Physiological and Subjective Responses to Low Relative Humidity

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Abstract In order to investigate the influence of low relative humidity, we measured saccharin clearance time (SCT), frequency of blinking, heart rate (HR), blood pressure, hydration state of skin, transepidermal water loss (TEWL), recovery sebum level and skin temperature as physiological responses. We asked subjects to judge thermal, dryness and comfort sensations as subjective responses using a rating scale. Sixteen non-smoking healthy male students were selected. The pre-room conditions were maintained at an air temperature (Ta) of 25°C and a relative humidity (RH) of 50%. The test room conditions were adjusted to provide a Ta of 25°C and RH levels of 10%, 30% and 50%.

RH had no effect on the activity of the sebaceous gland and on cardiovascular reactions like blood pressure and HR. However, it was obvious that low RH affects SCT, the dryness of the ocular mucosa and the stratum corneum of the skin and causes a decrease in mean skin temperature. Under 30% RH, the eyes and skin become dry, and under 10% RH the nasal mucous membrane becomes dry as well as the eyes and skin, and the mean skin temperature decreases. These findings suggested that to avoid dryness of the eyes and skin, it is necessary to maintain an RH greater than 30%, and to avoid dryness of the nasal mucous membrane, it is necessary to maintain an RH greater than 10%. Subjects felt cold immediately after a change in RH while they had only a slight perception of dryness at the change of humidity. *J Physiol Anthropol* 25(1): 7–14, 2006 <http://www.jstage.jst.go.jp/browse/jpa2>
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Introduction

In winter, indoor dryness due to heating causes many health problems. There are several regulations regarding the lowest limit for indoor humidity. In Japan, the “Law for Maintenance

of Sanitation in Buildings” states that the indoor relative humidity (RH) should be kept at more than 40% (Ogawa, 1999), but several surveys reported that it is difficult to maintain this level (Koshimizu et al., 2002). In offices in winter, under a low RH environment, the skin becomes dry and itchy, and skin problems occur (Gaul et al., 1952). When the mucous membrane of the nose and throat becomes dry (Rankin, 1998), bacteria and virus can easily infect the human body. Moreover, the survival rates of the influenza virus increase under low RH (Harper, 1961, 1963), and the virus becomes very active in the air, thus causing influenza, common colds, and other respiratory infections (Satsuta et al., 1985). Therefore, in our daily lives, it is important to maintain the optimum indoor humidity level as well as the optimum room temperature.

The amount of inspired air is estimated at about 10,000–20,000 liters per day. Because so much air is inspired, the respiratory tract can be easily infiltrated by foreign bodies. The particles in the air adhere to the nasal mucous membrane, from which they can be removed by nasal blowing or expectorated as sputum after passing through the nasopharynx by means of mucociliary movement. Sometimes they pass through the oropharynx, laryngopharynx, and esophagus to the stomach and are digested. This mucociliary clearance is the fundamental self-defense mechanism by which the dust, bacteria and viruses in the inspired air are filtered in order to maintain health. The factors influencing the mucociliary function are high or low temperature and dry air. Many studies have been carried out to investigate the effect of low RH on the human body, including the effect on skin dryness (Yoshikuni et al., 1985) and dryness of the eyes (Eng et al., 1982; Nilsson et al., 1986; Flynn et al., 1988), while very few studies on the activity of the upper respiratory tract mucous membrane have been conducted.

Therefore, this study aims to investigate how low RH caused by heating influences the human body during winter by measuring the mucociliary activity as well as the functions of the eyes and skin and the thermal, dryness and comfort sensations under RH of 50%, 30% and 10% at the same

Table 1 Physical characteristics of subjects ($n=16$) Values are Mean $\pm$ S.D.

Age	Height (cm)	Body weight (kg)	BMI
22.6 $\pm$ 2.7	174.5 $\pm$ 4.5	60.5 $\pm$ 5.4	19.8 $\pm$ 1.0

Fig. 1 Schedule for experiment.

temperature.

Methods

Subjects

Sixteen non-smoking healthy male students were selected. The means and standard variations of their age, height, body weight, and body mass index (BMI) are shown in Table 1. Written informed consent was obtained from all subjects after a full explanation of the experimental purpose and protocol.

Procedures

This study was conducted from February to March. The pre-room conditions were maintained at an air temperature (T_a) of 25°C and a relative humidity (RH) of 50%. The test room conditions were adjusted to provide a T_a of 25°C and RH levels of 10%, 30% and 50%. The subjects wore short pants, a long-sleeved sweat shirt and trousers (0.8 clo) in the pre-room. After waiting for 50 min in a sitting position in the pre-room, the subjects moved to the test room and sat on a chair for 120 min. Figure 1 shows the schedule for the experiment.

Measurements

Saccharin clearance time (SCT), frequency of blinking, heart rate (HR), blood pressure, hydration state of skin, transepidermal water loss (TEWL), recovery sebum level and skin temperatures were measured as physiological responses. Also, we asked the subjects to judge the thermal, dryness and comfort sensations with subjective responses using a rating scale.

Mucociliary transport was measured by SCT. A saccharin tablet (2.5 mm $\times$ 0.5 mm) was placed just behind the anterior end of the nasal septum on the level of the anterior end of the middle nasal concha. The subjects were asked to sit quietly with their heads forward and not to sniff or sneeze. The time was measured beginning at the first perception of the sweet taste.

Table 2 The scale of subjective judgments

	Thermal sensation	Sensation of dryness	Thermal comfort
3	hot	extremely dry	very comfortable
2	warm	dry	comfortable
1	slightly warm	slightly dry	slightly comfortable
0	neutral	neutral	neutral
-1	slightly cool	slightly humid	slightly uncomfortable
-2	cool	humid	uncomfortable
-3	cold	wet	extremely uncomfortable

Frequency of blinking was measured while the subjects counted the white spots flickering randomly on the center of the monitor for two minutes (each white spot was illuminated for one sec., and the interval between the illumination of the spots was 0.2–1.4 sec.). Blood pressure and HR were checked at the right upper arm using an automatic tonometer (HEM-737, OMRON, JAPAN) every 30 min. Both SCT and frequency of blinking were measured in the pre-room and 90 min after entering the test room.

The hydration state of the skin was obtained using the CORNEOMETER[®]CM825 (Courage+Khazaka electronic GmbH, GERMANY) and TEWL was obtained using the VapoMeter (Keystone Scientific, JAPAN). Both hydration state and TEWL were measured in the pre-room and in the test room on the right-side of the cheek and the back of the right hand three times every 30 min.

The recovery sebum level was obtained using the SEBUMETER[®]SM 810 (Courage+Khazaka electronic GmbH, GERMANY). It was measured in the pre-room after the removal of sebum using an alcohol sponge and in the test room every 60 min on the left-side of the cheek and the back of the left hand. Skin temperatures at eight local body sites (i.e., the forehead, chest, shoulder, forearm, abdomen, hip, thigh, and foot) were measured with thermistors every minute.

Mean skin temperature was calculated by applying Fukuda's 12-point method (Watanabe, 1976), i.e. (forehead $\times$ 9.8 + chest $\times$ 8.3 + shoulder $\times$ 8.3 + forearm $\times$ 19.6 + abdomen $\times$ 8.1 + hip $\times$ 8.1 + thigh $\times$ 30.6 + foot $\times$ 7.2)/100 = $\bar{T}_{sk}$.

Body weight loss was obtained by deducting the weight before the experiment from the weight at the end of the experiment.

Thermal, dryness and comfort sensations were evaluated once in the pre-room, once upon entering the test room, and then every 30 min thereafter. Subjects evaluated the thermal sensation for the head, trunk, legs and the whole body, and they evaluated the sensation of dryness for the nose, throat, eyes, face and hands. Table 2 shows the scales used for the subjective judgments.

Statistical analysis

Data for comparing the pre-room with the test room were analyzed by the Paired t-test. Results of the physiological and subjective data were analyzed by repeated-measure analysis of

Fig. 2 Saccharin clearance time in the pre-room and 90 min after entering the test room. Values are means $\pm$ S.D. for all 16 subjects. * $p < 0.05$ indicates significant differences between pre-room and test room values.

variance (ANOVA) using Visual State for Windows Release 4.5J Software (Stat Soft, Inc.).

The factors were conditions and time. A multiple comparison was performed using Scheffé. The relationship between SCT and hydration state was analyzed using Pearson's correlation coefficient test. Differences at $p < 0.05$ were significant for all statistical analyses.

Results

Physiological responses

Figure 2 shows SCT in the pre-room and 90 min after entering the test room. SCT in 10% RH increased meaningfully ($p < 0.05$) in comparison with SCT in the pre-room, the difference being 3.35 min., whereas the SCT values in 30% RH and 50% RH showed no significant differences.

Figure 3 shows the frequency of blinking in the pre-room and 90 min after entering the test room. Significant ($p < 0.05$) changes were observed in 30% RH and 10% RH in comparison with the pre-room level. Concerning heart rate, diastolic pressure and systolic pressure showed no significant change among humidity levels.

Figure 4 shows the hydration state of the skin. The hydration state of the face showed significant ($p < 0.05$) differences among humidity levels. Moreover, it was significantly ($p < 0.001$) affected by the interaction of humidity and time. Under RH levels of 10% and 30%, the hydration state of the face decreased beginning at 30 min after entering the test room. However, at 60, 90, and 120 min the hydration state did not decrease any further and was stabilized. The hydration state of the hand showed significant ($p < 0.001$) differences at each time-point but no significant differences among humidity levels.

Figure 5 shows the relationship between SCT and the hydration state of the face under 10% RH. There was a significant ($p < 0.05$, $r = -0.61$) negative correlation between SCT and the hydration state of the face in 10% RH, showing

Fig. 3 Frequency of blinking in the pre-room and 90 min after entering the test room. Values are means $\pm$ S.D. for all 16 subjects. * $p < 0.05$ indicates significant differences between pre-room and test room values.

Fig. 4 Hydration state on the cheek and the hand. Values are means $\pm$ S.D. for all 16 subjects. Significant interactions (humidity $\times$ time) were determined by ANOVA.

that as the SCT became longer, the hydration state of the face became lower. But, under RH levels of 30% and 50%, there was no significant correlation between SCT and the hydration state of the face.

Figure 6 shows the TEWL of the skin. The TEWL of the face showed significant ($p < 0.05$) differences among humidity levels. Moreover, it was significantly ($p < 0.001$) affected by the interaction of humidity and time. Under RH levels of 10% and

Fig. 5 Relationship between saccharin clearance time and hydration state on the cheek in 10%RH.

Fig. 6 Transepidermal water loss on the cheek and the hand. Values are means±S.D for all 16 subjects. Significant interactions (humidity×time) were determined by ANOVA.

30%, the TEWL of the face increased beginning at 30 min after entering the test room. However, at 60, 90, and 120 min the TEWL did not increase any further and was stabilized. The TEWL of the hand showed significant ($p<0.05$) differences at each time-point but no significant differences among humidity levels. The recovery sebum level in the skin increased significantly ($p<0.001$) as time passed, but there was no significant difference among humidity levels.

Figure 7 shows the change in mean skin temperature. The

Fig. 7 Change of mean skin temperature. Values are means±S.D for all 16 subjects. Significant interactions (humidity×time) were determined by ANOVA.

Fig. 8 Body weight loss. Values are means±S.D for all 16 subjects. * $p<0.05$, ** $p<0.001$ Indicates a significant main effect (humidity) as determined by ANOVA.

change at each humidity level was significant ($p<0.05$) showing the degree of decrease in mean skin temperature to be greater under 10% RH than 50% RH.

Figure 8 shows body weight loss. There were significant ($p<0.001$) differences among humidity levels showing a greater loss of body weight under 10% RH than under 30% RH and 50% RH.

Subjective responses

Figure 9 shows the thermal sensation for each site and for the whole body on entering the test room and 90 min after entering the test room. For the thermal sensation observed just after moving to the test room from the pre-room, there were significant ($p<0.001$) differences among humidity levels at the tested body sites except the head, showing that there was a subjective cooler sensation as the humidity decreased. Thermal sensation after 90 min, however there were no significant differences among humidity levels.

Figure 10 shows the sensation of dryness at each site on entering the test room and 90 min after entering the test room. Regarding the sensation of dryness just after moving to the test room from the pre-room, there were significant ($p<0.05$)

Fig. 9 Thermal sensation at each site and for the whole-body on entering the test room and 90 min after entering the test room. Values are means for all 16 subjects. $**p < 0.001$ indicates a significant main effect (humidity) as determined by ANOVA.

Fig. 10 Sensation of dryness at each site on entering the test room and 90 min after entering the test room. Values are means for all 16 subjects. $*p < 0.05$ indicates a significant main effect (humidity) as determined by ANOVA.

differences among humidity levels only in the eye, showing that the subjective feeling of dryness increases as humidity decreases. After 90 min, there were significant ($p < 0.05$) differences in the sensation of dryness in the nose and throat between each humidity level. There were no significant differences in thermal comfort among humidity levels.

Discussion

We investigated the effect of 10% RH, 30% RH, and 50% RH on SCT, dryness of ocular mucosa, physiological function of the skin and cardiovascular reaction under an environmental temperature of 25°C. In addition, we assessed the subjective thermal, dryness, and comfort sensations. In physiological responses, there was no effect of RH on the activity of the sebaceous gland or on cardiovascular reactions like blood pressure and HR. However, it was obvious that low RH affects

SCT, dryness of the ocular mucosa and the stratum corneum of the skin and causes the mean skin temperature to decrease as a result of this dryness. SCT under 10% RH increased more than it did in the pre-room with 50% RH. The frequency of blinking under 10% RH and 30% RH increased more than in the pre-room with 50% RH. Under the low RH levels of 30% and 10%, TEWL increased more than under 50% RH. As a result, it is obvious that the eyes and skin become dry in 30% RH, and the nasal cavity becomes dry as well as the eyes and skin in 10% RH.

Mucociliary clearance of the airway is an important self-defense mechanism, and it plays an important role in the removal of foreign bodies. When this mechanism is impaired, the possibility of respiratory infections is increased. The saccharin method used in this experiment is widely used to assess the function of mucociliary clearance (Lale et al., 1998). An increase in SCT suggests a decrease in the activity of the

mucociliary function. In this study, SCT increased significantly under the environment of 10% RH, suggesting that 10% RH caused a decrease in the ciliary activity of the nasal mucous membrane (Fig. 2). Harper (1961) reported that the survival rate of the influenza virus is only 3–5% after 6 hours in an environment of 20.5–24°C and 50% RH and above, but this rate increased to 66% under an environment of 20% RH. The influenza virus in the air loses infectivity in an environment with 50% RH and above, but its survival time is prolonged in an environment with an RH below 50% (Harper, 1963). Satsuta et al. (1985) reported that there is a seasonal factor in the rate of influenza infection, with respiratory infection prevalent especially in winter. This explains the long survival rate of the organism in environments with low humidity in winter, and the inflammation of the nasal and pharyngolaryngeal mucosa caused by cold air inhalation makes it easier for these mucosa to be infiltrated by the organism. Therefore, according to our study, in an environment with an RH below 10%, it is fairly easy to catch a respiratory infection caused by an influenza virus in the air due to the fact that dryness of the nasal mucocilia compromises the defense mechanism.

Frequency of blinking was measured to determine the effect of humidity on the mucous membrane of the eye in this experiment. The frequency of blinking seemed to reflect the state of dryness of the eye, because the blinking acts to supply moisture to the eye. In this experiment, the frequency of blinking increased significantly under environments of 10% RH and 30% RH, suggesting that a low RH environment influences the activity of the mucous membrane of the eye (Fig. 3). An increase in the frequency of blinking is known to cause discomfort, while blinking is known to be greatly affected by psychological factors (Stern et al., 1984). In an experiment involving contact lens wearers (Nilsson et al., 1986), subjects in low RH environments (approximately less than 30%) showed significantly shorter break-up times (BUT) on the lens and more prominent lens deposits than subjects in higher RH environments (RH of more than 40%). Many contact lens wearers in low RH environments complain about dry eyes and discomfort, whereas others seem to have no trouble at all. It was reported that for aircraft passengers and crew, low cabin humidity seemed to be the most significant factor contributing to discomfort for lens wearers (Eng et al., 1982). In recent years, as computer work has increased in office environments, problems related to the fatigability of eyes and psychological stress have emerged. In particular, because the RH in offices drops in winter due to excessive heating, an increase in the frequency of blinking occurs, and outbreaks of eye fatigue and stress are expected to result.

Grice et al. (1972) reported an increase in the TEWL of the skin as humidity decreases in the state of no perspiration. In our study, TEWL of the face increased significantly under 10% RH and 30% RH, which were both lower than the humidity level of the pre-room, and there was no change of TEWL under 50% RH, which was the same as the humidity level of

the pre-room (Fig. 6). A marked decrease in the hydration state of the face was observed under 10% RH and 30% RH (Fig. 4). This decrease is thought to be the result of the loss of moisture from the stratum corneum due to the increased evaporation of moisture from the skin surface. The loss of body weight after the experiment grew as the level of humidity decreased (Fig. 8), suggesting that the evaporation of water from the body occurred in accord with the level of humidity. Moreover, it seems that a decrease of the mean skin temperature occurred under 10% RH due to a loss of heat, which was caused by the evaporation of water from the body (Fig. 7). The recovery sebum level showed no significant difference among humidity levels. From this result involving the function of skin physiology, it was revealed that a change of RH affected parameters related to the moisture of the skin such as hydration state and TEWL, but there was no influence of humidity on sebum secretion. Cook et al. (1958) compared the texture of dry skin with that of non-dry skin according to the pattern of the skin surface. It is reported that the number of smaller peaks of crista cutis is reduced in dry skin. Also, Yoshikuni et al. (1985) concluded that decreases in the outdoor temperature and humidity cause cracking of the skin by decreasing the activity and water contents of the stratum corneum directly or indirectly. From our study it seems that dryness of the skin adversely affects the skin texture in the environment of 30% RH and below. And in addition to the change of the skin surface due to the decrease in moisture in the skin, outbreaks of dermatologic disorders like dry skin accompanied by itching occur.

Under 10% RH, a significant decrease in ciliary activity and hydration state of the skin were observed, and a significantly negative correlation between these parameters was also observed (Fig. 5). Under the environment of low RH in which the mucosa of the nasal cavity and the skin are apt to become dry, it was observed that dryness of the nasal mucosa became more severe as dryness of the skin became more severe. Therefore, it is thought that the response to the water loss that occurs under low RH is similar between the mucosa and the skin.

Maehara et al. (1991) reported that in a survey done in an airplane, the degree of dryness increased linearly as the RH in the environment decreased to below 40% RH, while with regard to thermal sensation, subjects tended to feel cool as RH decreased during the flight. Also, the subjects tended to feel warm when the average RH returned to 40–50% upon landing. In the present study, the subjects generally felt cool immediately after moving to the test room from the pre-room in 50% RH at all RH levels. However, after 30 min their sensation of coolness was slight, and after 90 min there seemed to be no difference in thermal sensation at each RH level (Fig. 9). Humans seem to feel the change of humidity as a change of thermal sensation only momentarily at a certain temperature.

Regarding dryness in the skin, there were significant differences in dryness in the skin with changes in RH as measured physiologically, while in the subjective assessment

the subjects felt no sense of dryness on the face and hands until after 90 min of RH change. In the case of the eyes, subjects felt dry just after the change of RH, but after 90 min they did not feel dry, suggesting that they grew acclimatized as time passed. Accordingly, there was no coincidence between physiological measurement and subjective assessment in the skin and the eyes. On the contrary, subjects did not feel dry in the nose and throat just after the change of humidity, but after 90 min, they felt dry under low RH (Fig. 10), showing a coincidence with the physiological measurement. It is thought that humans seem to feel dryness in the nose and throat more easily under low RH. Measurement of the frequency of blinking was not conducted just after moving to the test room, but based on the result of subjective assessment, we expect that physiological responses concerning the dryness of the body parts that are exposed to the environment for a long time, such as the eyes and skin, are sensitive to changes in humidity and respond rapidly to such changes. On the contrary, for dryness of the nose and the throat, SCT increased only under 10% RH, and subjects felt dry only 90 min after moving to the test room without any feeling of dryness just after moving, suggesting that they had a slower reaction to the change of humidity than in the eyes and the skin. This result may be due to the humidifying function of the nose and the fact that the nose and the throat are covered with mucous membrane and not exposed to the outer environment directly. The lack of direct exposure is especially relevant in the case of the nasal cavity, which has long ductal morphologic characteristics and the functional characteristics of regulating the temperature and humidity of inspired air. As mentioned previously, the nasal cavity cilia play an important role in the self-defense mechanism by protecting against foreign body infiltration and preventing viral infection. Therefore, these are thought to function well in 30% RH for short periods. In practical life, we are exposed to humidity levels below 10% RH when facing warm air blown directly from a heater. In this study, we evaluated the effect of low RH by measuring SCT after 90 min. However, based on the response of the activity of the nasal cavity cilia in this experiment, we can expect that their function will deteriorate if one is exposed to low RH for a long time, even a 30% RH environment. Thus, further evaluation on the physiological effects of prolonged exposure to various RH levels is recommended. It is not uncommon that the humidity in indoor environments in winter drops to lower than 30% RH due to the heating system. For that reason, skin diseases resulting from dryness of the skin, feelings of fatigue and stress due to dryness of the eyes, and influenza and respiratory diseases due to dryness of the nasal mucosa could be harmful to human health in the low RH of indoor environments in winter. According to the subjective evaluation, subjects felt cool immediately at the trunk, legs and throughout the whole body after RH was changed. However, subjects only slightly perceived dryness of the nose, throat, face and hands as a result of the change of humidity, and feeling this dryness took some time. As a result, the sense of dryness is not as sensitive

as that of temperature, and it is difficult for subjects to become aware of the change of humidity.

In conclusion, there was no effect of RH on the activity of the sebaceous gland and on cardiovascular reactions like blood pressure and HR. However, it was obvious that low RH affects SCT, causes dryness of the ocular mucosa and the stratum corneum of the skin, and causes a decrease in mean skin temperature. Namely, the eye and skin become dry in 30% RH, the nasal cavity becomes dry as well as the eye and skin in 10% RH, and the mean skin temperature decreases in 10% RH. These findings suggested that to avoid dryness of the eyes and skin, an RH higher than 30% must be maintained, and to avoid dryness of nasal mucous membrane, an RH higher than 10% must be maintained. Subjects felt cool immediately after the change of RH, while they perceived dryness only slightly at the change of humidity. Therefore, not only the temperature but also the humidity should be checked using a thermohygrometer in heated indoor areas in the winter season.

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