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Thermoregulation, peripheral vessel vasomotor regulation, and hormonal responses during cold exposure in wheelchair athletes

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Abstract

The purpose of this study is to clarify the characteristics of thermoregulation and physiological responses during exercise in a cold environment in wheelchair athletes. The subjects were male wheelchair athletes with spinal cord injury and healthy male college students. The maximal oxygen uptake as a parameter of endurance exercise ability was higher in the wheelchair athletes than in the college students. Measurements were performed at an environmental temperature of 12 ℃ with a mean relative humidity of 60% at a mean air stream of 0.5m/sec. After rest for 30 minutes, the subjects performed arm cranking exercise at 20 watts(50 rpm) for 60 minutes. The measurement items were tympanic temperature, mean skin temperature, heat production, catecholamine, and cold-induced vasodilation. During exercise under exposure to cold, the tympanic temperature, heat production, and catecholamine more markedly increased in the wheelchair athletes than in the college students. The resistance index as a value of cold-induced vasodilation were higher in the wheelchair athletes than college students during cold exposure. On the other hand, the decrease in the mean skin temperature was slighter in the wheelchair athletes than in the college students. The thermoregulation sensitivity and heat production responses to exercise in a cold environment were more markedly increased in the wheelchair athletes than in the college students.

Key words: spinal cord injury, wheelchair athletes , cold environment, catecholamine, cold-induced vasodilation

Introduction

As suggested by cross-adaptation between exercise training and cold (1,2) and relationships of metabolism and thermoregulation responses in a cold environment with the endurance exercise ability (3,4,5), exercise training generally improves the sensitivity of the thermoregulatory system and heat production responses to cold. Studying the relationship between cold-induced vasodilation (CIVD) using iced water and the maximum oxygen uptake ($\dot{V}O_2max$), which is an index of endurance exercise ability, Sugawara et al. (6) observed a close association between improvements in $\dot{V}O_2max$ and increases the values of various CIVD parameters and clarified that the strength of this association is determined by exercise training in addition to factors including chronic exposure to cold.

They also compared thermoregulatory responses and CIVD during exposure to cold according to $\dot{V}O_2max$ and showed that cold tolerance was acquired as hunting reaction increased the cutaneous blood flow to increase or maintain the finger skin temperature although it decreased the peripheral vascular resistance (7). Recently, as interest in sports has grown among disabled people, they began to participate in various events, and wheelchair sports have become particularly popular among individuals with spinal cord injuries. Wheelchair marathons have become professional sports in some parts of the world due to improvements in racing wheelchairs and athletic abilities of participants. Although there have been a number of reports on physiological responses during exercise and training effects in wheelchair athletes (8,9,10), evaluations of characteristics of thermoregulatory responses during exercise or physiological responses under cold stress have been scarce. The objective of this study was to clarify characteristics of thermoregulatory responses and physiological responses of wheelchair marathon athletes with spinal cord injuries during exercise in a cold environment.

Materials & Methods

Subjects

The subjects were 5 male wheelchair marathon athletes with spinal cord injuries (WG) and 5 male college students without disability (SG). This study was approved by the thical Committee of Nagasaki University and was carried out after explaining the objective and contents of the study to all subjects in advance and obtaining their informed consent.

Measurement of the maximal oxygen uptake ($\dot{V}O_2max$)

$\dot{V}O_2max$ was measured by the incremental loading method on an arm-cranking ergometer. Gas analysis was performed using a continuous expiratory gas analyzer (Sanei Sokki, Japan).

Measurements during cold exposure

In consideration of the effect of postprandial special dynamic action(SDA) on metabolism, the control values were obtained 6 or more hours after a meal by having the subjects rest in a room adjusted to a mean temperature of 25℃ for at least 1 hour. Then, the subjects rested in a long-sleeved shirt and training pants for 30 minutes in a wheelchair and exercised on an arm cranking ergometer at an exercise intensity of 20 watts(50 rpm) for 60 minutes in a climatic chamber adjusted to a mean ambient temperature of 12℃, mean relative humidity of 60%, and mean air current of 0.5 m/sec. The skin temperature and tympanic membrane temperature(Tty) were recorded serially at 1 minute-intervals using a thermister(Tecnol Seven, Japan), and mean values were calculated every 5 minutes. The skin temperature was measured in the forehead, chest, abdomen, back, brachium, medial side of the antebrachium, and dorsum of hand. The mean skin temperature(Tsk) was calculated by weighted loading of area ratios according to Hardy and DuBois method (11). The heat production(M) was calculated as a mean of 5 minutes by continuous expiratory gas analysis. The body weight was measured before and after measurements during cold exposure.

Measurements of cold-induced vasodilation

CIVD was measured over 30 minutes after the subjects were rested for 30 minutes in a cold room. The CIVD test was performed by Yoshimura's method (12): A thermister was attached to the dorsal side of the distal phalanx of the middle finger of the non-dominant hand, white petrolatum was applied to prevent wetting, and the finger skin temperature was measured with the thermister every 30 seconds before immersion and during immersion (30 minutes) in iced water (0℃). The temperature before water immersion (TBI), temperature at first rise (TFR), which is the temperature measured when the temperature began to recover from a nadir observed after immersion, time of temperature rise (TTR), which is the time from immersion to TFR, mean skin temperature (MST) during the 25 minutes from 5 to 30 minutes after immersion, and amplitude of temperature (AT), which was the difference between the minimum temperature during immersion and maximum temperature between 5 and 30 minutes after immersion, were determined as indices of CIVD. On the basis of these values, the resistance index (RI) was evaluated by a 5-point scale of Nakamura's method (13). CIVD was examined before the day of exercise tests.

Measurement of blood parameters

Blood was sampled after resting at a room temperature of 25℃ (control value), after 30-minute exposure to cold (resting), 30 minutes after the beginning of exercise, and at the end of exercise, and the blood lactate (LT), plasma adrenaline (A), plasma noradrenaline (NA), and plasma dopamine (D) levels were measured by high-performance liquid chromatography (Waters Co., Germany).

The above procedures were carried out between 10:00 and 15:00. The mean and standard deviation were calculated for the values of each item. Statistical analysis was made by unpaired t-test at the 5% level of significance.

Results

Table 1 shows the age, height, weight, and $\dot{V}O_2max$ of the subjects. The weight and $\dot{V}O_2max$ per unit weight were significantly greater in WG ($p < 0.01$). Tty decreased slowly in both groups during rest after exposure to cold and increased after the beginning of exercise but did not reach the control level. Tty differed significantly ($p < 0.001$) between WG and SG from immediately after the beginning of exercise to the end of exercise (Fig. 1). Tsk decreased in both groups after exposure to cold, and was reduced more

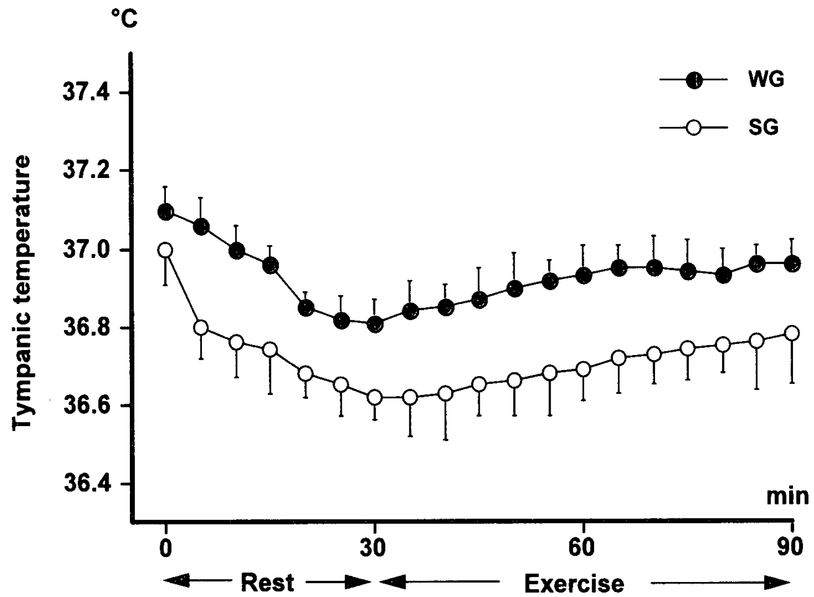

Fig.1 Time coures of tympanic temperature for the wheelchair group (WG) and students group (SG) during cold air exposure. Values are means ± SD.

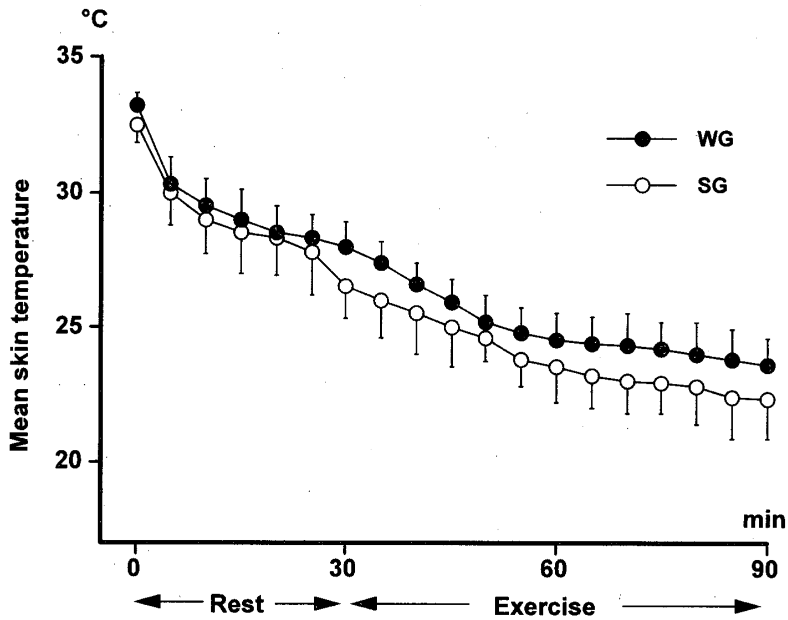

Fig.2 Time coures of mean skin temperature for the wheelchair group(WG) and students group(SG) during cold air exposure. Values are means ± SD.

Table 1 Mean values of physique and maximal oxygen uptake in the subject groups with wheelchair group(WG) and students group(SG).

Subject	Characteristics				
	Age	Height	Weight	$\dot{V}O_2max$	
	(yr)	(cm)	(kg)	(l/min)	(ml/kg/min)
WG	30. 5	168. 4	52. 6**	3. 34	63. 5**
(N=5)	±8. 9	±2. 5	±5. 7	±0. 84	±1. 3
SG	21. 1	171. 60	64. 5	3. 11	48. 2
(N=5)	±2. 1	±2. 8	±4. 6	±0. 46	±0. 8

Values are means ±SD;**:p <0. 01 by t-test between WG and SG.

notably in SG than in WG 30 minutes after the beginning of exercise(Fig. 2). M(W/m²) increased in both groups after exposure to cold, increased rapidly after the beginning of exercise, and reached a plateau in both groups 30 minutes after the beginning of exercise. It was consistently greater ($p < 0.001$) in WG than in SG from 10 minute after the beginning of exercise(Fig. 3). Table 2 shows LT, A, NA and D during rest and exercise. LT increased significantly ($p < 0.01$) in both WG and SG after the beginning of exercise, and the difference between the two groups was significant($p < 0.01$) 30 minutes after the beginning of exercise. A showed no change during the experiment, but NA and D increased significantly in both groups 30 minutes after exposure to cold, further increased after the beginning of exercise, and became highest at the end of exercise. NA and D

Table 2 Blood Lactate (LA) and Plasma catecholamine (adrenaline (A), noradrenaline (NA), dopamine(D)) concentration from the WG and SG during exercise in cold air exposure.

Room (℃)	Time (min)		Subject	LA	A	NA	D
25	0	Control	WG	1.12±0.16	0.69±0.21	1.96±0.45	0.15±0.14
			SG	1.03±0.12	0.86±0.19	1.87±0.44	0.17±0.09
10	30	Exercse 0min	WG	1.60±0.23	0.80±0.75	9.42±0.91*	0.31±0.10*
			SG	1.95±0.34	0.79±0.83	7.56±0.89	0.22±0.11
	60	Exercise 30min	WG	3.60±0.35**	1.00±1.12	16.80±2.14**	0.42±0.05*
			SG	4.50±0.56	0.89±1.14	14.60±2.43	0.34±0.12
	90	Exercise 60min	WG	5.40±0.56**	1.14±1.31	19.88±3.22**	0.59±0.09*
			SG	6.85±0.64	1.08±1.27	17.56±2.85	0.41±0.10

Values are means ±SD ;*: $p<0.05$,**: $p<0.01$ by t-test between WG and SG.

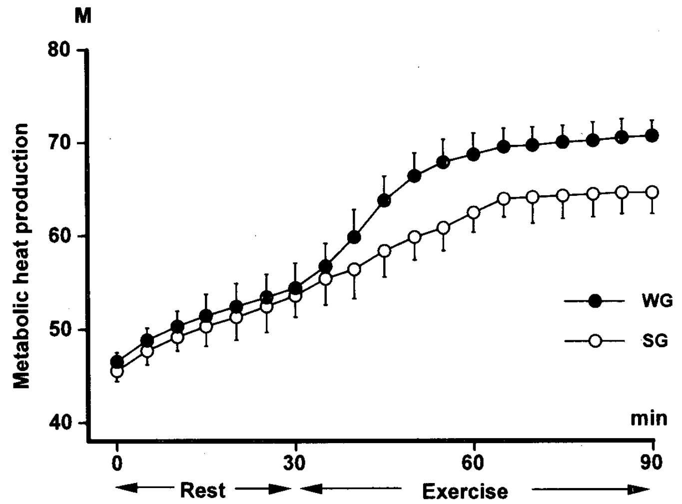

Fig.3 Time coures of metabolic heat production for the wheelchair group(WG) and students group(SG) during cold air exposure. Values are means ± SD.

Table 3 Mean values of cold-induced vasodilation responses of wheelchair group(WG) and students group(SG) in ice water immersion at cold air exposure.

Subject	Characteristics of CIVD in ice water					
	TBI (℃)	MST (℃)	TFR (℃)	TTR (min)	RI	AT (℃)
WG (N=5)	25.81 ±3.67	7.35* ±1.08	4.86* ±1.60	11.32 ±2.52	11.3* ±1.13	6.98 ±3.07
SG (N=5)	24.89 ±2.18	5.21 1.60	2.84 ±1.03	12.67 ±2.09	9.4 ±1.2	5.19 ±2.99

TBI:temperature before water immersion.
MST:mean skin temperature (values during the firs five minutes of water immersion are excluded).
TFR:temperature at first rise after water immersion.
TTR:time of temperature rise after water immersion.
RI:resistance index.
AT:amplitude of temperature reaction.
Values are means ±SD;*:$p<0.05$ by t-test between WG and SG.

were significantly higher in WG than in SG ($p < 0.05$ or $p < 0.01$) 30 and 60 minutes after the beginning of exercise. Table 3 shows CIVD values measured over 30 minutes after a 30-minute exposure to cold. MST was 7.35 ± 1.08℃ in WG and 5.21 ± 1.60℃ in SG ($p < 0.05$), TFR was 4.86 ± 1.60℃ and 2.84 ± 1.03℃ ($p < 0.05$), and RI was 11.3 ± 1.3 and 9.4 ± 1.2 ($p < 0.05$), respectively. The loss of body weight after exercise in a cold environment was small in both groups, being -0.30 ± 0.15 kg in WG and -0.40 ± 0.20 kg in SG.

Discussion

Concerning differences in physiological responses to cold stress according to age, Smolander et al. (14) measured the rectal temperature, skin temperature, and energy metabolism in children and adults during 30-minute light exercise on a bicycle ergometer at a low temperature and noted differences in the responses between children and adults depending on the site. Falk et al. (15) compared responses in a cold environment during light exercise among young individuals, elderly exercisers, and elderly non-exercisers and reported that there was no difference between the exercisers and non-exercisers and that increases in the heat production were not reflected in the rectal temperature in the elderly subjects.

Sugawara et al. (7) observed that the endurance exercise ability was related to the maintenance of the skin temperature and increase in heat production during resting at an ambient temperature of 12℃ and showed that the physiological regulatory mechanism to increase autonomic thermoregulatory responses to cold is an increase in energy metabolism, i.e. heat production. This has also been indicated by Lange Anderson et al. (1) that training in a cold environment over a long period increased heat production due to shivering and enhanced cold tolerance in humans and the report of Moriya et al. (5) that the degree of shivering and endurance exercise capacity at an ambient temperature of 7℃ were closely related to energy metabolism. As for its mechanism, Chin et al. (16) noted that training enhances cold tolerance by heat production through promotion of the actions of catecholamine to increase the cardiac output, improve the ability of oxygen uptake, increase the blood flows of visceral organs, and suppress skeletal muscle vasoconstiriction.

In this study, also, M increased during rest in a cold environment in WG with a higher endurance exercise capacity compared with SG to prevent the decrease in Tty and further increased rapidly after the beginning of exercise to maintain Tty at a high level. Tsk also decreased markedly during rest in a cold environment, but its decrease was prevented after the beginning of exercise, and the decrease was smaller in WG than in SG. Sugawara et al. (6,7) reported the results of their experiments concerning CIVD as follows. RI was higher as the duration of exercise experience was longer, and the values of various CIVD parameters were higher in those who practiced outdoor events more likely to be exposed to cold than in those who practiced indoor events. On the basis of the data obtained over 3 years, RI was related to $\dot{V}O_2max$(ml/kg/min), increases in the values of various CIVD parameters were closely related to improvements in the motor ability, and the values of various CIVD parameters were positively related with the endurance capacity also when the whole bodies of the subjects were exposed to cold. The results of the CIVD tests in this study obtained in a cold environment showed, similarly to earlier reports, that the values of various CIVD parameters were maintained at high levels in individuals with a greater endurance capacity, i.e. in WG with a higher $\dot{V}O_2max$ compared with SG, and that the finger skin temperature is increased as the blood flow increased due to dilation of arteriovenous anastomoses in the fingers.

Graham et al. (17) observed an increase in energy metabolism and an elevation of the mean skin temperature associated with an increase in catecholamine during exercise at 5℃ in adult males. In this study, NA and D increased significantly compared with the control values during rest and during exercise in a cold environment, and the increases were greater in WG than in SG. According to Strobel et al. (18), the increases in NA and D after exercise were significantly greater in long-distance runners than in non-athletic adults, and the differences between the two groups were also evident. In this study, A increased only slightly during rest and exercise similarly to the report of Pearson et al. (19): While NA increased with prolongation of exercise, A increased to a certain level but gradually decreased as exercise continued over a long period. The results of this study suggest that wheelchair athletes show significantly better thermoregulatory sensitivity and heat production responses during exercise in a cold environment than non-athletic students without disability.

References

1. LangeAndersen, K., EideR., Hammel, H.T., Hellstrm, B., Hildes, J.A., Lofstedt, B., Segrem, N., Simon, E., Stromme, S.and Wilson, O. Metabolic and circulatory aspects of tolerance to cold as affected by physical training. Fed Proc 25:1351- 1356, 1966.
2. Dressendorfer, R.H., Smith, R.M., Baker, D.G.and Hong, S.K. Cold tolerance of long-distance runners and swimmer in Hawaii. Int J Biometeor 21:51-63, 1977.
3. Billel, J.H.M. Heat debt as an index for cold adaptation in men. J Appl Physiol 62: 1627-1634, 1987.
4. Billel, J.H.M., Monotte-Varley, C., Livecchi-Gonnt, G.H., Savourey, G.L.M. and Hanniquet A.M. Physical fitness and thermoregulatory reaction in a cold environment in men. J Appl Physiol 65:1984-1989 ,1988.
5. Moriya, K., Suda, T., Hattori, M. and Yokoyama, S. The correlation of thermoregulatory reactions in young men exposed to cold air with their physical fitness. Jpn J Biometeor 30: 77-84, 1993(in Japanese).
6. Sugawara, M. and Hirata, F. Effect of regular exercise on cold-induced vasodilation. Jpn J Phys Fitness Sports Med 42: 495-501, 1993(in Japanese).
7. Sugawara, M. and Taimura, A. Relationship between thermoregulation and cold-induced vasodilation during cold exposure with regard to maximal oxygen intake. Jpn J Phys Fitness Sports Med 45:101-110, 1993(in Japanese).
8. Cowell, L.L., Squires, W.G., and Raven, P.B. Benefits of aerobic exercise for the paraplegic:a brief review. Med Sci Sports Exerc 18: 501-508, 1986.
9. Davis, G.M. Exercise capacity of individuals with paraplegia. Med. Sci. Sports Exerc., 25, 423-432, 1993.
10. Hoffman, M.D. Cardiorespiratory fitness and training in quadriplegics and paraplegics. Sports Medicine 11:67-73, 1986.
11. Hardy, J. D. and DuBi, E. F. The technic of measuring radiation and convection. J Nutr 15:461-475, 1938.
12. Yoshimura, H.and Iida, T. Studies on the reactivity of skin vessels on extreme cold. Part I. A point test on the resistance against frost bite. Jpn J Physiol 1:147-159, 1950.
13. Nakamura. M., Nohara, H., Tsuchimoto, M., Sugahara, K. and Sugawara, M. A new evaluation of cold vascular reaction. Jpn J Hyg 32: 268, 1977(in Japanese).
14. Smolander J., Bar-Or O., Korhonen O.and Ilmarinen J. Thermoregulation during rest and exercise in the cold in pre- and early pubescent boys and in young men. J Appl Physiol 72:1589-1594, 1992.
15. Falk B., Bar-Or O., Smolander J. and Frost G. Response to rest and exercise in the cold:effects of age and aerobic fitness. J Appl Physiol 76: 72-78, 1994.

16. Chin , A.K. , Seaman , R.and Kapileshwarker , M. Plasma catecholamine response to exercise and cold adaptation. J Appl Physiol 34: 409-412, 1973.
17. Graham T.E., Sathasivam P. and MacNaughton K.W. Influence of cold, exercise, and caffeine on catecholamines and metabolism in men. J Appl Physiol 70: 2052-2058, 1991.
18. Strobel G., Hack V., Kinscherf R. and Weicker H. Sustained noradrenaline sulphate response in long-distance runners and intrained subjects up to 2h after exhausting exercise. Eur J Appl Physiol 66: 421-426, 1993.
19. Pearson.R., Ungpakorn G. and Harrison G.A. Catecholamine and cortisol level in Oxford college rowers. Br J Sports Med 29: 174-177, 1995.