Different Impacts of Normobaric/Hypobaric Hypoxia on Physiological and Subjective Responses at a Cold Environment

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Abstract

Impacts of normobaric/hypobaric hypoxia on physiological and subjective responses were examined in resting eight healthy young males at a low environmental temperature of 17 °C. They were exposed to the sea level maintained at 27 °C as baseline and then to the three experimental conditions which were combination of barometric (Pe) and partial oxygen (O2) pressures; normobaric hypoxia (NH, Pe= 760 mmHg and O2= 87 mmHg), hypobaric hypoxia (HH, Pe= 418 mmHg and O2= 87 mmHg), and normobaric normoxia (Control, Pe= 760 mmHg and O2= 159 mmHg). Temperatures of rectum (Tre) and 10 sites of skin surface (Tsk), oxygen consumption were measured. Finger-tapping test was performed to assess manual performance. Thermal sensation and subjective shivering activity were also evaluated. A significant difference in the Tre was not seen during exposure to the aimed test condition. On the other hand, a significant difference in the Tsk was observed, the Tsk in both the HH (28.5 ± 0.6 °C) and the NH (27.8 ± 0.5 °C) indicated higher value than that in the Control (27.2 ± 0.7 °C). Despite of larger temperature differences between the Tsk and the environment in the HH and the NH, the heat loss from the body in the HH (87 ± 23 W/m²) was significantly smaller than that in the NH (105 ± 19 W/m²). This is because the convective thermal resistance from the body increases with the decreasing atmospheric pressure so that the convective thermal resistance in the HH was larger than that in the NH. As the consequence, decline in the manual performance was suppressed in the HH and voted score of the subjective shivering was also statistically higher in the HH than in the NH, even though the O2 in air was identically kept at the low level in both the HH and the NH.

Keywords: normobaric hypoxia, hypobaric hypoxia, core and skin surface temperatures, thermal responses, shivering

Introduction

When the body is exposed to cold environment, a temperature drop can be seen in skin surface to diminish the heat loss from the body surface, because the heat flux is mostly in proportion to the temperature difference between the skin surface and the surroundings. However, previous studies (e.g., Blatteis and Gilbert, 1974; Johnston et al., 1996) reported that thermal responses during exposure to a cold environment at the sea level are different from those in the cold environment with hypoxia and/or hypobaria.

For instance, Johnston et al. (1996), Blatteis and Gilbert (1974), and Robinson and Haymes (1990) reported that a larger fall in the core temperature was seen during exposure to a cold with hypoxia compared to the one exposed to the cold with normoxia. This was because heat production decreased in the hypoxia due to the low O2 concentration in air (Blatteis and Lutherer, 1973; Brown et al., 1952; Chalmers and Korner, 1966; Gautier and Bonora, 1992; Giesbrecht et al., 1994; Kotteke et al., 1948; Robinson and Haymes, 1990). On the other hands, fall in the skin surface temperature in the cold with the hypoxia was not so much steeper than the one in the cold with the normoxia (Blatteis and Gilbert, 1974; Chalmers and Korner, 1966). This implies that, in the cold environment with the hypoxia,
the body might dissipate a larger amount of heat energy due to the large temperature difference between the skin surface and the environment. Therefore, deficit of heat energy in the body, which is caused by both the low heat production and the large released heat energy, has been considered as a factor to induce hypothermia in the cold with the hypoxia.

However, according to Cipriano and Goldman (1975) and Yanagidaira et al. (1995), measured heat production in the cold with hypobaric hypoxia, which simulated high-altitude, was almost identical to the one at the sea level, if their environmental temperatures were kept at the same level. They have also shown that, although drop in the skin temperature at the simulated high-altitude was significantly smaller than that at the sea level, drop in the core temperature at the high-altitude was almost equal to that at the sea level. These interesting results have been also seen in studies made by Gautier et al. (1987) and Hannon and Sudman (1973). In addition, Blatteis and Lutherer (1976) reported interesting results, which were that diminishment of the core temperature was not so large at the high-altitude than at the sea level, although the skin temperature did not decrease so much as at the sea level during exposure to the same low environmental temperature.

The reasons has, however, not been clarified why decline in the core temperature was small despite of the large temperature difference between the skin surface and the environment in cold with hypobaric hypoxia such as at high-altitude.

The larger temperature difference between the skin surface and the surrounding under such the cold with hypobaric hypoxia condition suggests that there is a larger water vapour concentration difference as well between the body surface and the environment. Therefore, it may induce not only a larger amount of sensible heat flux but also a larger latent one from the body surface. Chang and Santee (1996) reported, however, evaporated water vapour from body surface of unclothed males, who were exposed to a cold ambient temperature, showed the same rate at a hypobaric hypoxia simulated high altitude as at the sea level. On the other hand, results obtained through experiments performed at simulated high-altitudes (e.g., Houdas et al., 1979; Kokka et al., 1987; Sagawa et al., 1986) indicated a tendency that the mass flux from human body including respiratory evaporation was lower under the hypobaric hypoxic condition than that at the sea level even if its ambient temperature was identical. As seen in these different results among the reports, the influence of evaporation from the body upon heat balance in human at the hypobaric hypoxia is still indistinct.

The convective thermal resistance from the body to the environment is plotted against the atmospheric pressure, in another word, altitude in Figure 1. Data in the figure quoted from our previous study (Fukazawa et al., 2003), which was made theoretically and experimentally using a thermal manikin with its surface temperature maintained at 34 °C evenly. The convective thermal resistance increases with the decreasing atmospheric pressure; that is, with the increasing altitude. This is because of the decrease in air density with increasing altitude. Thus, the figure elucidates that the heat loss from the body surface must be small with the increasing altitude, if the skin surface temperature is unchanged.

The purpose of this study is to confirm the effects of normobaric or hypobaric hypoxia on physiological and subjective responses, and to contribute designing for protective clothing system at altitude.

Method

Subject

Eight healthy un-acclimatized males, all were Japanese university students, took part in the study as test volunteers. All the subjects were given full information about aim of the study, procedure, and potential risks of the experiment prior to their participations. They all expressed an understanding of the experiment through signing a statement of informed consent.

The subjects were, in average, 22.2 ± 2.1 year-old in age, 170.4 ± 5.5 cm in height, 60.0 ± 3.4 kg in weight, 17.8 ± 3.1 % in body fat percentage, and 1.71 ± 0.06 m² in DuBois’s body surface area.

Test condition

In the study, three test conditions were employed; they were combination of atmospheric pressure (Pe),
Different Impacts of Normobaric/Hypobaric Hypoxia on Physiological and Subjective Responses at a Cold Environment

13

Oxygen concentration in air (O₂). The first one was control condition (Control), whose Pe was maintained at 760 mmHg and partial pressure of O₂ was kept at 159 mmHg (20.9 % in the Pe). The second one was normobaric hypoxic condition (NH), whose Pe was at 760 mmHg while partial pressure of O₂ was at 87 mmHg (11.5 % in the Pe). The last one was hypobaric hypoxic condition (HH), whose Pe was at 418 mmHg and partial pressure of O₂ was at 87 mmHg (20.9 % in the Pe).

In all the test conditions, their environmental temperature was constantly regulated at 17 °C with 77%RH with an air velocity of 0.15 m/s.

Procedure
The experiment was conducted in two climate chambers. The first chamber was pre-room for baseline, therefore in which environmental condition was maintained at 27 °C and 37 %RH with an air velocity of 0.15 m/s. The second chamber was employed for the test condition, because the chamber is able to realise simultaneously both Pe and O₂ concentration in air.

As shown in Figure 2, which indicates time schedule of the measurement, the subject stayed in the first chamber for 15 min and then moved into the second chamber. Thereafter, regulation of both the Pe and the partial pressure of O₂ in the second chamber started to attain the desired test condition with sparing 109 min, because its environment showed the standard condition (Pe= 760 mmHg and O₂= 159 mmHg) at just after moving in the chamber. Then, the subject was exposed to the aimed test condition in a period of 109 min to 139 min, that is, he was exposed to the test condition for 30 min in total. The subject kept resting posture in a whole period of the measurement.

Measurement
Rectal temperature (Tₑ) was measured using a thermistor probe (LT8A, Gram Corporation, Japan), which was inserted 12 cm beyond the anal sphincter. Local skin surface temperature was also measured with thermistor probes (LT8A, Gram Corporation, Japan), which were mounted on 10 sites (Hori et al., 1977). Mean skin temperature (Tₑ) was calculated using an equation derived by Hori et al. (1977). Theses measured temperatures were recorded every 1 min via portable data loggers (LT8A, Gram Corporation, Japan).

An analysis of oxygen consumption (VO₂) was performed using collected expired-air in Douglas bags in both periods of the baseline and the test condition (period from 109 min to 139 min). Concentrations of O₂ and CO₂ in the collected expired gas were obtained using an analyser (AE-300S, MINATO Medical Science, Japan). Volume of the expired gas was measured by a gas meter (W-NK-10A, SHINAGAWA CORPORATION, Japan). Manual performance level was evaluated through finger-tapping test using a counter (SIMPLEX, Maruzen Co. Ltd., Japan). In the finger-tapping test, the subject repeated pushing a bottom as many as possible for 15 sec.

A subjective questionnaire was also completed for thermal sensation in the whole body. According to ISO 10551 (2001), nine-point scale (4: very hot, 3: hot, 2: warm, 1: slightly warm, 0: neutral, -1: slightly cool, -2: cool, -3: cold, -4: very cold) was employed for the thermal sensation in the whole body. Shivering activity was also quantified in the test using four-point scale (0: not at all, -1: slightly shivering, -2: shivering, -3: violently shivering), which was referred and quoted from Blatteis and Lutherer (1976).

Statistical analysis
Data are given in terms of the mean and their SD. Results of physiological and subjective data were analysed by analysis of variance with repeated measurement (ANOVA) using STATISTICA 03J for Windows (Statsoft Japan Inc., Japan) at the baseline, 0 min, 12 min, 25 min, 42 min, 65 min, 109 min, 119 min, 129 min and 139 min in the measurement or periods of the

Figure 2 Time schedule of the experiment.
baseline for 15 min and the test condition for 30 min (period from 109 min to 139 min). In the ANOVA, the factor was test condition only. If significant difference is observed among the three test conditions, post-hoc test was conducted using Bonferroni-type multiple comparison to determine an origin of the differences. As common way, in the present study, time-changes in \(T_{\text{es}}\), \(T_{\text{sk}}\), local skin surface temperatures of the chest and the fingertip, the manual performance, and both the subjective evaluations of the thermal sensation and the shivering activity were also analysed using two-way ANOVA. In all the analyses, differences are considered to be significant, if the statistical significance is less than 0.05.

Results

**Temperatures of rectum and mean skin**

Figure 3 indicates \(T_{\text{es}}\) for the three test conditions in the whole period of the experiment. In the baseline in which temperature was maintained at 27 °C, \(T_{\text{es}}\) for all the test conditions of Control, NH, and HH were stabilized at around 37.0 °C. However, after moving into the 2nd climate chamber, \(T_{\text{es}}\) for the three test conditions gradually decreased with elapsed time and fell to around 36.7 °C in the period of exposure to the aimed test condition. No statistical difference was, however, found in the \(T_{\text{es}}\) among the test conditions at each time through ANOVA.

Figure 4 shows time course of \(T_{\text{sk}}\) in the three test conditions. \(T_{\text{sk}}\)s in all the three conditions indicated similar values of 33.2 °C to 33.4 °C during the baseline period, while \(T_{\text{sk}}\)s declined gradually due to exposure to the cold in the 2nd chamber. Although statistical differences among the test conditions for the \(T_{\text{sk}}\) were found to not be significant at the baseline and prior to exposure to the test condition period, those were found to be significant at 109 min (\(p<0.05\)), 119 min (\(p<0.01\)), 129 min (\(p<0.05\)) and 139 min (\(p<0.05\)); that is, the remarkable difference was seen among the three test conditions when the subjects exposed to the aimed test condition. In addition, during the test condition period, \(T_{\text{sk}}\) for the HH was significantly higher than that for the Control (at 109 min: \(p<0.05\), 119 min: \(p<0.01\), 129 min: \(p<0.05\), and 139 min: \(p<0.05\)), while \(T_{\text{sk}}\) for the NH was not statistically different from those for both the HH and the Control.

For both the \(T_{\text{es}}\) and the \(T_{\text{sk}}\), although there was no difference among the three conditions, the changes with elapse of time were found to be significant as noted in each figure.

**Local skin surface temperatures**

Profile of skin surface temperature of the chest (\(T_{\text{ch}}\)) in the whole period of the experiment is shown in Figure 5. Although the \(T_{\text{ch}}\)s in all the three test conditions stayed at 33.6 °C during the baseline period, they dropped differently to about 30.5 °C for the HH and to about 29 °C for the Control and the NH during exposure to the test condition. Statistical differences were observed at 119 min (\(p<0.05\)) and 129 min (\(p<0.05\)) among the three test conditions during exposure to the test condition. In addition, the host-hoc test indicated that those \(T_{\text{ch}}\)s for the HH were significantly higher than those for the Control (at 119 min and 129 min: \(p<0.001\)).

Figure 6 shows skin surface temperature of the fingertip (\(T_{\text{fin}}\)) during the experiment. Although the \(T_{\text{fin}}\)s in...
the three test conditions showed at about 33.5 °C during the baseline period, they did remarkably low values of 18 °C to 19 °C during the test condition period. There were not significant differences among the three test conditions during both the baseline and the test condition periods.

**Heat production**

Heat production is shown in Figure 7 during the baseline and the test condition periods. The heat production in the test condition period showed remarkable larger rate than that in the baseline for all the three test conditions. However, significant differences among the test conditions were found to be not significant in both the periods of the baseline and the test condition.

**Manual performance**

Figure 8 indicates results of the finger-tapping test. In all the three test conditions, manual performance indicated similar rate of about 83 times for 15 sec in the 1st chamber for the baseline, while it gradually declined due to exposure to the cold in the 2nd chamber. Statistical difference was found to be significant in the result of the counter test at 129 min. According to result of the post-hoc test, manual performance of the NH was significantly lower than those of both the Control (p< 0.05) and the HH (p< 0.05). However, statistical differences were found to be not significant among the three test conditions in the whole period of the experiment except at 129 min.

**Subjective response of thermal sensation**

Figure 9 indicates changes in thermal sensation for the whole body. For the baseline period, the thermal sensation was almost “neutral” in all the three test conditions. After moved in the 2nd chamber for the test condition, the thermal sensation steeply decreased and was “cold” to “very cold” in all the three test conditions. The thermal sensations were “cold” at the Control, “very cold” at the NH, and “cold” at the HH in the test condition period.

Results of ANOVA showed that statistical difference in the thermal sensation was found to be not significant in the whole period of the experiment except at 109 min, at which a statistical difference in thermal sensation was observed with a significance of p< 0.05. A result of the post-hoc test at 109 min indicated that the thermal sensation score for the HH was higher than that for the NH. Tendencies towards differences were, however, found at 65 min and 119 min (p= 0.07), and at 139 min (p= 0.08).

**Subjective shivering activity**

Results of the subjective shivering activity are shown in Figure 10. Although the subject did not shiver
at all in the 1st chamber for the baseline, they continuously shivered so much after entering the 2nd chamber for the test condition. The voted shivering activity score was “not at all” in the baseline and it gradually shifted “slightly shivering” at 0 min to “shivering” in the test conditions period.

According to results of the ANOVA, although statistical differences in the subjective shivering activity among the three test conditions were found to be not significant at the baseline and at 0 min to 25 min, those were found to be significant at 42 min to 139 min (42 min and 139 min: p< 0.01, 65 min to 129 min: p< 0.05). Results of the post-hoc test showed that the voted shivering activity scores of the NH were significantly lower than those of the HH at 42 min to 139 min (42 min, 65 min, 119 min, 139 min: p< 0.01, 109 min and 119 min: p< 0.05). Furthermore, the shivering activity scores of the NH were also statistically lower than those of the Control at 42 min, 109 min, 129 min, and 139 min (42 min and 139 min: p< 0.01, 109 min and 129 min: p< 0.05).

Discussion

Heat loss from the body surface is always modified by a change of the blood flow rate through regulation of the body core temperature including a control of the peripheral circulation. When human being is exposed to a cold environment, a steep skin surface temperature drop takes place always by induced vasoconstriction of the peripheral vessels in order to keep the core temperature at a specific level through reduction of the heat loss from the body. If an additional stress of hypoxia is superimposed to the cold stress, temperature drop in the skin surface was not so large compared to the one at the sea level (Blatteis and Lutherer, 1976; Gautier, 1996; Golja and Mekjavic, 2003; Sagawa et al., 1986), because exposure to hypoxia brings a gain in both carotid (Bailliart et al., 1990; Tamisier et al., 2004; Xie et al., 2001) and peripheral blood flows (Sagawa et al., 1986; Tamisier et al., 2004; Zamudio et al., 2001; Wagner et al., 1980). This means reduction of the vascular resistance, which is induced by decrease in the sympathetic activation by either hypoxia or peripheral chemoreceptor stimulation (Tamisier et al., 2004; Xie et al., 2001). Therefore, the arterial hypoxia inhibits the thermoregulatory vasoconstriction because of its chemoreceptor excitation, even if the body is imposed to a cold environment (Chalmers and Kornier, 1966; Sato et al., 1995). That was the reason why, in the present study, Tsks under both the NH and the HH decreased not so much as under the Control during the aimed test condition period, because the effect of the inhibited vasoconstriction by the hypoxia was clearly seen in the trunk such as the chest as shown in Figure 5 while it was not seen in peripheral regions such as the finger as shown in Figure 6.

In general, a larger temperature difference between the skin surface and the environment causes a larger heat loss from the body surface, which may induce drop in the core temperature in the body. In the present study, the Tsks in the NH and the HH during the period of the test condition decreased to about 36.7 °C and they stayed at almost the same level as in the Control, even though the Tsks in the NH and the HH did not drop so much as that in the Control. Therefore, a calculation was made to obtain heat storage in the body employing the obtained results during the test condition, according to reports about thermal responses in cold environments (e.g., Rissanen and Rintamäki, 1997; Cipriano and Goldman, 1973). In addition, the heat loss from the body was also calculated through subtracting the heat storage from the heat production.

The calculated heat storage and the heat loss during exposure to the aimed test condition are shown in Figure 11. For the heat storage, negative rates were obtained for all the test conditions. Through the ANOVA, statistical difference in the heat storage was seen among the test conditions (p< 0.05). In addition, post-hoc test showed that there was a significant difference in the heat storage between the HH and the Control.
and between the HH and the NH; that is, the heat storage in the HH was significantly smallest in the test conditions. This means that cold stress of the HH was lower than those of the Control and the NH. For the heat loss from the body during the test condition, the heat loss in the HH was smaller than those in the other 2 test conditions, although the ANOVA showed that there was a trend towards a difference among the three test conditions (p= 0.07). Thus, during the test condition period, the heat loss from the body in the HH was so smaller that the T_{ea} did not decrease largely, despite of the larger temperature difference between the T_{ea} and the environment.

The heat loss is determined not only by the temperature difference but also by thermal resistance. In the present study, the convective thermal resistances from the body surface were experimentally obtained 0.11 ± 0.02 m^2K/W for the Control, 0.12 ± 0.02 m^2K/W for the NH, and 0.16 ± 0.05 m^2K/W for the HH. The thermal resistance in the HH was about 40 % larger than those in the Control and the NH. The present results of the thermal resistances obtained by the subjective measurement indicated a good agreement with theoretical resistances of 0.13 m^2K/W at 760 mmHg of the Pe and 0.17 m^2K/W at 418 mmHg of the Pe under the same air velocity (Fukazawa et al., 2003) as shown in Figure 1. This was one of reasons why the heat loss in the HH during exposure to the test condition was less than those in both the NH and the Control despite of the largest temperature difference between the T_{ea} and the environment.

Ring and de Dear (1991) and Hensel (1981) have reported that the thermo-receptors are stimulated by released/given heat flux from/to the body. That is, the heat flux triggers the thermal sensations (Li and Holcombe, 1996; Senoo et al., 1986), which depends also upon ambient O_2 concentration in air; specifically, hypoxia diminishes sensitivity of the thermal sensation in the body (Golja et al., 2004). The diminishment of the thermal sensation sensitivity induced by hypoxia was, however, not clearly observed in the present study. During exposure to the test condition, there was not a significant difference in the thermal sensation between the NH and the Control, although the thermal sensation in the NH seems to be lower than that in the Control. Furthermore, during exposure to the test condition, the thermal sensation in the HH was resulted in “cold” which was almost equal to that in the Control. Those might be reason why the T_{es} among the three test conditions were kept at the same level of about 36.7 °C, because the thermal sensation is strongly affected by core temperature level in the body (e.g., Mower, 1976).

Influence of the decreasing atmospheric pressure was detected more remarkably for the subjective shivering activity than for thermal sensation. During exposure to the test condition, the score of shivering activity in the NH was statistically lower than those in both the Control and the HH. The subjects shivered severely in the NH, while they shivered slightly in the Control and the HH. This difference between the NH and the Control and the HH means that cold stress in the NH was larger than those in both the Control and the HH. On the other hand, there was no difference in the subjective shivering activity between the HH and the Control, although the atmospheric O_2 level at the HH was kept at the same level as the NH. This verifies the reduced ambient pressure can contribute reduction of the cold stress due to the increased convective thermal resistance.

Performance of human being in the cold environment is, in general, deteriorated because of remarkable decrease in cutaneous blood flow due to vasoconstriction. The decrease in performance in the cold can be notably observed in extremity such as hands and feet (e.g., Ozaki et al., 1998 and 2001; Rissanen and Rintamäki, 1997). Therefore, in the present study, the manual performance evaluated through the finger-tapping test indicated gradual decrease in all the three test conditions. During exposure to the test condition, the manual performance in the NH seems to be lower than those in both the Control and the HH despite of no significant difference, although there was no difference in temperature of fingertip as shown in Figure 6. This was probably because the exposure to low O_2 level in air induces excessive fatigue in central nervous system (Rietjens et al., 2005) so that it declines the physical activity (Hashimoto, 2003). On the other hand, the manual performance in the HH did not decrease so much as in the NH and indicated almost the same result as in the Control. Thus, this difference between the HH and the NH brought smaller cold stress in the HH due to the smaller heat loss from the body. In another word, reduced atmospheric pressure could contribute to prevent decrease in the manual performance in the present study.

Conclusion

Influence of normobaric hypoxia and hypobaric hypoxia upon human thermal responses and sensations has been investigated in a cold environment of 17 °C. It has been experimentally ascertained that there are different impact on the physiological and subjective responses between under the normobaric hypoxic and the hypobaric hypoxic conditions. Exposure to the hypobaric hypoxia diminishes both objective and subjective cold stresses compared to exposure to the normobaric hypoxia. The reason of the different impact is elucidated that the heat loss from the body decreases in the hypobaric environment because of increase in the convective thermal resistance from the body with the
decreasing atmospheric pressure, despite of its hypoxic condition.

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