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PREDICTION MODELING OF PHYSIOLOGICAL RESPONSES AND HUMAN PERFORMANCE IN THE HEAT WITH APPLICATION TO SPACE OPERATIONS

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ABSTRACT

This Institute has developed a comprehensive USARIEM Heat Strain Model for predicting physiological responses and soldier performance in the heat which has been programmed for use by hand-held calculators, personal computers, and incorporated into the development of a heat strain decision aid. This model deals directly with five major inputs: (a) the clothing worn, (b) the physical work intensity, (c) the state of heat acclimation, (d) the ambient environment (air temperature, relative humidity, wind speed, and solar load), and (e) the accepted heat casualty level. In addition to predicting rectal temperature, heart rate and sweat loss given the above inputs, our model predicts the expected physical work/rest cycle, the maximum safe physical work time, the estimated recovery time from maximal physical work, and the drinking water requirements associated with each of these situations. This model provides heat injury risk management guidance based on thermal strain predictions from the user specified environmental conditions, soldier characteristics, clothing worn, and the physical work intensity. If heat transfer values for space operations' clothing are known, NASA can use this prediction model to help avoid undue heat strain in astronauts during space flight.

INTRODUCTION

Since the early 1970s, our Institute has established the data base and developed a series of predictive equations for deep body temperature, heart rate and sweat loss responses of clothed soldiers performing physical work in the heat. Individual predictive equations for rectal temperature (4), heart rate (5), and sweat loss (16) as a function of the physical work intensity, environmental conditions and particular clothing ensemble have been published in the open literature. In addition, important modifying factors such as metabolic rate (2,11), state of heat acclimation (6), state of hydration (14,15), and solar load (1) have been studied and appropriate predictive equations developed.

Currently, we have developed a comprehensive USARIEM Heat Strain Model which has been programmed for use by hand-held calculators, personal computers, and incorporated into the development of a heat strain decision aid. The mathematical basis employed in the development of the various individual predictive equations and the predictive capabilities of our heat strain model have been published previously (12,13). Our model deals directly with five major assessment factors and associated inputs: (a) U.S. Army clothing systems as selected from a clothing menu; (b) physical work intensity entered at three fixed values (i.e., light, moderate, or heavy), or directly entered if a value for metabolic rate is known (i.e., watt, kcal/hr, or MET), or computed from march speed, soldier body weight, external load carried, terrain type and grade; (c) functional state entered as either non-heat acclimated or fully-heat acclimated; (d) the ambient environment entered as the air temperature (°C or °F), humidity (% relative humidity, vapor pressure or dew point), wind speed in three categories (calm, breezy or windy) or entered in user friendly units, and solar load/sky conditions as an index of cloud cover; and, (e) accepted heat casualty level inputted as light (<5%), moderate (20%), or heavy (>50%). In addition to predicting rectal temperature, heart rate and sweat loss given the above inputs, this model predicts the expected physical work/rest cycle, the maximum safe physical work time, estimated recovery time (shade or sun) from maximum physical work, as well as the drinking water requirements associated with each of these situations.

The USARIEM Heat Strain Model provides heat injury risk management guidance based on thermal strain predictions from the menus selected or the user specified environmental conditions, soldier characteristics, clothing, and physical work intensity. The military user can employ this heat strain prediction model to help avoid unnecessary casualties associated with exposure to the environmental heat extremes, and for prediction of appropriate physical work/rest cycles and water requirements to facilitate achievement of military mission objectives. If heat transfer values for space operations clothing are known, NASA can use this prediction model to help avoid unnecessary heat strain and develop better heat injury risk management guidance for astronauts during space flight.

The potential for astronauts experiencing significant thermal stress exists in several NASA space flight scenarios (3,8,9,18,19). During extravehicular activity (EVA) while wearing the shuttle Extravehicular Mobility Unit (EMU), the liquid cooling garment worn with the EMU has been shown to provide adequate cooling capacity for most EVAs conducted at an average metabolic rate of 200 kcal/hr and thought to provide adequate cooling at metabolic rates up to 400 kcal/hr (3,8). Astronauts are reported to become less heat acclimated, dehydrated, and maintain a state of hypohydration during sustained space flight which alters their ability to effectively thermoregulate (3,7). Therefore, EVAs conducted by astronauts at sustained high metabolic rates while in a state of hypohydration and less heat acclimated may provide a potential thermal challenge and possible adverse consequences on crew member performance. Under certain EVA scenarios such as above, Fortney (3) suggests that "proper work/rest cycles to prevent large rises in body temperature, and adequate fluid replacement" are desirable. During launch, re-entry and emergency egress, astronauts wear a Launch and Entry Suit (LES) which has a ventilation system that circulates cabin air through the suit (3,9). Kaufman et al. (9) have evaluated the LES (ventilated and unventilated) during simulated pre-launch conditions for up to eight hours at an ambient temperature of 27.2°C and reported insignificant levels of thermal strain. The potential for excessive heat strain exists while wearing the LES at higher ambient temperatures which could occur during re-entry, higher metabolic rates which could happen during emergency egress and/or crew members who are in a state of hypohydration and less heat acclimated during re-entry or emergency egress.

This paper briefly presents the capabilities of our heat strain model to predict physiological responses as depicted by rectal temperature as well as the expected physical work/rest cycle, maximum single physical work time, and associated water requirements for different military scenarios. In addition, our model evaluates certain NASA scenarios where thermal stress and the potential for heat strain could be present.

USARIEM HEAT STRAIN PREDICTION MODEL CAPABILITIES

Foreign and U.S. Military Scenarios

Figure I presents a comparison of observed and predicted rectal temperature responses for 12 soldiers while wearing three different military clothing ensembles (US NBC closed, UK NBC closed and jungle uniform) under two different climatic conditions (~30°C, 62% rh, shade; ~32°, 41% rh, sun) during a field study in Australia. These data which were collected by a group independent of our Institute are in quite good agreement with the predicted values, and in all but two instances, the observed responses are within ±1 standard deviation of the predicted responses using the USARIEM Heat Strain Model.

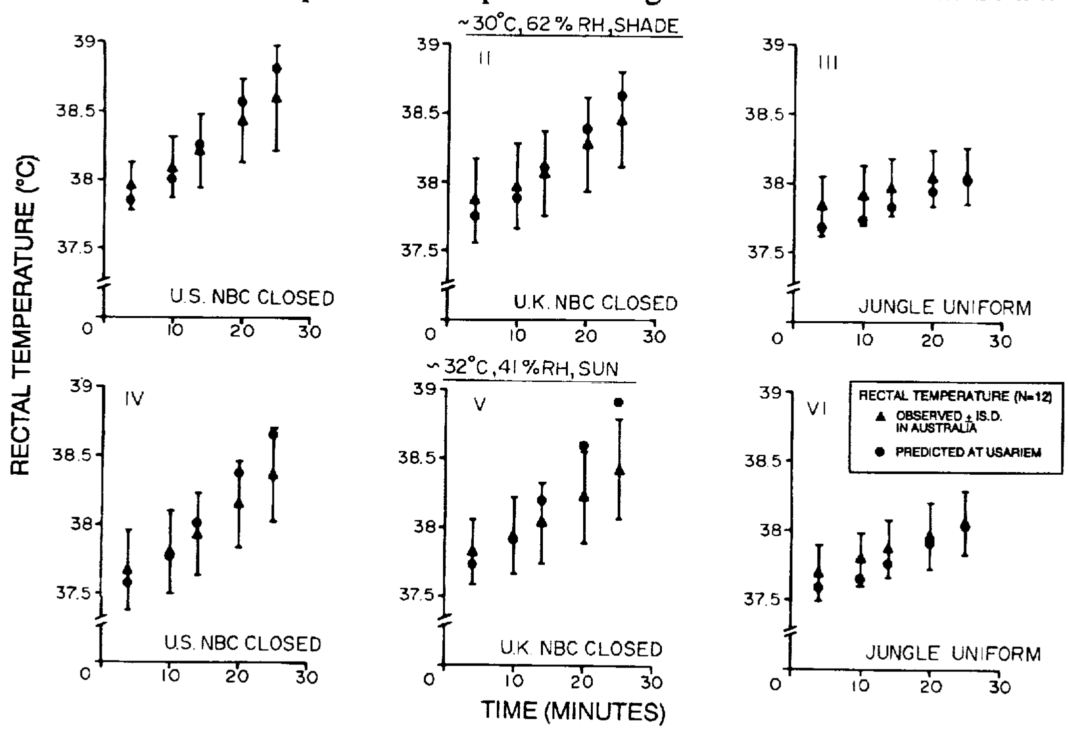

FIGURE I. COMPARISON OF PREDICTED AND OBSERVED RECTAL TEMPERATURE RESPONSES OF 12 SOLDIERS WHILE WEARING THREE DIFFERENT MILITARY CLOTHING SYSTEMS EACH UNDER TWO DIFFERENT CLIMATIC CONDITIONS.

Table I shows a comparison of observed and predicted final rectal temperatures while wearing Canadian Forces NBC protective clothing (10). Twenty-three unacclimated male soldiers performed light or heavy exercise in either a cool (18°C, 50% rh) or warm (30°C, 50% rh) environment for an attempted 300 minute exposure in protective clothing (TOPP High). As illustrated in Table I, the USARIEM Heat Strain Model predicted final rectal temperature responses of these soldiers at their respective tolerance times within ±1 standard error of measurement from the observed mean rectal temperature responses in three of the four test conditions with the exception being light exercise in the warm environment. These authors concluded: "Thus, US Army Guidelines for maximum allowable work times with minimal heat casualties, based on the Pandolf et al. model, can be considered to be applicable to our CF Infantry NBC protective clothing." (10).

TABLE I. COMPARISON OF OBSERVED AND PREDICTED FINAL RECTAL TEMPERATURES WHILE WEARING CANADIAN FORCES NBC PROTECTIVE CLOTHING*

Condition	Tolerance Time (min)**	Observed T_{re} (°C)	Predicted T_{re} (°C)
Light Exercise @ 18°C, 50% rh	242 (±33)	38.3 (±0.2)	38.2
Light Exercise @ 30°C, 50% rh	83 (±4)	38.9 (±0.1)	38.4
Heavy Exercise @ 18°C, 50% rh	57 (±7)	38.5 (±0.1)	38.5
Heavy Exercise @ 30°C, 50% rh	34 (±4)	38.3 (±0.2)	38.4

* Canadian Forces NBC Protective Clothing = TOPP High. **Attempted 300 min exposure. Values are means ±SEM.

CONCLUSION: "Thus, US Army guidelines for maximum allowable work times with minimum heat casualties, based on the Pandolf et al. model (16), can be considered to be applicable to our CF infantry NBC protective clothing."

FROM: McLellan, T.M. et al. Influence of Temperature and Metabolic Rate on Work Performance with Canadian Forces NBC Clothing. Aviation, Space and Environmental Medicine 64:587-594, 1993.

Table II illustrates the predicted physical work/rest cycles, maximum work times and associated water requirements for four different military scenarios as determined by the USARIEM Heat Strain Model. The required inputs for these four scenarios are the clothing worn (MOPP 1 or MOPP 4), physical work intensity (HVY. WRK. or MOD. WRK.), casualty level (HVY. CASLT.), acclimation state (ACCL.), environmental conditions (HOT DRY), wind speed (WINDY) and solar heat load (CLOUDY or CLEAR SKY). The expected outputs are the physical work/rest cycle (minutes), one-time only maximum work period (minutes), and the associated water requirements (canteens per hour). Compared to Scenario 1, the results of Scenario 2 depict the importance of the solar load in reducing both the physical work/rest cycle and one-time only maximum work period while increasing the associated water requirements. Results from Scenario 3 show the dramatic reduction in the work component of the physical work/rest cycle and the associated reduction in the one-time only maximum work period while wearing MOPP 4. The results from Scenario 4 display the benefits of reducing the metabolic work rate from heavy to moderate in terms of improvement in the work component of the physical work/rest cycle and enhancement of the one-time only maximum work period. Hopefully, the military user can employ the USARIEM Heat Strain Model to help avoid unnecessary casualties associated with exposure to the environmental heat extremes, and by predicting appropriate physical work/rest cycles and water requirements facilitate the achievement of mission objectives.

TABLE II. PREDICTED PHYSICAL WORK-REST CYCLES AND WATER REQUIREMENTS ASSOCIATED WITH FOUR DIFFERENT MILITARY SCENARIOS

Scenario 1	Scenario 2	Scenario 3	Scenario 4
INPUTS:			
MOPP 1 HVY.WRK. HVY.CASLT. ACCL. HOT DRY WINDY CLOUDY	MOPP 1 HVY.WRK. HVY.CASLT. ACCL. HOT DRY WINDY CLEAR SKY	MOPP 4 HVY.WRK. HVY.CASLT. ACCL. HOT DRY WINDY CLEAR SKY	MOPP 4 MOD.WRK. HVY.CASLT. ACCL. HOT DRY WINDY CLEAR SKY
RESULTS:			
Time W:R:M=33*27*84 Water W:R:C=2.3*0.9*1.7	Time W:R:M=28*32*74 Water W:R:C=2.4*1.1*1.7	Time W:R:M=14*46*52 Water W:R:C=2.4*1.1*1.4	Time W:R:M=24*36*87 Water W:R:C=2.2*1.1*1.6

W:R:M= work:rest:maximum work (time periods (minutes))
W:R:C= work:rest:combined (water requirements (canteens per hour))

NASA Scenarios

After evaluating available clothing heat transfer values (EMU (17) and LES (personal communication, C.M. Chang)) and the potential for experiencing excessive heat strain while wearing these clothing ensembles during space flight (3), we decided to model three NASA scenarios involving the LES primarily because the potential for excessive heat strain appeared greater than that for the EMU. The three scenarios involved pre-launch/launch, re-entry and landing, and emergency egress after re-entry and landing. The pre-launch/launch scenario (9) was an eight hour exposure to 27°C (50% rh) at a metabolic rate of 100 kcal/hr. The re-entry and landing scenario (18) was a five and one-half hour exposure to 24°C (50% rh) at a metabolic rate of 100 kcal/hr followed by a one and one-half hour exposure to 35°C (70% rh) at this same metabolic rate. The emergency egress scenario (personal communication, J.P.Bagian, M.D.) was the same as the re-entry and landing scenario except for an additional 10 minute attempted exposure (35°C, 70% rh) at a metabolic rate of 430 kcal/hr.

For each of the above three scenarios, the USARIEM Heat Strain Model was used to predict final rectal temperature, required cooling (air or liquid) to maintain minimal levels of heat storage, and if applicable the tolerance time (minutes) to reach a rectal temperature of 39.0°C. Prediction modeling was conducted with an unventilated or ventilated LES at clo values of 1.47 (unventilated), 1.29 (ventilated), and 1.20 (metabolic rate = 430 kcal/hr). During these scenarios, individuals were assumed to be either heat acclimated or unacclimated, and either euhydrated or 3% dehydrated.

TABLE III. PREDICTED FINAL RECTAL TEMPERATURES, REQUIRED COOLING AND TOLERANCE TIMES WHILE WEARING THE NASA LAUNCH AND ENTRY SUIT (LES) DURING SCENARIOS (UNVENTILATED OR VENTILATED) CONSIDERING HEAT ACCLIMATION AND HYDRATION STATE

SCENARIO *	UNVENTILATED				VENTILATED			
	ACCLIMATED		UNACCLIMATED		ACCLIMATED		UNACCLIMATED	
	Euhydrated	Dehydrated	Euhydrated	Dehydrated	Euhydrated	Dehydrated	Euhydrated	Dehydrated
Pre-Launch/Launch								
Final T_{re}(°C)	37.8	38.1	38.4	38.7	37.7	38.0	38.3	38.6
Cooling (W)	80	80	80	220	50	50	60	200
Re-Entry								
Final T_{re}(°C)	38.2	38.5	38.8	39.1	38.1	38.5	38.8	39.1
Cooling (W)	140	170	190	360	130	130	190	360
Emergency Egress								
Final T_{re}(°C)	38.4	38.8	39.1	39.4	38.4	38.7	39.0	39.3
Tolerance Time (min)	18	13	9	6	18	14	10	6

* Scenario: Pre-Launch/Launch = 27°C, 50% relative humidity for 480 min at a metabolic rate of 100 kcal/hr.
Re-Entry = 24°C, 50% relative humidity for 330 min (metabolic rate, 100 kcal/hr), 35°C, 70% relative humidity for 90 min (metabolic rate, 100 kcal/hr).
Emergency Egress = 24°C, 50% relative humidity for 330 min (metabolic rate, 100 kcal/hr), 35°C, 70% relative humidity for 90 min (metabolic rate, 100 kcal/hr), 35°C, 70% relative humidity for 10 min (metabolic rate, 430 kcal/hr).
LES clo values: 1.47 (unventilated); 1.29 (ventilated); 1.20 (metabolic rate = 430 kcal/hr).
Final T_{re} (°C) = final rectal temperature; Cooling (W) = air or liquid cooling; Tolerance Time (min) = time to reach T_{re} of 39.0°C; Euhydrated = 0% dehydration; Dehydrated = 3% dehydration.

Table III shows the predicted final rectal temperatures, required cooling and tolerance times while wearing the unventilated or ventilated LES, and considers the effects of heat acclimation and hydration state. For the pre-launch/launch scenario (unventilated or ventilated), the predicted mean final T_{re} for euhydrated-acclimated and euhydrated-unacclimated individuals is in close agreement with the observed final T_{re} values (~38.0°C) for this same scenario reported by Kaufman et al. (9) indicating minimal heat strain. For this scenario, dehydrated-unacclimated individuals, a state thought to occur during space flight (3,7), demonstrate moderate heat strain as depicted by final T_{re} values. For the re-entry and landing scenario (unventilated or ventilated), the predicted final T_{re} for euhydrated-acclimated individuals are indicative of minimal heat strain; however, moderate to excessive heat strain is exhibited for all of the other situations (dehydrated-acclimated, euhydrated-unacclimated, or dehydrated-unacclimated individuals). The required cooling (air or liquid) depicted in Table III for the above two scenarios demonstrates the required heat extraction from the body using a vest-cooling system and does not consider the efficiency factor of the particular vest-cooling system. For the emergency egress scenario (unventilated or ventilated), moderate to severe levels of heat strain are shown for all situations. In addition, tolerance time would be limited to approximately six minutes for emergency egress if individuals were dehydrated and unacclimated.

CONCLUSIONS

The USARIEM Heat Strain Model has been shown to accurately predict rectal temperature responses for soldiers wearing different military clothing ensembles in the heat during both foreign and U.S. military scenarios. This model can be used to predict the expected physical work/rest cycle, the maximum safe physical work time, the estimated recovery time from maximal physical work, and the drinking water requirements given the clothing worn, the physical work intensity, the state of heat acclimation, the ambient environment, and the accepted heat casualty level. The utility of this same model has been demonstrated presently for three NASA scenarios involving the Launch and Entry Suit (LES). The LES (unventilated and ventilated) was modeled during pre-launch/launch, re-entry and landing, and emergency egress after re-entry and landing scenarios to primarily evaluate the effects of heat acclimation and hydration state. During the pre-launch/launch scenario, predicted final rectal temperatures were in close agreement with observed values indicating minimal heat strain; however, dehydrated-unacclimated individuals exhibited moderate levels of heat strain for this same scenario. During the re-entry and landing and emergency egress scenarios, the separate and combined effects of dehydration and lack of heat acclimation were even more pronounced in producing excessive heat strain. Crew member performance should be predicted for other NASA scenarios and space operations clothing ensembles to assess the potential for heat strain and further consider heat acclimation and hydration state.

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DISCLAIMER

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. Approved for public release; distribution is unlimited.

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Session L5: BIOMEDICAL RESEARCH AND DEVELOPMENT

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