

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY <i>(Leave blank)</i>	2. REPORT DATE May, 2005	3. REPORT TYPE AND DATES COVERED Proceedings Article	
4. TITLE AND SUBTITLE USE OF HUMIDEX TO SET THERMAL WORK LIMITS FOR EMERGENCY WORKERS IN PROTECTIVE CLOTHING.		5. FUNDING NUMBERS	
6. AUTHOR(S) W.R. Santee and R.F. Wallace		8. PERFORMING ORGANIZATION REPORT NUMBER M05-21	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Biophysics and Biomedical Modeling Division U.S. Army Research Institute of Environmental Medicine Building 42 - Kansas Street Natick, MA 01760		9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army Medical Research and Materiel Command Fort Detrick, MD 21702	
11. SUPPLEMENTARY NOTES			
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited		12b. DISTRIBUTION CODE	
13. ABSTRACT <i>(Maximum 200 words)</i> Humidex (HD) is a temperature-humidity index used to provide guidance concerning heat hazards based on normal activities and clothing. Personnel responding to security or NBC threats often wear body armor or protective clothing which can impose a greater heat burden. Our proposal was to use HD to provide short-term guidance for specialized clothing. Our Heat Strain Decision Aid model was used to calculate rectal temperature (Tre) values for combinations of temperature and humidity. Corresponding HD values were calculated using Ta, Tdp, and constants for other inputs. Activity levels were light (139 W m-2), medium (236 W m-2) and heavy (333 W m-2). Equations were calculated for the relationship between Tre and HD. The mean R2 value for 24 polynomial equations was 0.97. To evaluate the utility of the prediction, the difference between Tre predicted by the equation and the model was calculated. The average maximum difference was 0.71°C. There was a clear relationship between HD and predicted thermal strain, but differences increase as Tre increases, until some differences fall outside of acceptable levels. For general use, the upper limit of the relationship between HD and Tre could be used to set conservative guidelines for a given level of thermal strain (Tre) and activity, but for true emergencies, better guidance is necessary.			
14. SUBJECT TERMS heat index, humidex, thermal modeling.		15. NUMBER OF PAGES 3	
		16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT Unlimited

USE OF HUMIDEX TO SET THERMAL WORK LIMITS FOR EMERGENCY WORKERS IN PROTECTIVE CLOTHING

William R. Santee and Robert F. Wallace*

U.S. Army Research Institute of Environmental Medicine, Natick, Massachusetts 01760, USA

*corresponding author william.santee@na.amedd.army.mil

Introduction

Humidex (HD) is a temperature-humidity index (1) developed and used primarily in Canada. HD and other heat indices, usually obtained from weather services, are widely disseminated by media outlets to provide general guidance to the public concerning comfort and potential heat hazards (2). Although usually not specified, guidance for using heat indices is presumably based on normal activities and clothing. Unfortunately police, military and other emergency personnel, responding to security threats, overt violence, or nuclear, biological, or chemical (NBC) contamination, including accidents, must wear either protective body armor or NBC protective clothing which can impose a greater heat burden than most normal clothing. Although thermal models (3) provide more precise guidance, at present the public does not have ready access to those models, nor the requisite inputs for novel applications. Given the wide availability via the media and simplicity of heat indices, it would be useful to adapt civilian indices to emergency conditions.

In a prior study (3), we compared HD to the Heat Index (HI), the U.S. National Weather Service index for heat exposure, by using body core temperatures predicted with our Institute's Heat Stress Decision Aid (HSDA). Input limits, including a minimum value for T_a of 26.7°C, were based on guidance for HI. In that study, HI and HD were considered equivalent, but HD was preferred as it used dew-point temperature rather than relative humidity. An additional advantage of HD is that it is not limited by the 26.7°C threshold imposed on HI. Our proposal was to use HD to provide short-term (30-120 min) heat exposure guidance for emergency workers wearing specialized clothing.

Methods

HSDA (3) was used to calculate core temperatures (T_{core}) for different combinations of air temperature and relative humidity (RH). Corresponding HD values were calculated by estimating T_{dp} from T_a and RH, then using a simplified equation (4) to calculate HD from T_a and T_{dp} . Constant values were selected for other model inputs. Activity levels used were light ($139 \text{ W}\cdot\text{m}^{-2}$), medium ($236 \text{ W}\cdot\text{m}^{-2}$) and heavy ($333 \text{ W}\cdot\text{m}^{-2}$). When simulating body armor, insulation (R_c) and water vapor permeability (R_e) values were $0.27 \text{ m}^2\cdot\text{K}\cdot\text{W}^{-1}$ and $0.43 \text{ m}^2\cdot\text{Pa}\cdot\text{W}^{-1}$. For fully encapsulated NBC clothing (Level A PPE), $R_c = 0.27 \text{ m}^2\cdot\text{K}\cdot\text{W}^{-1}$ and $R_e = 0.41 \text{ m}^2\cdot\text{Pa}\cdot\text{W}^{-1}$. Other constants used in the simulation were subject height 180 cm, weight 80 kg, wind $2.5 \text{ m}\cdot\text{s}^{-1}$ and no solar radiation. A second dataset was generated for an indoor wind speed of 0.1 m/s. Second order polynomial equations were then calculated for the relationship between T_{core} and HD. To set an upper thermal limit for the derivation of the equations, the maximum value included in the data sets was $T_{core} \leq 42$. For our evaluation, 2861 sets of activities and environmental conditions were used.

Results

The mean R^2 value for all forty-eight polynomial equations comparing the HSDA simulations and the HD index was 0.97. Equations for 60 min model simulations are presented in Table 1. To evaluate the utility of these polynomial predictions, the difference between T_{core} predicted by the equation and the model was calculated. The upper limit for this evaluation was set at 41°C – when most individuals would be experiencing significant heat injuries. The average maximum difference was 0.36°C. As environmental conditions became more extreme, with a corresponding increase in thermal strain, the predicted T_{core} values become less precise due to increased variability in the model output (Figure 1), with predicted values in the upper range exceed $\pm 0.25^\circ\text{C}$. The data can be used to set HD thresholds for a given level of thermal strain (T_{core}) and activity. When predicted T_{core} approach 41°C, an under prediction of 0.25°C would not be

acceptable. If the maximum T_{core} value is $\geq 39.5^{\circ}\text{C}$ values, the deviation between the values predicted with the second order equations and the HSDA values are minimized. At 39.5°C most individuals will be heat casualties. Figure 2 compares T_{core} values calculated for the two wind conditions.

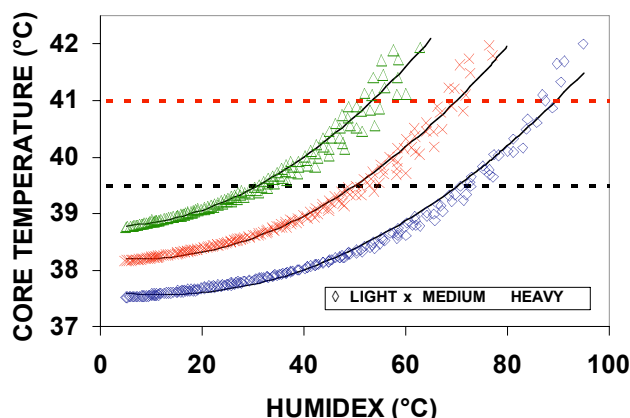


Figure 1. HSDA predicted core temperature at 60 min, wind= $2.5\text{ m}\cdot\text{s}^{-1}$ versus Humidex at 3 work intensities, Light = $139\text{ W}\cdot\text{m}^{-2}$ (\diamond), Medium = $236\text{ W}\cdot\text{m}^{-2}$ (\times) and Heavy = $333\text{ W}\cdot\text{m}^{-2}$ (Δ), in Chemical Protective (CP) clothing. Solid lines represent second order linear fit to HSDA values. Dashed lines at 39.5°C and 41°C represent critical T_{core} values for heat casualties.

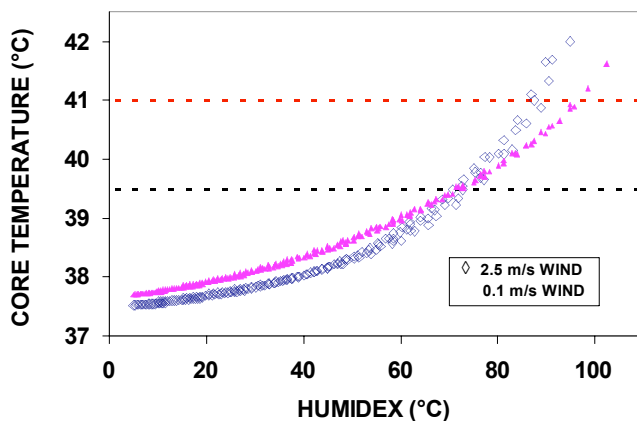


Figure 2. HSDA predicted core temperature at 60 min, wind= $0.1\text{ m}\cdot\text{s}^{-1}$ versus Humidex for Light ($139\text{ W}\cdot\text{m}^{-2}$) work in Chemical Protective (CP) clothing. Dashed lines at 39.5°C and 41°C represent critical T_{core} values for heat casualties.

Discussion

During an emergency operation, the maximum continuous exposure limit that can be sustained without incurring permanent thermal injury – or which allows a sustained work-rest cycle – is of critical importance. A complete discussion of those limits is beyond the scope of this paper. When the predicted T_{core} values approach critical upper thermal thresholds, there is less tolerance for variability. Deviations from T_{core} values predicted by the equations tend to increase in the upper, more extreme, ranges of HD, T_{core} and activity levels. When these upper limits ($T_{core} \geq 41^{\circ}\text{C}$) are approached, the importance of evaporative cooling, and thus humidity, in determining core temperatures, increases. When T_a is greater than skin temperature, greater clothing insulation, normally a disadvantage, may now afford protection from convective heat gain. The crossover of T_{core} values for 2.5 and $0.1\text{ m}\cdot\text{s}^{-1}$ wind speeds in Figure 2 indicates that the direction of

convective heat transfer has been reversed. Simple heat indices, which are based on a constant relationship between T_a and humidity, fail to adequately reflect the increasing importance of humidity. There is a distinct preference by government agencies and private industry to present thermal guidance in look-up or survival tables, but the necessity of generating multiple tables to compensate for each significant difference in parameters eventually becomes too unwieldy. Figure 1 clearly illustrates the problem of using HD or other heat indices during emergencies, when personnel may be pushed to perform beyond normal thermal limits.

Table 1. Predictive Equations for core temperature [$T_{core} = \beta_0 + \beta_1 \cdot HD + \beta_2 \cdot HD^2$ ($^{\circ}C$)] from Humidex (HD) for Body Armor (BA) and Chemical Protective (CP) Clothing for 2 wind speeds

GARMENT	WIND $m \cdot s^{-1}$	TIME MIN	ACTIVITY $W \cdot m^{-2}$	β_0 ND	β_1 ND	β_2 ND	R^2 ND
BA	2.5	60	139	37.67303	-0.02627	0.00075003	0.96
CP	2.5	60	139	37.64962	-0.01398	0.00057254	0.98
BA	2.5	60	236	38.19958	-0.02448	0.00088363	0.96
CP	2.5	60	236	38.23653	-0.01035	0.00071054	0.98
BA	2.5	60	333	38.69937	-0.02056	0.00096736	0.94
CP	2.5	60	333	38.77277	-0.00191	0.00081473	0.97
BA	0.1	60	139	37.75628	-0.00360	0.00041062	0.99
CP	0.1	60	139	37.73435	0.00268	0.0003148	0.99
BA	0.1	60	236	38.41555	-0.01711	0.00083443	0.99
CP	0.1	60	236	38.34544	0.00269	0.00054633	0.99
BA	0.1	60	333	38.87185	-0.01407	0.0010400	0.98
CP	0.1	60	333	38.95729	0.00682	0.00078602	0.99

Conclusion

There was a clear relationship between HD and predicted thermal strain. For less extreme thermal limits ($T_{core} \leq 39.5^{\circ}C$), the polynomial equations relating HD to T_{core} may be useful. However, at the upper limit for human tolerance ($T_{core} \geq 41^{\circ}C$) under extreme conditions, differences between the HSDA model and HD predictions for the polynomial equations are too large to provide adequate guidance for personnel management during emergency situations.

References

1. Masterton JM, Richardson FA. CLI 1-79. HUMIDEX: A method of quantifying human discomfort due to excessive heat and humidity. Downsview, Ontario: Environment Canada; 1979.
2. Gonzalez RR, McLellan TM, Withey WR, Chang SK, Pandolf KB. Heat strain models applicable for protective clothing systems: comparison of core temperature response. *J. Appl. Physiol.* 1997; 83(3):1017-1032.
3. Santee WR, Wallace RF. Comparison of weather service heat indices using a thermal model. *J. Thermal Biology* 2005; 30:65-72.
4. Meteorological Service of Canada. Weather: what is "humidex"? [online]. 2004 [cited 2005 Apr 6]. Available from: URL: http://weatheroffice.ec.gc.ca/mainmenu/faq_e.html

Disclaimer

Approved for public release; distribution is unlimited. The opinions or assertions contained herein are the private views of the author(s) and are not to be construed as official or reflecting the views of the Army or the Department of Defense. Any citations 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 services of these organizations.