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Physiological responses to changes in relative humidity under thermally neutral, warm and hot conditions ☆

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ABSTRACT

Four hypothetical thermophysiological responses to changes in relative humidity (Rh) under thermally neutral, warm, and hot conditions were proposed for a person at rest. Under thermally neutral and warm conditions, the first hypothetical response to an increase in Rh was a decrease in mean skin temperature ($\bar{T}_{sk}$) due to increase in mean evaporation rate ($\bar{E}_{sk}$), and the second hypothetical response to a decrease in Rh was a decrease, an increase, or no change in $\bar{T}_{sk}$, depending on changes in the $\bar{E}_{sk}$. Under hot conditions, the third hypothetical response to an increase in the Rh was an increase in $\bar{T}_{sk}$ or decrease in $\bar{T}_{sk}$ upon decrease in the Rh due to changes in $\bar{E}_{sk}$, and the forth hypothetical response to an increase in Rh was an increase in $\bar{T}_{sk}$ due to increase in the peripheral blood flow rate (S_kBF). To test these hypotheses, the $\bar{T}_{sk}$ and $\bar{E}_{sk}$ of four young male volunteers were measured at 28 °C, 30 °C, or 32 °C while the Rh was maintained at 40% or 80% Rh for 60 min after 20 min exposure at 60% Rh (control condition). In a second experiment, the $\bar{T}_{sk}$, $\bar{E}_{sk}$, and S_kBF of five young male volunteers were measured at 34 °C-40% Rh or 36 °C-40% Rh, or 34 °C-70% Rh or 36 °C-70% Rh for 60 min after 20 min exposure at 28 °C-60% Rh (control condition). The first hypothesis was partly supported by the findings that the $\bar{T}_{sk}$ was lower than the control values at 28 °C-80% Rh and the $\bar{E}_{sk}$ was higher than the control values at 80% Rh at any tested temperature. The second hypothesis was partly supported by the findings that the $\bar{T}_{sk}$ was lower than the control values at 28 °C-40% Rh, and there were small changes in both $\bar{T}_{sk}$ and $\bar{E}_{sk}$ at 30 °C-40% Rh. The third and fourth hypotheses were supported by the findings that the $\bar{T}_{sk}$ at 36 °C-70% Rh was significantly higher ($p < 0.01$) than at 36 °C-40% Rh, the $\bar{E}_{sk}$ was significantly higher ($p < 0.01$) at 70% Rh than at 40% Rh, and SkBF was positively correlated with $\bar{T}_{sk}$.

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1. Introduction

According to the fundamentals of thermophysiology (Hardy, 1970; Hensel, 1981), the human skin contains receptors for heat and cold. Temperature receptors in the skin transmit signals through afferent nerves to the hypothalamus, and the perception of heat or cold occurs. In response to the signals sent to the hypothalamus, effectors may trigger vasoconstriction and/or shivering for cold signals, and vasodilation and/or sweating for heat signals.

In contrast to the physiological responses to cold and heat, the human body may not respond directly to changes in relative humidity (Rh), because there are no specific receptors for changes in Rh. However, it responds indirectly to changes in the Rh, which causes imbalance in the exchange between the body and environment. Therefore, the thermophysiological response to changes in Rh has long been a research target among the physiologists and engineers who focus on evaluating thermal environments. Studies (Berglund and Gonzalez, 1977; Brebner et al., 1958; Hall, 1963; Hale et al., 1958; Klemm and Hall, 1972) have revealed psychological and physiological responses to changes in Rh and other environmental factors. For example, Berglund and Gonzalez (1977) carried out a human experiment where the ambient temperature was maintained at the level of the mean skin temperature ($\bar{T}_{sk}$), i.e., in the range of 34–36 °C; and the vapor pressure (P) was increased stepwise from 10 to 40 Torr. The results showed that the $\bar{T}_{sk}$, heart rate, and metabolic heat production were unaffected by humidity until P reached the critical P, which is the point when the entire skin is completely wetted with sweat. Brebner et al. (1958) also demonstrated that the $\bar{T}_{sk}$, body temperature, and perspiration rate of nude resting subjects were unaffected by humidity until P reached the critical P. Hale et al. (1958) focused on the effect of barometric and vapor pressure on

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evaporation of sweat, and reported that body weight loss in a sweat-free subject was inversely dependent on both water vapor pressure and barometric pressure. Thus, they confirmed that insensible weight loss was dependent on physical factors. Those studies focused on the maximum sweat evaporation associated with the critical P under thermal conditions, where intense sweating was induced. However, the underlying mechanisms related to the response to changes in Rh under thermally neutral and warm conditions have not yet been fully investigated.

Based on measurements of insensible water loss from small areas of human skin, Goodman and Wolf (1969) proposed a revised model and additional theoretical considerations on the mechanism of water loss from human skin in response to changes in Rh. Under thermally neutral and cool or warm conditions, water loss though evaporation takes place mainly through molecular diffusion combined with eccrine sweat gland secretion, which is dependent on the diameter of sweat glands. According to this model, sweating from eccrine sweat glands will prevail as sweat flows out and spreads over the skin. In the process, therefore, the mechanism of water loss from human skin becomes complicated.

Because humans appear to be able to detect daily changes in the Rh, as reflected by the common expressions "hot and humid" and "cool and dry", physiological responses to changes in Rh under thermally neutral and cool or warm conditions probably occur. The purpose of this study was to determine the mechanism of thermophysiological responses to changes in Rh by testing four hypotheses.

2. Theoretical background

The amount of heat exchange between the skin and environment is defined by the following equation.

$$H_{sk} = H_{C+R} + \bar{E}_{sk} = h_a \times (\bar{T}_{sk} - t_a) + h_e \times (\bar{P}_{sk} - P_a) \quad (1)$$

where H_{sk}=the amount of heat exchange between the skin and environment (W/m^2), H_{C+R}=the amount of sensible heat exchange (W/m^2), h_a=total heat transfer coefficient (W/m^2 K), t_a=ambient temperature (°C), h_e=evaporative heat transfer coefficient (W/m^2. P_a), $\bar{P}_{sk}$=mean vapor pressure at the skin (P_a), P_a=ambient vapor pressure (P_a).

Since dermatological studies (Blank, 1952, 1953; Brebner et al., 1956) reported that skin permeability to water changes with changes in the water content of the stratum corneum, the P_{sk} will change after Rh changes. Therefore, $\bar{E}_{sk}$ is changed to the sum of the initial $\bar{E}_{sk} \mp \Delta\bar{E}_{sk}$. Assuming that H_{sk} remains unchanged upon a change in Rh because a change in Rh may not induce a thermophysiological response driven by the central nervous system, the H_{C+R} will change to the sum of the initial $H_{C+R} \pm \Delta H_{C+R}$ to compensate for $\Delta\bar{E}_{sk}$. The ΔH_{C+R} will lead to a change in $\bar{T}_{sk}$ because of lack of change in both h_a and t_a. Blank (1952) reported that the stratum corneum may dry out at higher temperatures. This implies that the $\bar{P}_{sk}$ is changed with the $\bar{T}_{sk}$. These sequential responses can be described by the following equation:

$$\begin{aligned} H_{sk} &= (H_{C+R} \pm \Delta H_{C+R}) + (\bar{E}_{sk} \mp \Delta\bar{E}_{sk}) \\ &= h_a \times \{\bar{T}_{sk} \pm \Delta\bar{T}_{sk} - t_a)\} + h_e \times (\bar{P}_{sk} \mp \Delta\bar{P}_{sk} - P_a \mp \Delta P_a) \\ &= \text{constant} \end{aligned} \quad (2)$$

Since the $\bar{E}_{sk}$ changes again because of change in $\bar{P}_{sk}$, the response will start again from the beginning. The initial $\Delta\bar{T}_{sk}$ and $\Delta\bar{E}_{sk}$ may be the largest values but become smaller as the cycle continues. Finally, $\bar{T}_{sk}$ and $\bar{E}_{sk}$ are stabilized at new values different from the initial ones.

3. Hypotheses

3.1. First hypothesis: changes in $\bar{T}_{sk}$ and $\bar{E}_{sk}$ after an increase in Rh under thermally neutral and warm conditions

When the Rh increases, skin permeability to water increases with an increase in the water content of the stratum corneum, which enhances the diffusion of water; and the $\bar{P}_{sk}$ increases. Along with this change, the difference between $\bar{P}_{sk}$ and P_a (ΔP) increases and results in an increased $\bar{E}_{sk}$. As described earlier, $\bar{T}_{sk}$ should decrease based on the assumption of consistent H_{sk}. The decrease in $\bar{T}_{sk}$ leads to a decreased H_{C+R}. Finally, $\bar{T}_{sk}$ may be stabilized at a slightly lower temperature than it was before the increase in Rh. Thus, it can be hypothesized that an increase in Rh leads to a decrease in $\bar{T}_{sk}$ with an increase in $\bar{E}_{sk}$ when the Rh increases.

Along with this assumption, change in the value for skin wettedness (w_{srw}) can also be predicted. An increased Rh leads to increased $\bar{E}_{sk}$, whereas the maximum evaporative capacity (E_{max}) decreases because of decreased saturated vapor pressure at the skin, which is solely determined by $\bar{T}_{sk}$. Therefore, w_{srw} should increase with an increase in the Rh.

3.2. Second hypothesis: changes in $\bar{T}_{sk}$ and $\bar{E}_{sk}$ after a decrease in Rh under thermally neutral and warm conditions

When the Rh decreases, the prediction of ΔP may be complicated because ΔP depends on the condition of underlying tissues. Skin permeability and the rate of peripheral blood flow are involved in determining the ΔP.

There are three possible outcomes. In the first case, $\bar{P}_{sk}$ may decrease due to decreased permeability of the skin to water vapor. With a decrease in ΔP, H_{C+R} increases together with a decrease in $\bar{E}_{sk}$. Therefore, $\bar{T}_{sk}$ may be stabilized at a slightly higher temperature than the initial value. In the second case, the ΔP is assumed to increase. H_{C+R} then decreases together with an increase in $\bar{E}_{sk}$. Therefore $\bar{T}_{sk}$ may decrease until H_{sk} becomes stabilized, as described earlier. The $\bar{T}_{sk}$ will be then stabilized at the new value, which is slightly lower than the initial value. In association with these predictions, the w_{srw} is expected to decrease in the first case and increase in the second case. The third case is simple. No change in ΔP results in no change in $\bar{T}_{sk}$ and w_{srw}.

3.3. Third hypothesis: changes in $\bar{T}_{sk}$ and $\bar{E}_{sk}$ after change in Rh under hot conditions

When Rh increases, $\bar{T}_{sk}$ may increase because of an increase in the rate of peripheral blood flow, which can be represented by the rate of skin blood flow, as (S_kBF). Therefore the $\bar{T}_{sk}$ should increase. However, when Rh decreases, the $\bar{T}_{sk}$ should decrease.

The $\bar{E}_{sk}$ may depend on both the diffusion of water through the layers of the skin and evaporation of sweat from the skin. The permeability of the stratum corneum to water vapor increases with an increase in the Rh, and therefore $\bar{P}_{sk}$ is expected to increase with an increase in P_a. However, predicting change in the ΔP after the Rh increases is difficult. Since Horikoshi et al. (1987) demonstrated that E_{sk} increased upon an increase in Rh under warm and hot conditions, where T_a ranged from 32 °C to 36 °C, $\bar{E}_{sk}$ should increase along with an increase in the ΔP. On the other hand, when Rh decreases, the $\bar{E}_{sk}$ should decrease along with a decrease in $\bar{T}_{sk}$.

Changes in w_{srw} values under hot conditions can be predicted along with these predictions. The ΔP increases with an increase in the Rh, resulting in an increase in E_{max}. Since the amount of water diffusing through the stratum corneum is linearly correlated with the ΔP, the w_{srw} will increase with an increase in Rh.

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