making the relationship between the human body and the cooling garment more "consumer friendly". Additional, more comprehensive study following up on these demonstration experiments is indicated.

ACKNOWLEDGMENTS

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