PHYSIOLOGICAL FACTORS IN PROTECTIVE HELMET DESIGN

by

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ABSTRACT

The heat transfer properties of protective headgear have been determined in chamber studies using a physical model (copper manikin). The evaporative heat transfer (i_m/clo) from a head in "still" air was constant above a standoff distance of 1.27 cm. for helmets with a constant head area coverage (67%). Reducing the head area coverage from 67% to 47% was necessary to significantly increase the evaporative heat transfer for a helmet standoff distance of 1.27 cm. The effect of wind on the heat transfer properties of selected headgear with varying designs was to decrease the values of insulation (clo) by about 60% and increase those for the evaporative heat transfer (i_m/clo) by about 4 times the "still" air values.

i (sub m)

INTRODUCTION

There are American National Standard safety requirements for industrial head protection which established specifications for protective helmets (1). However, even though heat stress is considered an occupational hazard, little quantitative information is available in the literature on the contribution of protective helmets to the total heat stress imposed on individuals working in a hot environment. This lack of information was made evident when the US Army Research Institute of Environmental Medicine (USARIEM) was asked to provide physiological research support to a program for the design and development of a new helmet for the infantry soldier (2). As part of this support, this study presents a review and analysis of experimental approaches using data (clo (3), i_m/clo (4), and i_m (5)) obtained on a heated sectional manikin which allows direct measurement of the heat loss from just the head section. One "clo" is defined as that amount of insulation required to maintain a resting man (metabr f 58 w/m^2) in comfort with a mean skin temperature of 33.3°C (92°F), at an ambient temperature of 21.1°C (70°F), an air movement of 0.05 m/s (10 ft/min) or less, and the relative humidity of the air equal to 50% or less. One "clo" is equivalent to an insulation value of $0.155 m^2 \cdot C/w$ in S.I. units. The i_m/clo is the evaporative heat transfer term. For a given value of insulation (clo), the greater the value of i_m/clo, the greater the efficiency of evaporative heat transfer through the insulation. The i_m term is a dimensionless quantity with a theoretical lower limit of 0 (a system with no evaporative heat transfer) and an upper limit of 1 (air layer over a wet bulb in wind). Thermal evaluations of available standard U.S. and foreign helmets, a riot control helmet and a football helmet measured under both "still" and forced air conditions are included.

a. Some Heat-Stress Problems Caused by Wearing Helmets

Heat-stress problems caused by wearing helmets usually involve considerable wearer discomfort, including sweat dripping into the eyes and causing them to burn, sweat collecting in the ear cushions of "crash" helmets and running into the ears, sweat gathering in foam pads and running down the face when the pads are compressed, and an itchy scalp caused by sweatband irritation of the skin. Since these types of problems continue as long as the helmet is worn, temporary relief is usually obtained by removal of the helmet. In addition, there appears to be an instinctive feeling for promoting air ventilation around the head by spacing the helmet away from the head and, in some cases, holes are drilled in helmets, even at the risk of compromising their head protection features, although the evidence for extra comfort is debatable.

b. Review of Physiological Studies on Head Heat Loss

Three publications are of particular interest in any study of the heat transfer properties of headgear. Siple (6) stated that exposure of the head in the cold accounts for a large percentage of body heat loss since heat is lost in increasing quantities from the head as the thermal gradient increases. This prediction was verified by Froese and Burton (7) who directly measured the nonevaporative heat losses from a bare head using a temperature gradient calorimeter. This study showed that, because there is little or no vasoconstriction in the head when it is exposed to cold temperatures, the heat loss from the head amounts to half of the total resting heat production of a man. Finally, Edwards and Burton (8) investigated the distribution of skin temperature over the surface of the head and presented a figure showing a detailed mapping of these surface temperatures.

c. Review of Published Helmet Studies

A report by Winsmann (9) deals with the thermal protective characteristics of a CVC (Combat Vehicle Crewmen, e.g., tankers) helmet in arctic and hot environments. His results were based on measured head temperatures, and subjective comments, and indicated that the CVC helmet provided environmental protection equal to a pile cap with ear laps down at -23.4°C air temperature and about 1.3 meters/second air flow. Environmental protection in a heat stress situation was about equal to a baseball cap at 29.4°C air temperature and about 1.3 meters/second air flow.

Van Graan and Strydom (10) investigated the effect of reducing heat stress by providing ventilating holes in hard hats. They compared a hard hat without holes, a second hard hat with two 1.27 cm. diameter holes at the top of the hard hat and a third with six equally spaced 0.635 cm. diameter holes around the circumference of the hard hat. These hard hats were compared on the basis of temperature results using three thermocouples: one located at the top of the subject's head. another spaced 2.54 cm. from the top of the head, and a third placed at the inside crown area of the hard hat. Their results showed no difference in head surface temperature among the three hard hats. The air temperature above the head showed no difference between wearing the hard hat without holes or the hard hat with the two 1.27 cm. diameter holes at the crown of the hard hat. However, the results for the hard hat with six equally spaced 0.635 cm. diameter holes around the rim suggested that the air temperature at the thermocouple measuring position inside the hard hat was higher with the six holes, than with either the two 1.27 cm. diameter holes or no hole, for the cool air environmental conditions, when the subjects were at rest; when the subjects were doing a step test in the hot-dry condition a lower inside air temperature was registered. These latter two findings suggest that some of the incoming air was diverted through the six holes around the rim of the hard hat rather than passing over the top of the head. However, these air temperature differences had no significant effect on head cooling since, for all hard hats, head and inside crown area of the hard hat, temperatures showed no difference for any of the respective experimental conditions and subject activity levels.

Coleman and Mortagy (11) studied the heat retention qualities of five different models of football helmets. These helmets differed primarily in the design and composition of their suspension systems. Air temperatures measured "with thermistors inserted 2.5 cm into the right anterior and left posterior quadrant of each helmet" showed a significant difference between helmets with web suspension system (lower air temperatures), and those with form fitting, inflatable and hammock-suspension systems.

d. Review of Previous Laboratory Studies (unpublished)

Both "snug-fitting" and "close-fitting" headgear with ventilating holes were studied previously at USARIEM using the electrically heated sectional copper manikin as the physical model. A "close-fitting", "hard" helmet (original Hayes-Stewart) containing an air ventilation opening at the top (see Figure 1A) was evaluated on the manikin to determine if this ventilation opening significantly improved head cooling in "still" air or in air flows up to 5 meters/second. This study showed that the ventilating opening provides little advantage in increasing evaporative heat transfer (i_m/clo) from the head in "still" air conditions, although with higher air flows there appears to be a slight advantage; both helmets provide an air space around the head which is readily disturbed in wind.

A "snugly-fitting", "soft" helmet (standard West German tankers) consisting of a foam-rubber liner and reinforced from skull to nape of the neck by a flexible polyethylene strip was also studied. Some ventilation is presumably available at the sides by three screen grommets and through two air passages running from the front to the back of the head (see Figure 1B). This helmet was evaluated on the manikin to determine the effect of such air-ventilating grommets on the evaporative heat transfer (i_m/clo) from the head. The results showed that sealing the ventilating grommets on the side of the helmet made little difference in the evaporative heat transfer from the head in "still" air. However, in an air flow of 3 meters/second, sealing these ventilating grommets reduced the evaporative heat transfer by about 10%. Apparently, since this helmet fits snugly to the head, increasing the air movement around the head with the ventilating grommets sealed has little effect on the evaporative heat transfer from the area of the head covered by the helmet.

GENERAL METHODS

Manikin head section clo, i_m, and i_m/clo values were determined by the methods described in an earlier paper (12) following the standardized, experimental procedures set forth in our Standard Manikin Procedure memoranda (13). The head section of the manikin is considered as the test section; the remaining five sections (torso, arms, hands, legs, and feet) are considered as guard sections. The manikin is completely enclosed in a skin of form-fitting underwear material and dressed in a basic clothing ensemble consisting of tropical fatigues, one pair of socks, and a pair of black leather boots. In these studies, the manikin was placed in a standing position near the center of an environmental chamber, facing two fans which directed air at the head of the manikin. A helmet was placed on the manikin's head and the insulation value (clo) was determined for the 0.1 m/s normal chamber air flow (i.e., "still" air condition, with the two fans off) and for a forced air flow condition of ~ 3 m/s (i.e., with the two fans running). Similarly, after the manikin's skin (underwear material) was wet, the evaporative heat transfer value i_m/clo was determined for the "still" and the forced air conditions.

RESULTS

Substudy 1: <u>Thermal Properties as a Function of Standoff Distance from the Head</u>

There was little or no systematic data on the evaporative heat transfer cooling range (i_m/clo) for any close-fitting helmet system. Such information for a selected close-fitting helmet configuration, added to information on similar helmets with less or greater spacing distances from the head, should define an optimum spacing from the head for evaporative heat transfer, if any such optimum exists.

A master mold of the manikin's head was made, and a set of molds were cast which contained a controlled amount of standoff. Five helmets were vacuum formed with standoff distance ranging from approximately 0 cm. (snugly-fitting) to 2.54 cm. (very loosely-fitting) in 0.635 cm. increments. All five helmets provided a constant head area coverage of approximately 67% of the total manikin head surface area (see Figure 2).

Figure 3 graphically depicts insulation (clo) and evaporative heat transfer (i_m/clo) as a function of standoff distance for these 5 helmets.

These results show that helmet No. 1 and 0 cm. standoff, practically eliminated any evaporative heat transfer from the area of the head covered by the helmet; essentially all the evaporative heat transfer from the head occurred over the uncovered area of the head (about 33% of the head surface area). Furthermore, for the "still" air condition, there is little difference in the evaporative heat transfer (i_m/clo) between this snugly-fitting helmet and one spaced 0.635 cm. away from the head (helmet No. 2). Apparently the first 0.635 cm. spacing around the top of the head consists of essentially dead air space. However, once the standoff distance reaches 1.27 cm., there is a significant increased heat transfer but there is little difference in i_m/clo between this and the next two helmets covering the 1.27 cm. to 2.54 cm. spacing range. Thus 0.635 cm. is too small to have much effect on evaporative heat transfer in "still" air while 1.27 cm. produces as much benefit as 1.905 or 2.54 cm. It can be seen that the insulation values (clo) reach a maximum value 0.635 cm. standoff distance and then decrease with increasing standoff distance.

Although the snugly-fitting helmet (no standoff) did not have a trapped air space to provide insulation between the head and the helmet in "still" air, at 3 meters/second air motion the snugly-fitting helmet and the .635 cm. standoff helmet provide greater insulation than any of the other helmets; the "dead" air space between the helmet and the head at standoff distances beyond 0.635 cm. is now disturbed. Conversely, the evaporative heat transfer from the head, which did not show an increase in "still" air conditions until the 1.27 cm. standoff distance was reached (again because of the dead air space with the 0.635 cm. standoff helmet), with moving air (3 meters/second) shows a disturbance of the "dead" air in the 0.635 cm. space; the value for the 0.635 cm. standoff increases toward the nearly constant evaporative heat transfer value of the 1.27, 2.005, and 2.54 cm. helmets.

Substudy 2: Effect of Ventilating Slots in an M-1 Helmet Liner on Evaporative Heat Transfer

Although neither our helmet study using a ventilating cap at the top of the original Hayes-Stewart helmet nor the study (10) comparing miners hard hats with ventilating openings showed any significant improvement in the ventilating properties of the respective helmets, a further look at the air ventilating openings in helmets was undertaken to see if a combination of ventilating slots at the top, and around the helmet, equal to about 8% of the total surface area of the helmet would show a difference in net evaporative heat transfer in "still" air. An M-1 helmet liner was modified by cutting out ten ventilating slots, removing about 8% of the total helmet liner surface area. Two of these slots were located on each side of the helmet, two in the rear, three in the front, and one on top of the helmet (see Figure 4). It is apparent from the results given in Table I that this amount of open area in a helmet, and the location of these ventilating slots, does allow an increase in net evaporative heat transfer in "still" air, but offers little benefit at an air flow of 3 meters/second. Since this helmet liner is spaced about 1.27 cm. from the head, these results are important in illustrating the order of magnitude of ventilating openings and their location around this type of "close-fitting" helmet.

Substudy 3: Area Coverage Effects

The effect of head area coverage on the heat transfer properties of helmets was investigated by removing three 2.54 cm. strips from the bottom edge of the experimental helmet with the 1.27 cm. standoff distance. This provided four helmet samples with a head area coverage range of from 47% to 67%. The clo and i_m/clo values are plotted against head area coverage in Figure 5. The insulation values (clo) in "still" air, increase linearly with increasing head area coverage (Figure 5B); in an air flow of 3 meters/second (Figure 5A), they do not increase until a head area coverage of about 55% is reached. The evaporative heat transfer (i_m/clo) values in "still" air do not show an increase until head area coverage is reduced to less than 60%; they are relatively constant at an air flow of 3 meters/second. It is of interest to consider the two extreme head area coverage helmets (67% and 47% head area coverage). The quantity of helmet material removed consists of about 30% of the material of the 1.27 cm. standoff helmet. The increase in evaporative heat transfer (i_m/clo) in "still" air as a result of this decrease in head area coverage amounts to about 20%. The helmet liner studied with the ten ventilating slots, equal to removal of about 8% of the helmet liner material, increased the evaporative heat transfer (i_m/clo) about 35% in "still" air. Comparing these results with the previous findings with helmets with ventilating openings, suggests that the number and locations of these ventilating openings could be more important than the total area coverage of the helmet.

Substudy 4: Removable Suspension Systems for M-1 Helmet Liner

Any given suspension system modifies the evaporative heat transfer properties of a helmet, in part by the total head-suspension system contact area, by the distribution of this contact area over the head, and by the material composition and thickness of the suspension system. Three removable suspension systems (Figure 6) for the M-1 helmet liner were studied to determine if any measurable differences in the evaporative heat transfer (i_m/clo) from a head could be detected. An earlier study using a single circuit copper manikin determined total clo and i_m/clo values for these three helmet liner/suspension systems as part of a complete ensemble. These experimental results obtained in "still" air are shown in Table IIA. Since these values are for the total manikin surface area, the contribution from the head is masked by the contributions from the other areas of the manikin. Table IIB shows the evaporative heat transfer values (i_m/clo) for these three helmet liner/suspension systems determined on the sectional manikin. Although the i_m/clo values in each Table are grouped closely together, the evaporative heat transfer from the head given by the i_m/clo values in Table IIB are almost twice those for the complete ensemble. However, even restricting the evaporative heat transfer measurements to the head alone showed little differences among the i_m/clo values for the helmet liner with either the standard, HEL (Human Engineering Laboratory, Aberdeen Proving Ground, MD), or the Welson-Davis removable suspension systems.

Substudy 5: Face Shield Effects

A standard M-1 helmet and a commercial riot control helmet (see Figure 7) were studied to determine the effect on the heat transfer properties of helmets when a face shield is worn in the down position. Table III shows that measurable differences in insulation (clo) and evaporative heat transfer (i_m/clo) were obtained when comparing face shields in the "up" and "down" positions. The insulation values increased by about 0.1 clo and the evaporative heat transfer values decreased by about 0.05 i_m/clo. Increasing the air flow decreased the insulation values of both helmets by about 60%, with face shields in the "up" or "down" position, and increased the evaporative heat transfer values by about 5 times the "still" air values.

Substudy 6: Thermal Characteristics of Selected Helmets

The helmets shown in the photographs of Figure 8 are of assorted shapes and sizes, ranging from "snug-fitting" to "loose-fitting", from comparatively rigid suspension systems to flexible suspension systems, and include suspension systems fabricated from materials of various moisture permeabilities. From Table IV it is noted that the data for the Aircrew APH-5 helmet are consistently among the highest insulation values (clo) and the lowest evaporative heat transfer values (i_m/clo) for the "still" and 3 meters/second air flow conditions. This is mainly because of its very close-fitting design. The English and the Italian infantry helmets consistently show the lowest insulation (clo) and the highest evaporative heat transfer values (i_m/clo), apparently because of their high proportion of uncovered head surface area. Overall, increasing the air flow from "still" air to 3 meters/second reduces the insulation (clo) for all helmets by about 60% and increases the evaporation (i_m/clo) by about 4 times the "still" air values.

DISCUSSION AND CONCLUSIONS

It is difficult to establish any meaningful differences in "still" air in the heat transfer properties of headgear with and without ventilating holes. Although the M-1 helmet liner with 10 ventilating slots spaced over the helmet, providing about 8% of open space in the helmet liner, did show an increase in evaporative heat transfer from the head, simply making several holes around the helmet or at th top is apparently of little benefit in increasing the evaporative heat transfer from the head. Removing strips of material from the bottom edge of a helmet, originally covering about 67% of the head (standoff distance of 1.27 cm.), shows little improvement in evaporative heat transfer until about 30% of the helmet material has been removed. For a constant head area coverage of 67%, the evaporative heat transfer was constant above a standoff distance of 1.27 cm. In wind, ventilating holes appear to increase the evaporative heat transfer for a snugly-fitting helmet but have negligible effect on all other helmets. Increasing the air flow from "still" air to 3 meters per second reduces the insulation (clo) for all nine selected headgear items by about 50% and increases the evaporative heat transfer (i_m/clo) by about four times the "still" air values.

The surface area affected by a helmet is relatively small compared with the total body surface area. Any benefit in the heat transfer properties is more apt to be reflected in improved head comfort, rather than in any extension of overall physiological tolerance time. A decrease in headgear insulation of 0.1 clo with an insulation range of 1.0 to 1.5 clo will result in an increase in convective heat transfer from the head of between 0.4 and 1.0 watts. Increasing the i_m/clo by 0.1 increases the evaporative heat transfer from the head by about 2 watts for a vapor pressure difference between the head surface and ambient air of 10 mm Hg. Thus, in terms of practical differences in heat loss from the head, none of these helmet alterations seem impressive. Nevertheless, in addition to the problem of weight, the problem of thermal discomfort associated with wearing helmets is a significant deterrent to their use. Any design modification making wear of the helmet more acceptable, without unacceptably compromising protection, is worth pursuing.

SUMMARY

Once a conventional helmet is placed on a head in a heat-stress environment, some degree of subject discomfort due to problems with dripping sweat is inevitable. However, there is a range of helmet designs which should minimize subject discomfort. This study shows that the evaporative heat transfer from the head is not significantly affected either by bringing the helmet to within 1.27 cm. of the head surface or by increasing coverage of the head area from about 50% to 67%. Also, physical differences in helmet-suspension systems studied did not have a significant effect on the evaporative heat transfer from the head. However, physical contact with the head should be kept to a minimum since this area will not contribute to the evaporative heat transfer from the head. Furthermore, when there is an air space between the head and a helmet, any benefit provided by ventilating holes in helmets for removal of moisture from around the head is lost. Finally, wind minimizes any effect on evaporative heat transfer from the head caused by differences in helmet design.

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TABLE I. Thermal Characteristics of the M-1 Helmet Liner with and without Ten Ventilating Slots which Provide Open Spaces Equal to 8% of the Total Helmet Liner Surface Area

	Air Flow					
	"Still" Air			3 Meters/Second		
Helmet Liner	CLO	i_m/CLO	i_m	CLO	i_m/CLO	i_m
Open Slots	0.94	0.55	0.52	0.36	2.2	0.79
Sealed Slots	1.03	0.41	0.42	0.36	2.1	0.76

TABLE IIA Total Thermal Characteristics in "Still" Air of a Tropical Combat Fatigue Ensemble Using the M-1 Helmet Liner with Removable Suspension Systems

Removable Suspension Systems	CLO	i_m/CLO	i_m
Standard	1.54	0.23	0.36
HEL	1.57	0.23	0.36
Welson-Davis	1.59	0.21	0.34

TABLE IIB Thermal Characteristics of Selected Removable M-1 Helmet Liner Suspension Systems

	Air Flow					
	"Still" Air			3 Meters/Second		
Suspension Systems w/Helmet Liner	CLO	i_m/CLO	i_m	CLO	i_m/CLO	i_m
Standard	1.10	0.40	0.44	0.39	2.0	0.78
HEL	1.10	0.38	0.42	0.39	1.8	0.70
Welson-Davis	1.04	0.39	0.41	0.38	1.9	0.72

TABLE III Thermal Characteristics of the Standard M-1 Helmet and a Commercial Riot Control Helmet with a Face Shield in the Up and Down Positions

Headgear	Air Flow "Still" Air			3 Meters/Second		
	CLO	i_m/CLO	i_m	CLO	i_m/CLO	i_m
M-1 Helmet System w/Face Shield Up	1.08	0.43	0.46	0.44	1.9	0.84
M-1 Helmet System w/Face Shield Down	1.20	0.38	0.46	0.52	1.7	0.83
Commercial Riot Helmet w/Face Shield Up	1.35	0.38	0.51	0.50	2.0	1.0
Commercial Riot Helmet w/Face Shield Down	1.43	0.33	0.47	0.54	1.5	0.81

TABLE IV Thermal Characteristics of Selected Helmets

	Air Flow					
	"Still" Air			3 Meters/Second		
Helmets	CLO	i_m/CLO	i_m	CLO	i_m/CLO	i_m
Aircrew AFH-1	1.72	0.38	0.65	0.48	1.8	0.88
Aircrew APH-5	1.45	0.32	0.47	0.51	1.4	0.72
Standard CVC	1.28	0.36	0.46	0.43	1.9	0.83
English Infantry	0.97	0.45	0.44	0.37	1.9	0.70
Football Helmet	1.16	0.32	0.37	0.47	1.6	0.78
Experimental Hayes-Stewart	1.11	0.35	0.39	0.45	1.9	0.87
Italian Infantry	1.03	0.43	0.44	0.42	2.0	0.84
Experimental Parachutist Liner	1.36	0.37	0.50	0.54	1.5	0.81
Standard M-1 Helmet Liner	1.10	0.40	0.44	0.39	2.0	0.78

LIST OF FIGURES

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The effect of wind on the heat transfer properties of selected headgear with varying designs was to decrease the values of insulation (clo) by about 60% and increase those for the evaporative heat transfer (i_m/clo) by about 4 times the "still" air values.