Prediction of WBGT-based clothing adjustment values from evaporative resistance

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Abstract: Wet bulb globe temperature (WBGT) index is used by many professionals in combination with metabolic rate and clothing adjustments to assess whether a heat stress exposure is sustainable. The progressive heat stress protocol is a systematic method to prescribe a clothing adjustment value (CAV) from human wear trials, and it also provides an estimate of apparent total evaporative resistance ($R_{e,T,a}$). It is clear that there is a direct relationship between the two descriptors of clothing thermal effects with diminishing increases in CAV at high $R_{e,T,a}$. There were data to suggest an interaction of CAV and $R_{e,T,a}$ with relative humidity at high evaporative resistance. Because human trials are expensive, manikin data can reduce the cost by considering the static total evaporative resistance ($R_{e,T,s}$). In fact, as the static evaporative resistance increases, the CAV increases in a similar fashion as $R_{e,T,a}$. While the results look promising that $R_{e,T,s}$ can predict CAV, some validation remains, especially for high evaporative resistance. The data only supports air velocities near 0.5 m/s.

Key words: Thermal stress, WBGT, Evaporative resistance, Clothing adjustment value, Clothing

Introduction

Occupational heat stress assessment considers a combination of environmental conditions, metabolic rate and clothing requirements. The ACGIH® Threshold Limit Values (TLV®) for heat stress and strain1, the NIOSH Recommended Exposure Limit (REL)2 and the ISO 74233 are examples of a wet bulb globe temperature (WBGT) based method. The threshold establishes a point at which most acclimatized, healthy adults can maintain thermal equilibrium for a long period of time; that is, it is a sustainable exposure4. In this way, the WBGT limit is suitable for screening heat stress exposures.

The idea of adjusting the heat stress threshold based on clothing has been around for 35 yr5. In its current form, a Clothing Adjustment (CAV) is added to the ambient WBGT to assign an effective WBGT that accounts for the added heat stress burden1, 3, 6–8. At first, the CAV was determined by professional judgment based on experience with the clothing ensemble. The method evolved with the use of a progressive heat stress protocol9. At University of South Florida (USF), the CAV was determined from wear trials using a progressive heat stress protocol6, 7, 10 where the difference in critical WBGTs between work clothes trials and the trials of the ensemble of interest was the CAV. While the method of developing CAVs appears to be robust8, the costs associated with the progressive protocol are high.

Working from manikins, the method to determine static total evaporative resistance ($R_{e,T,s}$) is well established...
through standards and practice. It is clear that the evaporative resistance is related to basic qualities of the fabrics (e.g., woven versus monolithic films, microporous versus vapor barrier, porosity) and the construction of the ensemble. A step toward accounting for the actual evaporative resistance due to convection of ambient air under the clothing was embodied in ISO 9920[11], which provided a method to calculate a resultant evaporative resistance ($R_{c,T,a}$) based on ambient air movement and walking speed[12]. The progressive heat stress protocol can also be used to estimate apparent total evaporative resistance ($R_{c,T,r}$)[13–15]. Because it is a wear trial, the progressive protocol can provide a real-world heat transfer coefficient for evaporative cooling. A gap in our knowledge is the relationship between $R_{c,T,r}$ and $R_{c,T,a}$.

Because of the wide variety of clothing and the costs associated with setting a CAV, it would be helpful to use manikin data rather than human trials to establish a CAV for a given clothing ensemble. The purpose of this paper is to (1) present the relationship between CAV and $R_{c,T,a}$ based on data from USF studies, and (2) relate CAV to $R_{c,T,a}$ based on a more limited set of pairs of manikin and wear trial data.

Methods

Progressive heat stress protocol

For the data reported here, the progressive heat stress protocol began with a comfortable environment that was easily sustainable. After thermal equilibrium was established, the temperature and humidity were slowly increased in 5-min intervals. That is, once the participant reached thermal equilibrium (no changes in $T_{re}$ and HR for at least 15 min), dry bulb temperature ($T_{db}$) was increased about 0.8 °C at a fixed relative humidity every 5 min. Rectal temperature ($T_{re}$), heart rate (HR), skin temperature ($T_{sk}$), and ambient conditions were recorded. Metabolic rate was estimated from the assessment of oxygen consumption via expired gases sampled every 30 min in a trial. The transition from a steady value for $T_{re}$ to values that were steadily increasing were marked as the critical WBGT (WBGT-crit)[4, 6, 7, 10].

The working assumption was that the person at the critical condition was near thermal equilibrium. The apparent total evaporative resistance ($R_{c,T,r}$) was estimated from ambient and physiological measurements[14]:

$$R_{c,T,r} = \frac{(P_{dd} - P_a)}{[H_{net} + (T_{db} - T_{sk})] / T_{re}},$$

and

$$H_{net} = M - W_{ex} - S + C_{res} - E_{res},$$

where

$P_{dd}$ = water vapor pressure saturated at $T_{dd}$, kPa
$P_a$ = ambient water vapor pressure, kPa
$T_{sk}$ = skin temperature, °C
$M$ = metabolic rate, W
$W_{ex}$ = external work, W
$S$ = estimated heat storage rate, W
$C_{res}$ = convective heat gain in the lungs, W
$E_{res}$ = evaporative cooling in the lungs, W.

Study designs

The data presented in this paper came from one of three different study designs. The first study was interested in the effects of relative humidity on CAV and $R_{c,T,a}$[7]. It used the progressive heat stress protocol to find the effect of relative humidity (RH) on WBGT-crit for five clothing ensembles that included work clothes, cotton coveralls, particle-barrier coveralls, microporous film (water-barrier) coveralls, and vapor-barrier coveralls. The non-woven coveralls were limited-use coverall designs without a hood or closures at the wrists and ankles. The metabolic rate was fixed at approximately 160 W m$^{-2}$ to approximate moderate work. The acclimatized subjects were exposed to three levels of RH: 20, 50 and 70%.

The second study design was interested in the effects of metabolic rate on CAV and $R_{c,T,a}$ at 50% RH[9]. The three levels of metabolic rates were 115, 175 and 250 W m$^{-2}$ to approximate light, moderate, and heavy work. The same five clothing ensembles were used.

The third study design was the general design used for most other studies to compare different ensembles using work clothes as a reference/control. These studies were at 50% RH and moderate metabolic rate (160 W m$^{-2}$). Ensembles included in these studies ranged from woven flame resistant (FR) coveralls[16] to prototype particle barrier coveralls[17] to various configurations of chemical protective clothing for demilitarization of chemical munitions[18] to hazmat suits.

CAV for any given study was based on the work clothes control for that study at 50% RH. In this way, the reference point was specific to the population and other possible confounders to determining CAV across studies. Within a study, the assigned CAV was the WBGT-crit for the ensemble/conditions minus the WBGT-crit for work clothes at 50% RH.

Results

Clothing adjustment and $R_{c,T,a}$

The dataset for the relationship between CAV and $R_{c,T,a}$ came from four published studies[6, 7, 18, 19] and one unpub-
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There were 37 combinations of ensemble and trial conditions (plus 4 controls) for the published studies and 8 more ensembles plus one control for the unpublished study. The mean CAV and \( R_{e,T,a} \) for each ensemble/trial pair is illustrated in Fig. 1 along with a log-normal curve through the data.

For five clothing ensembles, the expected interactions between \( R_{e,T,a} \) and metabolic rate and between \( R_{e,T,a} \) and relative humidity were examined. Figure 2 demonstrates the interaction between the computed value of \( R_{e,T,a} \) for the five clothing ensembles for metabolic rate (Fig. 2a) and for relative humidity (Fig. 2b).

**Fig. 1.** Relationship between \( R_{e,T,a} \) and CAV for 24 different clothing ensembles plus 5 work clothes controls with log-linear regression fit of the data.

**Fig. 2.** Relationship by clothing ensemble between \( R_{e,T,a} \) and (a) metabolic rate and (b) relative humidity.

**Fig. 3.** Relationships of \( R_{e,T,s} \) to (a) \( R_{e,T,a} \) and to (b) CAV.

USF received manikin data on \( R_{e,T,s} \) for nine ensembles as reported to us from two laboratories using ASTM F
Table 1. Values for CAV [°C] based on analysis of variance (ANOVA), logistic regression, and predicted from static total evaporative resistance

| Ensemble                        | CAV based ANOVA\(^{6,7}\) | CAV based on Logistic Regression\(^{6}\) | \(R_{e,T,a}\) \([\text{kPa m}^2/\text{W}]\) | Predicted CAV from \(R_{e,T,a}\) | Predicted CAV from \(R_{e,T,a}\) |
|--------------------------------|----------------------------|------------------------------------------|------------------------------------------|---------------------------------|---------------------------------|
| Woven Clothing (reference value) | 0                          | 0                                        | 0.013                                    | −0.2                           | 0.0312                          |
| Particle Barrier                | 0.7                        | 0.5                                      | 0.014                                    | 0.4                            | 0.0348                          |
| Water Barrier                   | 2.2                        | 2.0                                      | 0.018                                    | 2.3                            | 0.0412                          |
| Vapor Barrier (pooled)          | 7.7                        | 6.9                                      | 0.047                                    | 9.7                            | 0.0844                          |
| Vapor Barrier at 20% rh         | 11.4                       | 10.6                                     | 0.032                                    | 6.7                            |                                 |
| Vapor Barrier at 50% rh         | 7.8                        | 6.5                                      | 0.032                                    | 6.7                            |                                 |
| Vapor Barrier at 70% rh         | 5.4                        | 5.0                                      | 0.027                                    | 5.4                            |                                 |
| Unpublished Data at 50% rh      |                            |                                          |                                         |                                 |                                 |
| Level B Ensemble (THL = 900)    | 4.8                        | 0.028                                    | 5.7                                      | 0.048                          | 3.1                             |
| Level B Ensemble (THL = 800)    | 6.1                        | 0.037                                    | 7.8                                      | 0.056                          | 4.0                             |
| Level B Ensemble (THL = 500)    | 6.7                        | 0.036                                    | 7.6                                      | 0.073                          | 5.5                             |
| Level B Ensemble (THL = 200)    | 14.0                       | 0.077                                    | 13.5                                     | 0.486                          | 16.5                            |

2370 Standard Test Method for Measuring the Evaporative Resistance of Clothing Using a Sweating Manikin. Five of the ensembles were tested at USF under six conditions (3 levels of RH at moderate metabolic rate and 3 levels of metabolic rate at 50% RH); and the other four ensembles were tested under condition (moderate metabolic rate at 50% RH). Fig. 3 illustrates the relationships for \(R_{e,T,a}\) from \(R_{e,T,a}\) and for CAV from \(R_{e,T,a}\) for these data. A log-linear function was fitted to each set of data.

**Discussion**

**Clothing adjustment value and \(R_{e,T,a}\)**

There was a clear overall trend between CAV and \(R_{e,T,a}\). The log-linear fit was likely dominated by two factors. First, about half the data were for low evaporative resistances and tended to follow the line closely. Second there was one point at high evaporative resistance that may have influenced the overall trajectory (see Level B Ensemble (THL = 200) in Table 1). The line tended to underestimate the CAV at \(R_{e,T,a}\)’s between 0.03 and 0.05 kPa m\(^2\)/W. To examine the magnitude of the potential error, CAV data from USF based on analysis of variance\(^{6,7}\) and logistic regression\(^{6}\) are provided in Table 1. The table also includes \(R_{e,T,a}\) for vapor barrier which was divided into overall and three RH levels and for two test ensembles in a Level B configuration with negative pressure respirator.

Figure 2 illustrates the computed value of \(R_{e,T,a}\) for the five clothing ensembles against metabolic rate and relative humidity. As expected, there was generally a decrease in \(R_{e,T,a}\) as the metabolic rate increased, which was accomplished by increasing treadmill speed. The increased treadmill speed would increase both the relative air velocity and the pumping effect due to increased motion. The changes in \(R_{e,T,a}\) were relatively small for four of the clothing ensembles and of the magnitude that would be expected from ISO 9920\(^{11}\). For vapor barrier clothing, the magnitude of decrease with increasing metabolic rate was not expected. Havenith et al.\(^{20,21}\) relate this decrease to the moisture that condensates inside this type of clothing, which could create errors in the traditional methods of calculating evaporative resistance. This means that future models to predict some sort of real-world evaporative resistance may need to include an interaction term with fabric permeability. As reported by Bernard, et al.\(^{6}\), the CAV remained relatively constant for all four of the ensembles with changes in metabolic rate. That may suggest some robustness of the approach to assigning CAVs based on a moderate metabolic rate.

There was also a clear interaction between \(R_{e,T,a}\) and relative humidity, which was driven by the vapor-barrier ensemble. Relative humidity also had a strong effect on CAV for high evaporative resistance\(^{7}\). The effect was expected for CAV because of the relatively small contribution of evaporative cooling with vapor-barrier clothing. That is, WBGT was not a good tool to predict heat stress level for ensembles with low evaporative cooling. But decreasing values for vapor-barrier \(R_{e,T,a}\) was not expected. The underlying assumption was that evaporative resistance was independent of water vapor pressure. This assumption may not hold up for ensembles with high apparent total evaporative resistance due to complex heat exchange mechanisms (e.g., heat pipe effect)\(^{20,21}\). Again, considering an interaction with relative humidity (and presumably water vapor pressure) may better explain real-world heat transfer while wearing clothing with low permeability.
unaccounted for and unknown effects add to the current uncertainty in the relationship between CAV and R_{e,T,a}.

In summary, there was a relationship between CAV and R_{e,T,a}. The most interesting feature was the log-linear relationship with diminishing effects on CAV with increasing evaporative resistance. The overall finding of a positive trend was expected and was somewhat trivial because the same protocol and end point was used to arrive at both parameters to express an effect of permeability. More interesting and in need of further investigation were the interactions with metabolic rate and humidity driven by vapor-barrier coveralls. The value of the relationship between CAV and R_{e,T,a} will come with a link of R_{e,T,a} to R_{e,T,r}.

\textit{Clothing adjustment value and R_{e,T,s}}

An obvious question was whether manikin data can be used to predict and prescribe a CAV. This can be approached by considering the static values of total evaporative resistance (R_{e,T,s}) from a manikin. A logical next step was to determine R_{e,T,r} from ISO9920 or similar approach. The working assumption was that R_{e,T,r} and R_{e,T,a} were tightly related. There was such a narrow range of conditions among the USF data compared to the range implicit in ISO9920 that the bridge from R_{e,T,r} and R_{e,T,a} cannot be evaluated. For this reason, the leap from static manikin data to R_{e,T,a} and CAV was made in this paper as a starting point until more data are available.

Using manikin data on R_{e,T,s} for seven ensembles, Fig. 3 illustrates the relationships of R_{e,T,a} from R_{e,T,s} and to CAV from R_{e,T,a} for these data. The characteristic shape of the log-normal fit was similar to R_{e,T,s}. That is, there was a diminishing effect with higher evaporative resistance. The shape, however, was largely driven by one point that was far from the other data. In Fig. 3a, the very high vapor resistance ensemble was a totally encapsulating suit with negative pressure respirator (Level B configuration) with an evaporative resistance that was about five times higher than the next highest ensemble. This made the extrapolation of the curve tenuous. In Fig. 3b, the other outlier at a R_{e,T,a} value of 0.084 was a vapor-barrier coverall without a hood at 20% RH. This condition also represented the highest observed R_{e,T,a} and CAV. Again, this introduces the concern about the interaction of humidity and permeability.

Manikin data on total evaporative resistance can provide a reliable prediction of CAV for ensembles with low to moderate R_{e,T,a} (<0.05 kPa m^2/W). For the range of ensembles included in the sample this would be single layers of woven or non-woven coveralls (specifically particle-barrier fabrics) over modesty clothing. As the R_{e,T,a} increases to higher values, there is some risk of underestimating the CAV. Table 1 also includes R_{e,T,a} for six ensembles (woven clothing combined work clothes and cotton coveralls) and an estimated CAV (= 5.70 ln(R_{e,T,a}) + 20.2). Again, the agreement between CAVs was reasonable with the same caveat about lack of validation. More data for R_{e,T,a} values above 0.015 kPa m^2/W is essential because the shape of the curve was dictated by one point.

A clear limitation of this study was the range of air velocities. All of the studies took place in a chamber with air velocity of 0.5 m/s.

\textit{Conclusions}

The principal purpose of this paper was to map a course from Clothing Adjustment Values (CAV) used in WBGT-based exposure assessment to static total evaporative resistance data from manikins. While there were not enough data to finish the journey, there were some considerations for future studies that will improve the use of manikin data to represent real-world heat exchange.

At the most practical level, static total evaporative resistance can predict CAV for single layers of woven and some non-woven fabrics with adequate air permeability. It appears that clothing with R_{e,T,a} less than 0.015 kPa m^2/W can be used to predict and prescribe a CAV.

The other findings pointed to further areas of research. It appeared that ensembles with high total evaporative resistance may be associated with interactions with metabolic (likely as a surrogate for a pumping factor) and with water vapor pressure. At the least, vapor-barrier clothing, even in relatively unrestrictive use as coveralls, falls out of the limits for current methods of predicting real-world evaporative resistance from mankin data. In a broader scope, models to explain the interaction of high evaporative resistance with the environment should be explored and validated.

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Disclaimer

The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health. Mention of company names or products does not constitute endorsement by NIOSH.

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