HUMAN TOLERANCE TO WORK IN HEAT WITH SEMI-PERMEABLE CLOTHING: **VALIDATION OF** PREDICTIONS

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INTRODUCTION

Protective clothing is commonly used to prevent worker contamination with toxic industrial chemicals, pesticides, asbestos or radioactive substances. The military services use analogous clothing to protect personnel from agents which might be used in chemical warfare. Unfortunately, such clothing slows heat dissipation from the body by inhibiting both convective air exchange and the evaporation of sweat. The need to protect workers from undue heat stress has led to the wide use of Wet Bulb Globe Temperature (WBGT) as an index of environmental heat load. However, WBGT was developed for conventional clothing (shirt and trousers), and must be modified when protective ensembles are worn. The Texas Model developed by Dr. Wissler (1,2) was used in an earlier parametric analysis of work, air temperature and humidity for persons wearing USAF chemical defense (CD) clothing. Results indicated that WBGT tended to over-emphasize the effects of external humidity and sunlight, and that a better index of environmental heat load was the "Discomfort Index" where DI = 0.5 Tdb + 0.5 Twb. The main objectives of this study were: A) To compare the output of the Texas Model with the data obtained from human experiments with CD clothing, and B) To examine the validity of the DI as a predictor of environmental heat stress.

METHODS

DI values of 20, 30 and 33°C were selected and combined with various work loads to produce eight experimental conditions representing a range of heat stress levels (see table). The DI's of 20 and 30 were each produced by two combinations of Tdb and Twb to test the validity of the 50/50 weighting of these variables. In addition, these DI's were also used with different work loads to examine the interaction between external and internal heat load for persons wearing protective clothiig.

Condition	Discomfort Index	Work Load (Watts)	Tdb (°C)	Twb (°C)	Tbg (°C)	Vapor Pressure (Torr)	Predicted Tolerance Times (min)	Experimental Tolerance Times (min)
C.1	20	541	22	18	27	14.0	∞	97.4 ± 8.6
C.2	20	541	28	12	33	3.0	∞	103.3 ± 16.0
C.3	30	393	32	28	37	26.5	90	65.7 ± 5.5
C.4	30	541	32	28	37	26.5	49	52.2 ± 6.3
C.5	30	541	40	20	45	7.5	54	58.9 ± 5.0
C.6	30	738	32	28	37	26.5	33	34.5 ± 5.6
C.7	33	393	35	31	40	32.0	59	57.7 ± 3.8
C.8	33	738	35	31	40	32.0	29	32.1 ± 3.9

Nine healthy male subjects agreed to participate in this study and signed a statement of informed consent. The physical characteristics were (mean ± SD): age 35.1 ± 9.9 years; weight 73.9 ± 11.6 kg and height 174.3 ± 8.7 cm. Subject's peak aerobic capacity (VO2 Max) and corresponding heart rate (HRmax) were determined using a progressive treadmill test. The mean values were: V02 Max 45.5 ± 3.5 ml O_2/Kg body weight and HRmax 190 ± 12 bpm.

Subjects reported at 0800 h on each testing day and were instrumented with skin thermistors, a rectal probe and ECG electrodes. They wore tee-shirt, military fatigue shirt and trousers, and a chemical defense overgarment consisting of charcoal-impregnated jacket and trousers. Subjects wore their own tennis shoes, cotton gloves with rubber overgloves, a vapor-impermeable hood, and a chemical defense mask with the filter canister removed to reduce inspiratory resistance. The thermal insulation value of the outfit was about 2.4 clo. Each subject was tested under all eight experimental conditions in randomized order at a rate of 1-2 experiments per month. Subjects walked continuously on the treadmill at the pre-determined workload (low, moderate or high) until they reached a Tre=39.0°C or were unwilling to continue. Thermal tolerance time (TIT) was defined as the time required to reach Tre=39°C. Rectal and skin temperatures and HR were recorded at 30-s intervals during the experiments.

The eight experimental conditions were divided into subsets for analysis of the various factors affecting TTT. Comparison of conditions 1 vs. 2 and 4 vs. 5 allowed the evaluation of environmental heat load effects in order to assess the validity of the Discomfort Index. Conditions 3, 4 & 6 allowed examination of workload effects in a single hot, humid environment. Conditions 7 & 8 used low and high workloads in a hotter, humid environment.

Group means wen calculated for: TTT, final Tmsk, final HR, SR, ER, percent of sweat evaporated (E) **and** change in body weight (ΔBW). Group means for each variable were analyzed among the eight conditions using a two-way analysis of variance. When significant F values were found, a Duncan's Multiple Range Test was used to test for significant differences at the **p** <0.05 level.

RESULTS

Predicted TTTs obtained from the Texas Model were compared with the mean TTTs obtained during the experiments *(see* table). Overall, the model provided a good estimate of TIT. The model's predictions on TTT under conditions **4,5,6,7 & 8** were within **2** to 5 min of experimental TTTs. Exposure times (both predicted & experimental) under these conditions were limited to less than **1** h due to the seven net heat load that resulted from metabolic generation of beat and environmental heat **stress.** Under C.1 & **C.2** the model showed that with an elapsed time of **175 min** Tre **equilibrated ai 38.8°C,** resulting on an "infinite" TIT. Under C.3 the model predicted a TIT = 90 min, while the mean experimental TTT **was** 65.7 min. We can **speculate** ***that*** under **C.1** and **C.2** the model predicted an unimpaired sweat evaporation mechanism (through the clothing), that resulted in greater *skin* cooling **and** led the to the attainment of a thermal equilibrium. It is possible that during exposure to either **mild** ambient conditions (C.1 **& C.2)** *or* to **a** low workload **(C.3),** the model's estimates of heat transfer to the environment appear to be higher compared to what **can** be expected due to clothing **characteristics** (insulation, water vapor permeability). However, **this** error in overestimation of body cooling through the various clothing layers should not be attributed entirely to the model. ***An*** accurate measurement of beat transfer in complex clothing systems (multi-layer) is a very difficult **task.** This task **becomes** even more difficult when a human body has to be considered an integral element of such a determination. This **difficulty** is due in **part** to technical limitations in the static copper **manikin** generally used to determine the heat transfer **characteristics** of clothing. Limitations associated with the use **of** such a manikin include: **1)** Changes in sweat rates (local **and** total), evaporation rates and distribution patterns observed on humans are difficult to reproduce, **2)** Effects of body motion on heat transfer through the clothing cannot be reproduced. Therefore, static copper manikins measurements ***of*** clothing characteristics do not adequately represent heat exchange from the moving, sweating human body ***to*** the environment. However, **data** used in the specification of the thermal **transfer** characteristics of clothing for input to the **Model** came from static copper **manikins,** which explains some of the conflicting *result.?*previously **discussed** **This** problems with the static manikin have led to **the** development of a new generation of dynamic manikins intended to reproduce human movements and to simulate regional sweat **rates** and distribution patterns. Data from studies **using** this new type of manikins will be necessary to refine the representation of heat transfer though complex clothing systems in the Texas Model.

The validity of the Discomfort Index for the assessment of heat stress tolerance *can* be evaluated by looking ai the results from comparing **C.1** (humid) vs. **C.2** *(dry),* and **C.4** (humid) vs. **C.5** *(dry).* Experimental TTT's under these two set.? of conditions indicate that ambient heat stress under each set was physiologically equivalent Furthermore, C.6 and **C.8** had **similar**, but not the same DI's (30 and **33);** however, they also showed the same tolerance times. These results indicate that the Discomfort Index is useful ***for*** a general assessment of the physiological impact of exposure to ambient heat stress under *similar* clothing conditions. This index could be specially useful applied to conditions where individuals **are** required to wear semi-permeable or impermeable clothing. On the other hand, **this** index should **not** be used to **assess** heat stress while **wearing** different types ***of*** clothing, even if the 50-50 weighting ***of*** Tdb and Twb is the ***same*** for these conditions.

CONCLUSIONS

The model showed an adequate accuracy in predicting heat tolerance for highly stressful conditions, which represent various combinations of **work,** heat and humidity. The model had difficulties to predict the physiological impact ***of*** semi-permeable clothing during exposure to a low workload or to mild environments (humid & ***dry).*** Under these conditions, the model seemed to overestimate the body's capacity to hansfer heat to the environment through the clothing layers. In **this** respect, input **data** *€or* the model could be *improved* by incorporating new data on the heat transfer coefficients through different clothing layers using a dynamic **manikin.** In addition, this studies could **also** provide additional **data** on the **magnitude** of indirect (convective) vs. **direct** (conductive) skin cooling which results from the evaporation of sweat from the clothing. Our results also indicate **that** the use of the Discomfort Index **as** a predictor of heat stress is useful when individuals are wearing similar protective clothing that isolates them from the environment partially *or* completely.

REFERENCES

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