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Studies on Functional Modifications of Thermoregulatory Mechanisms in Heat−Acclimated Rabbits*

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Abstract: In order to clarify the functional modifications which appeared during heat acclimation, male albino rabbits weighing from 2.5 kg to 2.8 kg were continuously exposed to a warmer environment (ambient air temperature (Ta)=30.0℃, relative humidity (r.h.)=60%) for 24 weeks (Heat−Acclimated). And, various parameters to general thermal stimulation were compared with those in control rabbits (Control) which were reared in thermoneutral environment (Ta = 25.0℃, r.h. = 60%) for same duration. For the general thermal stimulation, rabbits were lightly restrained only around the cervical region under the conscious condition. The changing rate of Ta was set to be 0.5℃/min. Pattern changes in rectal temperature (Tre) during Ta displacement was 1.1±0.2℃ (Mean±S.D.) in Heat−Acclimated, and 1.6±0.3℃ in Control, respectively. Mean threshold temperature of Ta at the beginning of vasodilation of the ear skin was 27.5±1.2℃ in Heat−Acclimated, but in Control, vasodilation already occurred under the thermoneutral condition in 25.0℃ of Ta. On the other hand, vasoconstriction of the ear skin in Heat−Acclimated occurred at 21.8±3.3℃ of Ta, about 7.0℃ higher than that of Control (14.7±2.9℃). It is supposed that during heat acclimation, shift of threshold temperature of Ta for inducing peripheral vaso−dilation and −constriction appeared, resulting in prevention of the change of core temperature. Under anesthesia with sodium pentobarbital (20 mg/kg, i.p.), however, differences in pattern changes of the parameters between two groups disappeared. These differences during Ta displacement could be observed again two or three days after anesthesia. From these results, it is assumed that functional modifications during heat acclimation might occur in the neuronal mechanisms which were influenced by anesthesia. In order to know what is important for these differences, vasomotor responses in the ear to intravenous administration of α adrenergic−blocker (phentolamine mesylate, 3 mg/kg, i.v.) were observed

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and these sympathetic vasoconstrictor tones were compared. Before intravenous administration of phentolamine, Tea at 25.0℃ was maintained at near the Ta both in Control and Heat−Acclimated. After administration of the drug, however, the degree of vasodilation in the ear skin was larger in Control than in Heat−Acclimated. From this result, it is suggested that at the same Ta, vaso−constrictor tone is different between Heat−Acclimated and Control.

Key words: Heat acclimation, Thermoregulation, Core temperature, Cutaneous vasodilation and −constriction, Sympathetic vasomotor activity

INTRODUCTION

Homeothermic animals can control their core temperatures within the limits of about ± 2℃ in spite of much larger variations in ambient temperature. They constantly detect the organisms' thermal fluctuations and attempt to keep them in balance (Bligh, 1978). It has been considered that they have a dynamic balance between heat production and heat loss, and regulate them according to their external and internal condition (Hensel, 1973). And, a combination of thermal inputs lead to some kinds of integrated thermoregulatory responses, such as shivering, non−shivering thermogenesis, vasoconstriction, vasodilation, panting, and sweating, as well as thermal comfort or behaviors (Hensel, 1981). In spite of many data regarding the physiological and biochemical changes during prolonged thermal exposure (Chaffee & Roberts, 1971; Janský, 1973; Hales, 1973; Hensel, 1981; Fujiwara *et al.*, 1986; Horowitz *et al.*, 1986), knowledge about the modifications in the regulatory mechanisms that are induced during heat or cold exposure is somehow limited. Recently, it has been considered that the changes in nervous mechanisms during thermal stimulation may occur at any level of the thermoregulatory system (Hensel, 1973). In the present experiments, therefore, in order to clarify the functional modifications which appeared during heat acclimation, thermoregulatory responses were simultaneously recorded in rabbits which have been submitted to long−term heat exposure.

MATERIALS AND METHODS

Animals

Male adult albino rabbits (*Oryctolagus cuniculus*) weighing from 2.5 kg to 2.8 kg were used in these experiments. They were housed individually in a cage, and were provided 150 g of commercial rabbits chow and 500 ml of tap water per day. Ambient air temperature (Ta) and relative humidity (r.h.) of animal room were kept at 25.0℃ and 60%, respectively. Light−darkness photoperiod was 12h:12h, with light period from 7 to 19 o'clock. After two weeks, rabbits were divided into two groups at random, and one group began to be exposed to a hot environment at 30.0℃ of Ta and 60% of r.h. for 24 weeks as a model of long−term heat acclimated animal (Heat−Acclimated), and the other group

remained at 25.0℃ of Ta and 60% of r.h. in the thermoneutral condition for the same duration as control (Control). Rabbits of both groups were checked for their general conditions (rectal temperature, respiratory frequency and body weight) in every morning at 10 o'clock.

Experimental Procedure

In order to minimize the influence of diurnal variation, all experiments were performed from about 10 to 16 o'clock, and were carried out in an environmental control chamber which could regulate Ta automatically. Relative humidity was kept constant at 60% throughout the experiment. Temperatures of the rectum (Tre), right and left ear (rTea, lTea) and ambient air (Ta) were continuously recorded in every minute with the thermistor probes (K−270, Takara Kogyo). Respiratory frequency (RF) was detected by a strain gauge transducer which was attached around animal's abdomen and counted by data analyser (ATAC 450, Nihon Koden). Blood pressure (BP) was measured from the right femoral artery, and heart rate (HR) was calculated from its pulse by the same data analyser.

Experiment 1

Animal was restrained minimum only around the cervical region, but allowed free motion of its limbs. To assess the thermoregulatory responses against the heat and cold loads, each rabbit from both groups was submitted to the following 'general thermal stimulation'; 25.0℃ (as thermoneutral environment for 30 min) → 40.0℃ (as hot environment for 30 min) → 10.0℃ (as cold environment for 30 min) → 25.0℃ (as thermoneutral environment again for 30 min). As the changing rate of Ta was constantly set to be 0.5℃/min throughout the experiment, Ta was raised from 25.0℃ to 40.0℃ within 30 min, and it took 60 min to reach 10.0℃ and raised to 25.0℃ in another 30 min. In total, 240 min were required to one series of experiment.

Experiment 2

In order to know what is important for these thermoregulatory modifications during heat acclimation, effects of general anesthesia were observed in the same rabbits used in Experiment 1. The same protocol as Experiment 1 was followed, except that rabbit was previously anesthetized with intraperitoneally administrated sodium pentobarbital (Nembutal, Abbott; 20 mg/kg) and, that fixed the limbs lightly.

Experiment 3

To compare the cutaneous sympathetic activities between two groups, adrenergic α−blocker was administrated at 25.0℃ of Ta. A polyethylene canula (SR−OT2225C, Terumo) was guided into the right retroauricular vein for the administration of phentolamine mesylate (Regitin, Ciba−Geigy). The amount of administration was always 3 mg/kg for each animal, using the drug dissolved in 1.0 ml of physiological saline solution. Experiments were started when Tea became approximately the value of Ta. For checking the direct effects by intravenous injection itself, same volume of physiological saline solution was injected before the drug administration through the canula. The

degree of vasodilation in the left ear was compared between two groups of rabbits at 25.0℃ of Ta.

Statistical analysis

Differences between two groups were compared by U−test. Significance was assumed when the value was $p<0.05$ or $p<0.01$.

RESULTS

The following parameters of Tre, RF and increasing rate of the body weight (ΔW) per day were compared between two group of rabbits. In Fig. 1, solid circles (●−●) and open squares (□−□) represent the mean value ± standard deviation of a week in Control (N=8) and Heat−Acclimated (N=6), respectively. Arrows at zero in the horizontal

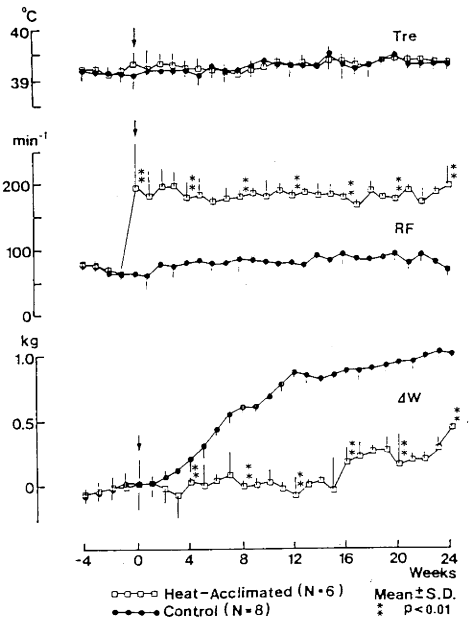

Fig. 1. Effects of long−term thermal exposure on rectal temperature (Tre), respiratory frequency (RF) and increasing rate of body weight per day (ΔW) in Heat−Acclimated (N = 6) and Control (N = 8) rabbits. Open squares for Heat−Acclimated (□−□) and solid circles for Control (●−●) show mean values ± standard deviations (M. ± S.D.) of one week's values measured at 10 o'clock in every morning. At arrows, randomly selected one group of rabbits was exposed to 30.0℃ of ambient air temperature (Ta), and the other group remained at 25.0℃ of Ta. Asterisks (*) show the statisically significant differences ($p<0.01$) between the values for Heat−Acclimated and Control.

axis mean the starting point of heat exposure. Although Tre of Heat−Acclimated was shifted to higher level (38.9±0.8℃) compared with that before heat exposure (38.3±0.6℃) during the first week of the exposure, it returned to the initial level at the second week, and thereafter there were no significant differences between Control (38.3±0.4℃) and Heat−Acclimated (38.4±0.3℃) during heat exposure. On the other hand, RF of Heat−Acclimated remarkably increased from 91±11 breaths/min to 220±24 breaths/min just after starting heat exposure. This significantly ($p<0.01$) high frequency of RF was maintained during heat exposure for 24 weeks. Body weight of the Control tended to increase with time, however, the increasing rate of Heat−Acclimated became smaller for about 70% of it's initial value during the first week of heat exposure and

Table 1. Mean valus of Ta and Tre in both groups when vaso−dilation and −constriction occurred in the ear skin

		Control (N=8)	Heat−Acclimated (N=6)
Thresholds for Vasodilation of Ear Skin	(℃)	Ta < 25.0	Ta = 27.5±1.2 Tre= 38.9±0.4
Thresholds for Vasoconstriction of Ear Skin	(℃)	Ta = 14.7±2.9 Tre= 38.8±0.2	Ta = 21.8±3.3* Tre= 39.4±0.5*
⊿ Tea(Max−Min)	(℃)	27.5±1.9	27.9±2.2
⊿ Tre(Max−Min)	(℃)	1.6±0.3	1.1±0.2*

Asterisks (*) represent the significant differences ($p<0.05$) from Control values. Abbreviations are same as shown in Fig. 1.

reached the initial level at the 5th week, and it increased to about 115% at the 7th week. It reflected the decrease of food consumption. After 24th week of acclimation, mean values (M.±S.E.) of body weight were 3.5±0.3 kg and 3.1±0.4 kg in Control and Heat−Acclimated, respectively.

Experiment 1

Various kinds of parameters such as Tre, right and left Tea, RF, BP and HR were simultaneously recorded. During the time course of general thermal stimulation for 240 min, about 1℃−3℃ of Tre change, and dynamic changes in right and left Tea from about 10.0℃ to about 40.0℃ were observed. Change patterns between Tea and Ta were colsely related. Initial values of RF at the beginning of the general thermal stimulation at 25.0℃ varied in each rabbit. However, according to Ta shift from 25.0℃ to 40.0℃, RF gradually increased and finally 'panting reaction' occured in all animals. But, threshold of Ta for the panting reaction was not always consistent in each experiment. On the other hand, BP and HR were maintained fairly constant at 125±19 mmHg, and 225±26 beats/min during Ta displacement. Changing patterns in Tre and Tea against Ta displacement (For details, *see* Fujiwara *et al.*, 1985; Ye−Win *et al.*, 1985) were plotted as shown in Figs. 2−A and 3−A. They were analyzed as the indexes of body core temperature and cutaneous vasomotion, respectively. In Table 1, it summarized that mean values and standard errors of Ta and Tre in both groups when vaso−dilation and −constriction occurred in the ear. In Heat−Acclimated, vasodilation of ear skin started at 27.5±1.2℃ of Ta, and Tre at that point was 38.9±0.4℃. In Control, on the other hand, Tea was kept at high level of 35.9±0.3℃ at the starting point of general thermal stimulation at 25.0℃ of Ta. Therefore, threshold of Ta for the vasodilation of the ear skin was thought to be under 25.0℃. Thresholds of Ta for vasoconstriction of the ear skin were 21.8±3.3℃ at 39.4±0.5℃ of Tre and 14.7±2.9℃ at 38.8±0.2℃ of Tre in Heat−Acclimeted and Control, respectively. ⊿Tea ((Max.−Min.)Tea) during general thermal stimulation between two groups were similar (27.5±1.9℃ in Control, 27.9±2.2℃ in

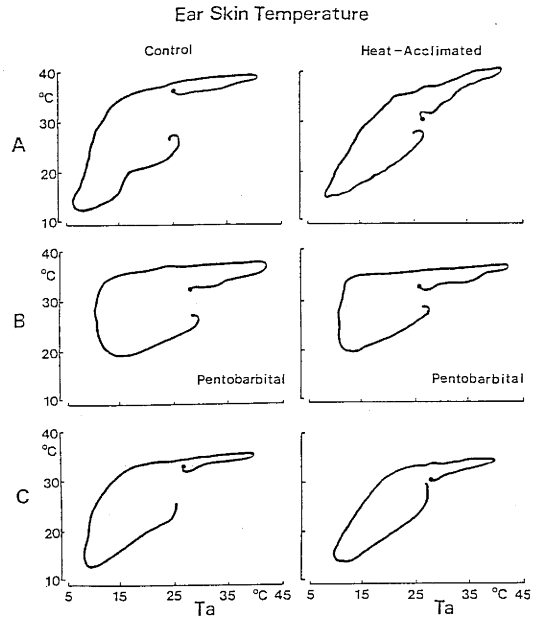

Fig. 2. Typical pattern changes in ear skin temperature (Tea) plotted against Ta displacement during the time course of general thermal stimulation changing from 10.0℃ to 40.0℃ in Control (right column) and in Heat−Acclimated (left column) groups, respectively. Rows A, B and C represent the pattern changes of Tea before, during and after anesthetized conditions with intraperitoneal administration of sodium pentobarbital (20 mg/kg), respectively.

Heat−Acclimated). ⊿Tre ((Max.−Min.)Tre) during general thermal stimulation were significantly ($p<0.05$) smaller in Heat−Acclimated (1.1±0.2℃) than in Control (1.6±0.3℃).

Experiment 2

In order to know what is important for these differences shown in Experiment 1, effects of general anesthesia on Tea and Tre during the general thermal stimulation were observed. Figure 2 shows a typical effect of general anesthesia on Tea in Control (left column of the figure) and Heat−Acclimated (right column) used in Experiment 1. Rows A, B and C show the results before, during and after general anesthesia, respectively. In row B, 20 mg/kg of sodium pentobarbital was intraperitoneously administrated. As the effects of general anesthesia varied from rabbit to rabbit, it is difficult to analyze the threshold of Ta for the vaso−dilation and −constriction of the ear skin. However, Tea at maximal Ta at 40.0℃ tended to be lower in the anesthetized rabbit (about 37.8℃) than in the unanesthetized one (39.1±1.8℃), and in the time course of general cooling, Tea showed only slight decrease. Rapid fall in Tea was observed after Ta reached to 10.0℃, but the fall in the anesthetized rabbit was quite smaller than that of the unanesthetized one. In case of general heating from 10.0℃ to 25.0℃, vasodilation of the

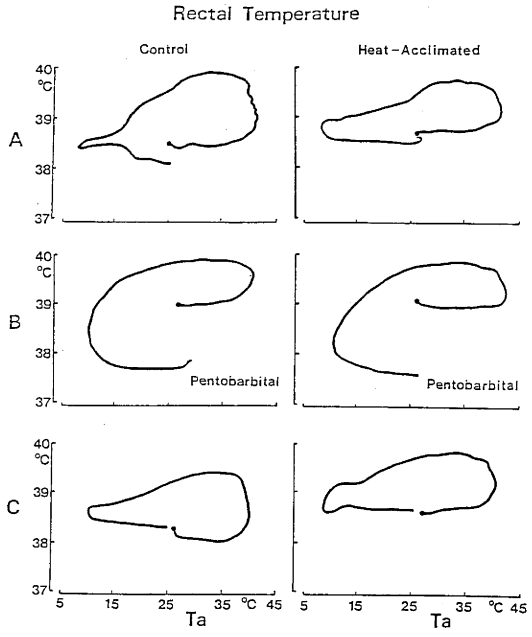

Fig. 3. Typical pattern changes in rectal temperature (Tre) plotted against Ta displacement in the same Control (right column) and Heat−Acclimated (left column) rabbits as shown in Fig. 2. Rows A, B and C represent the pattern changes of Tre before, during and after anesthetized conditions with intraperitoneal administration of sodium pentobarbital (20 mg/kg), respectively.

ear skin slowly occurred, and its slope in the anesthetized rabbit was less than that of the unanesthetized one. Two or three days after the experiments under anesthesia, the same rabbits were submitted again to the same general thermal stimulation (Fig. 2−C). Changing patterns of Tea against Ta displacement were quite similar to those observed before anesthesia. Figure 3 shows the effect of general anesthesia on Tre in the same rabbit used in Fig. 2. As shown in Fig. 2, right and left columns of the figure show the changing patterns in Control and Heat−Acclimated, and rows A, B and C show the results before, during and after general anesthesia, respectively. When Ta shifted from 25.0℃ to 40.0℃, Tre of both groups showed slight increases. However, in the time course of general cooling, Tre fell remarkably down to under 38.0℃. Both groups of rabbits showed severe hypothermia. And, these hypothermia did not recover after the time course of general heating to 25.0℃. Changing patterns in Tea and Tre under general anesthesia were somehow different in each animal, as shown in various different patterns. However, differences between Control and Heat−Acclimeted which were observed in unanesthetic condition disappeared both showing similar patterns not only in Tea but also in Tre.

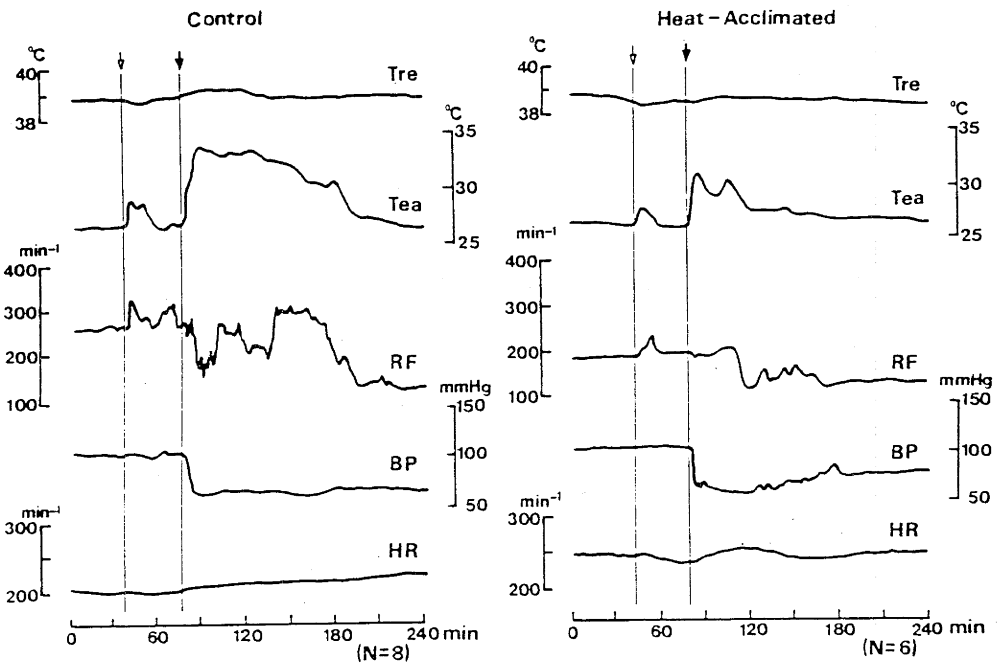

Fig. 4. Effects of intravenous administration of phentolamine mesylate on various parameters at 25.0℃ of Ta in Control (right column, N = 8) and in Heat−Acclimated (left column, N = 6). Solid and open arrows represent intravenous administration of phentolamine (3 mg/kg, i. v.) and same volume (1 ml/body, i. v.) of physiological saline solution. BP and HR represent the blood pressure and heart rate, respectively. Other abbreviations are same as shown in Fig. 1 and 2.

Experiment 3

Experiments were performed to compare the vasomotor tones between two groups. In Figure 4, effects of intravenous administration of phentolamine, one of the most potent α−adrenergic blocker, on various parameters at 25.0℃ of Ta were shown both in Control (right column of the figure) and Heat−Acclimated (left column) groups. Solid and open arrows show the points of administration of phentolamine (3 mg/kg, i.v.) and the same volume (1 ml/body, i.v.) of physiological saline solution, respectively. Before intravenous administration of phentolamine, Tre were kept constant at about 39.0℃ and Tea were maintained at near the Ta both in Control and in Heat−Acclimated. RF was higher in Control than in Heat−Acclimated. On the contrary, HR was lower in Control. BP were almost the same at about 100 mmHg in both groups. After administration of the drug, Tre tended to increase slightly in both groups. The degree of vasodilation in the ear skin was larger in Control. Both RF and BP depressed their values. On the other hand, HR increased slightly in both groups.

DISCUSSION

As well as other homeothermic animals, rabbits can control their core temperatures within the limits of about ±1℃ in spite of much larger variation in ambient temperature (Hensel, 1973). In the present experiments, Tre as an index of body core temperature in Heat−Acclimated shifted temporarily toward the higher level (0.6℃) by heat exposure than that in Control, but it returned to the initial Tre after one week of heat exposure. It may be thought that the capabilities of evaporative heat loss rised according to the remarkable increases in RF. It was also reported (Cassuto, 1968) that the metabolic rate decreased in golden hamster which have been exposed to chronic heat (29−30℃) as compared with the 24.5℃ group. He indicated that less energy is required for body maintenance and may reflect enzymatic changes in metabolic activity in a hot environment. Furthermore, it is well established that the rabbit's ear is one of the most important effectors in their thermoregulatory systems. As the ear is a cutaneous thin tissue and all blood vessels are near the surface, it can easily exchange heat with environment. At 25.0℃ and 30.0℃ of Ta, mean Tea were maintained at 26.3±1.1℃, and 31.9±1.9℃, respectively. However, they suddenly rose up to near 37℃ reflecting the emotional reflexes by the treatments such as attachments of thermistor probes or fixation, and it took long time, for about one hour, to recover. Therefore, at the start of this experiment, Tre in both groups were maintained at relatively high values. For Heat−Acclimated, however, the decrease in Ta from 30.0℃ to 25.0℃ was thought to be severer stimuli than emotional one, and fall of Tea was observed. Mean threshold temperature of Ta which induced the vasodilation of the ear skin in Heat−Acclimeted was 27.5±1.2℃. On the other hand, 25.0℃ of Ta was familiar to the Control, and Tea was maintained at 35.9±2.3℃ at thermoneutral condition. Vasoconstriction of the ear skin in Heat−Acclimated occurred at 21.8±3.3℃ of Ta. The difference in Tre during Ta displacement was 1.1±0.2℃ in Heat−Acclimated, and it was significantly ($p<0.05$) smaller than that in Control (1.6±0.3℃). These results support the idea that threshold temperatures of Ta to induce peripheral vaso−dilation and −constriction shifted according to the continuous heat exposure resulting in the effective maintenance of the body core temperature.

In the present experiments, effects of relatively deep anesthesia on Tea and Tre during the general thermal stimulation were observed. Barbiturates is one of the most commonly used injectable anesthetics for animals. Generally, anesthetic drugs reversibly produce an unconscious state, or unawareness of pain. They cause depression of the nervous system and, in addition, may alter various functions of the organism (Strobel and Wollman, 1969). Since the susceptibility to anesthesia in rabbits varies widely according to their conditions, it is difficult to regulate the depth of anesthesia (Murdock, 1969). In the present experiments, as shown in Figs. 2 and 3, differences in pattern changes of the parameters between two groups disappeared under anesthesia. It has been reported (Strobel and Wollman, 1969) that the rabbits anesthetized by barbiturates may still be ataxic on the following day. However, two or three days after anesthesia, the differences on Tea and Tea during Ta displacement were observed again in both groups. From

these facts, it is assumed that functional modifications in heat acclimation might occur in the neuronal mechanisms which were influenced by anesthesia.

Grant and his colleagues (1932) performed extensive investigations on neural and thermal influences over the blood flow of rabbit ear. It is well known that blood flow through the extremities is controlled exclusively via noradrenergic sympathetic fibers (Folkow, 1955). Increase in sympathetic tone causes vasoconstriction and its decrease in tone causes vasodilation (Hensel, 1973). And, there were many studies about the importance of the sympathetic nervous system and the cutaneous blood flow in the control of body temperature (Walther *et al.*, 1970; Iriki *et al.*, 1971; Riedel *et al.*, 1972). For example, a direct comparison of sympathetic activity and cutaneous blood flow during thermal stimulation of the central nervous system was made by Simon (1971). When either the hypothalamus or the spinal cord of rabbits was heated, vasoditlation in the ear vessels and decrease in discharge of the ear sympathetic nerve were observed. These vasomotor reactions which are mediated by adrenergic nerves are regulated under the general thermoregulatory control of the cutaneous circulation (Brück & Hinckel, 1982; Roberts and Zygmunt, 1984).

In the present experiments, to compare the sympathetic vasoconstrictor tones of the ear skin, the degree of vasodilation in the ear skin to intravenously administrated phentolamine (3 mg/kg) were studied in both groups. Before administration of the drug, Tea was maintained at near Ta both in Heat−Acclimated and Control, after the drug administration, however, it was larger in Control than in Heat−Acclimated. As phentolamine is one of the most potent sympathetic α−adrenergic blocker, it is suggested that vasoconstrictor tone might be different between Heat−Acclimated and Control at the same Ta of 25.0℃.

It is considered that controlling mechanisms in the central nervous system and/or the gain of the effectors against the inputs may be modified during continuous heat exposure. Further study is required for revealing the functional modifications in heat acclimation.

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暑熱順化ウサギの体温調節能変化に関する研究

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暑熱環境への長期暴露により生体の体温調節反応がいかに変化するのかを知るために，体重2.5 kg から2.8 kg の雄性成熟ウサギを用いて実験を行なった．
まず，室温30.0℃・相対湿度60％の暑熱環境下で24週間飼育した暑熱順化ウサギと，室温25.0℃・相対湿度60％の中性温域で同期間飼育した対照ウサギの両群に，頚部のみの軽固定下にて，10.0℃から40.0℃の温度帯の温熱負荷を全身に加え，その間に深部体温の指標としての直腸温，

耳介皮膚血管運動の指標としての耳介皮膚温等を測定した．その結果，暑熱順化ウサギの直腸温の変動幅は，1.1±0.6℃（Mean±S.D.）で，対照ウサギの1.6±0.3℃に比べ有意に小さくなった．更に，暑熱負荷による耳介皮膚血管拡張，及び寒冷負荷による耳介皮膚血管縮小誘発の閾値温は，各々27.5±1.2℃，21.8±3.3℃と対照ウサギのそれら（<25.0℃，14.7±2.9℃）に比べ，高温側へシフトしていた．しかしこの両群における差異は，Sodium Pentobarbital（20 mg/kg，i.p.）による全身麻酔下では消失した．この結果から，連続的な暑熱暴露によりウサギは，1）末梢の温熱刺激に対する感受性が増大する事により，2）温熱負荷時の深部温の変動幅が減少する事，3）この反応の修飾には神経機構が関与している可能性がある事が示唆された．さらに，同一環境温下において，両群に adrenaline の α− blocker の一つである phetolamine mesylate（3 mg/kg，i.v.）を投与した時の耳介皮膚血管拡張の程度が異なる事から，耳介皮膚に於ける交感神経 vaso−constrictor の tone は，両群で異なるものと思われる．

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