# Prediction of WBGT-based clothing adjustment values from evaporative resistance

**Thomas E. BERNARD[1]\*, Candi D. ASHLEY[2], Ximena P. GARZON[1],
Jung-Hyun KIM[3] and Aitor COCA[3]**

[1]College of Public Health, University of South Florida, USA
[2]College of Education, University of South Florida, USA
[3]National Institute for Occupational Safety and Health, National Personal Protective Technology Laboratory, USA

**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 strain[1], the NIOSH Recommended Exposure Limit (REL)[2] and the ISO 7423[3] 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 exposure[4]. 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 yr[5]. 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 burden[1, 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 protocol[9]. At University of South Florida (USF), the CAV was determined from wear trials using a progressive heat stress protocol[6, 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 robust[8], 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

*\*To whom correspondence should be addressed.
E-mail: tbernard@health.usf.edu*

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 ($R_{e,T,r}$) based on ambient air movement and walking speed[12]. The progressive heat stress protocol can also be used to estimate apparent total evaporative resistance ($R_{e,T,a}$)[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 $R_{e,T,r}$ and $R_{e,T,a}$.

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 $R_{e,T,a}$ based on data from USF studies, and (2) relate CAV to $R_{e,T,s}$ 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 ($R_{e,T,a}$) was estimated from ambient and physiological measurements[14]:

$R_{e,T,a} = (P_{sk} - P_a) / [H_{net} + (T_{db} - T_{sk}) / I_{T,r}]$, and

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

where

$P_{sk}$ = water vapor pressure saturated at $T_{sk}$, kPa

$P_a$ = ambient water vapor pressure, kPa,

$T_{sk}$ = skin temperature, °C

M = metabolic rate, W

$W_{ext}$ = 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 $R_{e,T,a}$[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 $R_{e,T,a}$ at 50% RH[6]. 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 $R_{e,T,a}$

The dataset for the relationship between CAV and $R_{e,T,a}$ came from four published studies[6, 7, 18, 19] and one unpub-
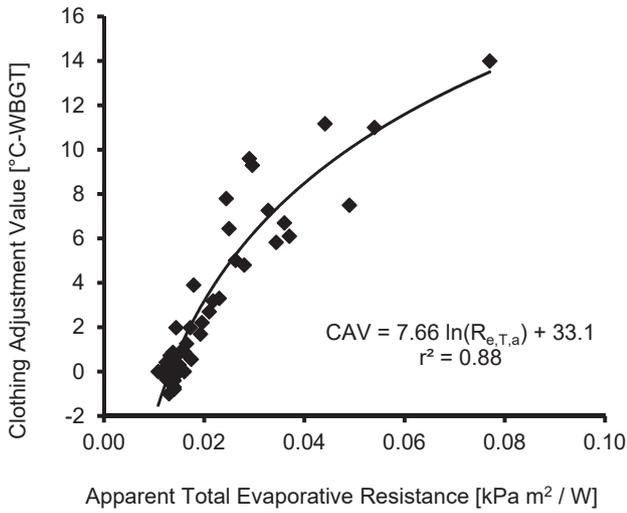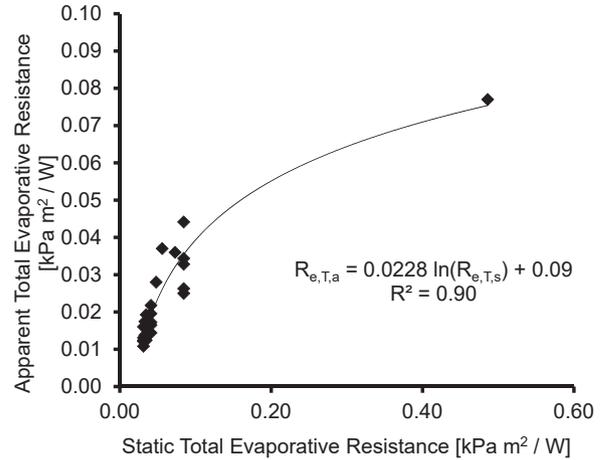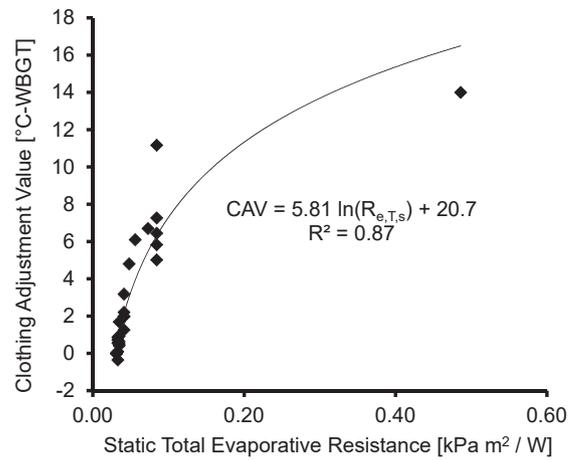
Fig. 1.   Relationship between $R_{e,T,a}$ and CAV for 24 different clothing ensembles plus 5 work clothes controls with log-linear regression fit of the data.
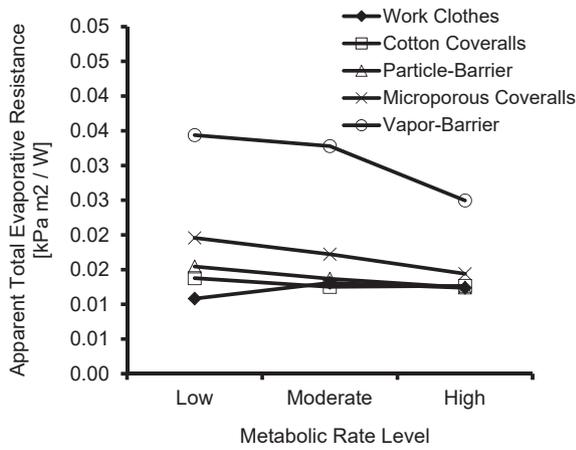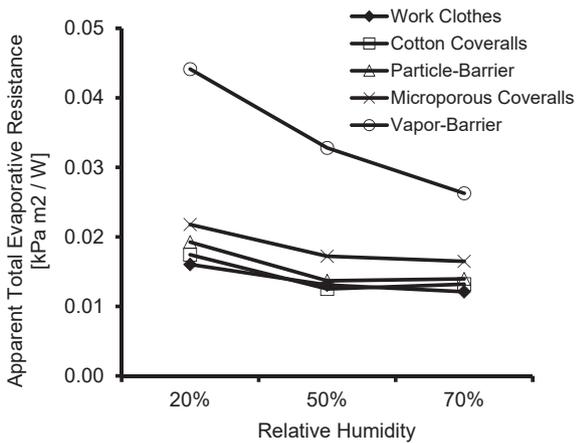


a



b

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



a



b

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

lished study. 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).

*Clothing adjustment value and $R_{e,T,s}$*

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[8] | $R_{e,T,a}$ [kPa m²/W] | Predicted CAV from $R_{e,T,a}$ | $R_{e,T,s}$ [kPa m²/W] | Predicted CAV from $R_{e,T,s}$ |
|---|---|---|---|---|---|---|
| Woven Clothing (reference value) | 0 | 0 | 0.013 | −0.2 | 0.0312 | 0.6 |
| Particle Barrier | 0.7 | 0.5 | 0.014 | 0.4 | 0.0348 | 1.2 |
| Water Barrier | 2.2 | 2.0 | 0.018 | 2.3 | 0.0412 | 2.2 |
| Vapor Barrier (pooled) | 7.7 | 6.9 | | | 0.0844 | 6.3 |
| Vapor Barrier at 20% rh | 11.4 | 10.6 | 0.047 | 9.7 | | |
| 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 on condition (moderate metabolic rate at 50% RH). Fig. 3 illustrates the relationships for $R_{e,T,a}$ from $R_{e,T,s}$ and for CAV from $R_{e,T,s}$ 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 m²/W. To examine the magnitude of the potential error, CAV data from USF based on analysis of variance[6, 7] and logistic regression[8] 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. The

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 $R_{e,T,r}$.

*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 $R_{e,T,s}$ for these data. The characteristic shape of the log-normal fit was similar to $R_{e,T,a}$. 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 capsuling 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 $R_{e,T,s}$ value of 0.084 was a vapor-barrier coverall without a hood at 20% RH. This condition also represented the highest observed $R_{e,T,a}$[14] and CAV[7]. 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 $R_{e,T,s}$ (<0.05 kPa m²/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 $R_{e,T,s}$ increases to higher values, there is some risk of underestimating the CAV. Table 1 also includes $R_{e,T,s}$ for six ensembles (woven clothing combined work clothes and cotton coveralls) and an estimated CAV ($=5.70 \ln(R_{e,T,s})+20.2$). Again, the agreement between CAVs was reasonable with the same caveat about lack of validation. More data for $R_{e,T,s}$ values above 0.015 kPa m²/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.

## 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 $R_{e,T,s}$ less than 0.015 kPa m²/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 manikin data. In a broader scope, models to explain the interaction of high evaporative resistance with the environment should be explored and validated.

## Acknowledgments

recognize and thank the many laboratory assistants and trial participants who made this paper possible.

## 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.

## References

1) ACGIH® (2016) Heat Stress and Strain TLV®, in Threshold Limit Values and Biological Exposure Indices for Chemical Substances and Physical AgentsACGIH®: Cincinnati, OH.

2) Jacklitsch B, Williams WJ, Musolin K, Coca A, Kim J-H, Turner N NIOSH criteria for a recommended standard: occupational exposure to heat and hot environments. NIOSH.

3) International Organization for Standardization (ISO) (1989) ISO7243: Hot environments—Estimation of the heat stress on working man, based on the WBGT-index (wet bulb globe temperature)Geneva: ISO.

4) Garzon-Villalba XP, Wu Y, Ashley CD, Bernard TE (2017) Ability to Discriminate Between Sustainable and Unsustainable Heat Stress Exposures-Part 1: WBGT Exposure Limits. Annals of work exposures and health. [CrossRef]

5) Ramsey JD (1978) Abbreviated guidelines for heat stress exposure. Am Ind Hyg Assoc J **39**, 491–5. [Medline] [CrossRef]

6) Bernard TE, Caravello V, Schwartz SW, Ashley CD (2008) WBGT clothing adjustment factors for four clothing ensembles and the effects of metabolic demands. J Occup Environ Hyg **5**, 1–5, quiz d21–3. [Medline] [CrossRef]

7) Bernard TE, Luecke CL, Schwartz SW, Kirkland KS, Ashley CD (2005) WBGT clothing adjustments for four clothing ensembles under three relative humidity levels. J Occup Environ Hyg **2**, 251–6. [Medline] [CrossRef]

8) Garzón-Villalba XP, Wu Y, Ashley CD, Bernard TE (2017) Heat Stress Risk Profiles for Three Non-Woven Coveralls. J Occup Environ Hyg (doi:10.1080/15459624.2017.1388514). [CrossRef]

9) Kenney WL (1987) WBGT adjustments for protective clothing. Am Ind Hyg Assoc J **48**, 576–7.

10) O'Connor DJ, Bernard TE (1999) Continuing the search for WBGT clothing adjustment factors. Appl Occup Environ Hyg **14**, 119–25. [Medline] [CrossRef]

11) International Organization for Standardization (2007) ISO 9920: Ergonomics of the thermal environment—Estimation of thermal insulation and water vapour resistance of a clothing ensembleGeneva: ISO.

12) Havenith G, Holmér I, den Hartog EA, Parsons KC (1999) Clothing evaporative heat resistance—proposal for improved representation in standards and models. Ann Occup Hyg **43**, 339–46. [Medline] [CrossRef]

13) Barker DW, Kini S, Bernard TE (1999) Thermal characteristics of clothing ensembles for use in heat stress analysis. Am Ind Hyg Assoc J **60**, 32–7. [Medline] [CrossRef]

14) Caravello V, McCullough EA, Ashley CD, Bernard TE (2008) Apparent evaporative resistance at critical conditions for five clothing ensembles. Eur J Appl Physiol **104**, 361–7. [Medline] [CrossRef]

15) Kenney WL, Mikita DJ, Havenith G, Puhl SM, Crosby P (1993) Simultaneous derivation of clothing-specific heat exchange coefficients. Med Sci Sports Exerc **25**, 283–9. [Medline] [CrossRef]

16) Ashley CD, Bernard TE (2008) Effects of hoods and flame-retardant fabrics on WBGT clothing adjustment factors. J Occup Environ Hyg **5**, 59–62. [Medline] [CrossRef]

17) Bernard T, Ashley C, Trentacosta J, Kapur V, Tew S (2010) Critical heat stress evaluation of clothing ensembles with different levels of porosity. Ergonomics **53**, 1048–58. [Medline] [CrossRef]

18) Fletcher OM, Guerrina R, Ashley CD, Bernard TE (2014) Heat stress evaluation of two-layer chemical demilitarization ensembles with a full face negative pressure respirator. Ind Health **52**, 304–12. [Medline] [CrossRef]

19) Gonzalez NW, Bernard TE, Carroll NL, Bryner MA, Zeigler JP (2006) Maximum sustainable work rate for five protective clothing ensembles with respect to moisture vapor transmission rate and air permeability. J Occup Environ Hyg **3**, 80–6. [Medline] [CrossRef]

20) Havenith G, Brode P, den Hartog E, Kuklane K, Holmer I, Rossi RM, Richards M, Farnworth B, Wang X (2013) Evaporative cooling: effective latent heat of evaporation in relation to evaporation distance from the skin. J Appl Physiol (Bethesda, Md.: 1985), **114**, 778–85. [Medline] [CrossRef]

21) Havenith G, Richards MG, Wang X, Brode P, Candas V, den Hartog E, Holmer I, Kuklane K, Meinander H, Nocker W (2008) Apparent latent heat of evaporation from clothing: attenuation and "heat pipe" effects. J Appl Physiol (Bethesda, Md.: 1985), **104**, 142–9. [Medline] [CrossRef]