Abstract  The cutaneous vasodilation and sweating responses of prepubertal children to heat stress were examined. Seven prepubertal boys (9–11 years old) and 9 young men (20–24 years old) were seated wearing only swimming trunks while the air temperature ($T_a$) was linearly increased from 28°C to 40°C over 50 min and then maintained at 40°C for an additional 10 min. Skin temperature, cutaneous vascular conductance (CVC), and local sweating rate ($m_{sw}$) were measured at multiple sites on the body. The boys had a significantly greater mean surface area-to-mass ratio compared with the young men. The rectal temperature did not change in either group with increasing $T_a$, although it was significantly higher in the boys. During the first half of the exposure period, when $T_a$ was less than the mean skin temperature ($T_{sk}$), the boys had significantly higher CVC on the chest and significantly lower $m_{sw}$ on the chest and thigh as compared with the young men. During the latter half of the exposure, when heat stress was increased as $T_a$ exceeded $T_{sk}$, the boys had significantly higher CVC on the chest and significantly lower $m_{sw}$ on the chest and thigh as compared with the young men. The mean body temperature at the onset of sweating was significantly greater in the boys than in the men. These results suggest that, compared with young men, prepubertal boys manifest greater physiological and perceptual strain under heat stress induced by $T_a$ exceeding $T_{sk}$, which is most probably attributable to a combination of lower evaporative heat loss, as evidenced by lower $m_{sw}$, and greater heat gain owing to a larger surface area-to-mass ratio. The maturation-related differences in heat loss responses vary according to body site. J Physiol Anthropol 28(3): 137–144, 2009 http://www.jstage.jst.go.jp/browse/jpa2 [DOI: 10.2114/jpa2.28.137]

Keywords: children, cutaneous vascular conductance, sweating rate, thermoregulation, body temperature

Introduction

Cutaneous vasodilation and sweating are the two main heat-loss responses to internal or external heat stress in humans. During exercise in neutral or warm conditions, children manifest thermoregulatory responses that depend more on dry heat loss by elevation of skin temperatures (possibly implying greater cutaneous vasodilation) rather than by wet heat loss (sweating), compared with young adults (Araki et al., 1979; Davies, 1981; Delamarche et al., 1990). The skin blood flow has been reported to be higher in children than in adults during or immediately following exercise in warm conditions (Drinkwater et al., 1977; Falk et al., 1992b). In addition, Shibasaki et al. (1997a, 1999) reported that, compared with young men, prepubertal boys had a higher skin blood flow on the trunk despite a lower sweating rate during both moderate exercise under warm conditions and at rest with passive heating. However, the boys regulated rectal temperature as effectively as did the men. These observations indicate that children rely more on dry heat loss via cutaneous vasodilation for heat dissipation when air temperature is lower than skin temperature.

Physical characteristics such as the surface-area-to-body-mass ratio and body fatness are related to cutaneous vascular and sweating responses (Havenith et al., 1995). Children have a larger surface-area-to-mass ratio, which promotes heat loss when the air temperature is lower than the skin temperature (Bar-Or, 1989; Falk, 1998) but results in greater heat gains when the air temperature is higher than the skin temperature. However, there have been no reports of the cutaneous vasodilation and sweating responses in relation to body site in children when the air temperature is higher than the skin temperature.

We hypothesized that when the air temperature is higher than the skin temperature, 1) prepubertal boys would exhibit greater physiological and perceptual heat strain and 2) the
differences in heat-loss responses related to maturity would vary depending on body site. To examine these hypotheses, we compared the thermoregulatory responses, especially heat-loss responses, of prepubertal boys and young men at rest in response to a linear increase in air temperature from 28°C to 40°C.

Methods

Subjects

Seven prepubertal boys (9–11 years old) and nine young men (20–24 years old) served as volunteer subjects. The boys were elementary school children without pubic hair and with prepubertal voices, and the young men were college students. All subjects were in good health, not under a physician’s care, and not taking any medication. All subjects and the parents of the children were given oral and written information about the procedures and possible risks involved in the study. Written informed consent was obtained from all subjects and the parents of the children. Verbal assent was also given by the children immediately before participation in the study. This study was approved by the institutional ethics committee at Osaka International University.

Experimental procedure

The subjects wore swimming trunks and maintained a sitting position on a chair in an environmental chamber at an air temperature ($T_a$) of 28°C and relative humidity (RH) of 40% for at least 60 min while instrumentation was attached. While the subjects remained seated at rest, the $T_a$ was increased linearly from 28°C to 40°C (at a constant rate of 0.24°C/min) over 50 min and then maintained at 40°C for an additional 10 min. The RH remained at 40% during the entire test period. The experiments were conducted in February and March, a season during which the subjects were not acclimated to heat. The subjects were asked to refrain from intense physical activity on the day of the test. To avoid the effects of diet-induced thermogenesis and to better control hydration, no food or water was ingested from at least 2 h prior to arrival at the laboratory until the end of the test period.

Measurements

Body surface area was determined according to the method of Fujimoto and Watanabe (1969). Skinfold thickness was measured at seven sites (chest, abdomen, back, flank, triceps, forearm, and thigh), and the mean skinfold thickness was calculated with equal weighting for each site. Percentage body fat was calculated from the sum of skinfold thickness of back and triceps (Nagamine and Suzuki, 1964). The maximal oxygen uptake ($\dot{V}O_{2\text{max}}$) was estimated for each subject while they exercised at a submaximal level by pedaling on a cycle ergometer at a constant frequency of 50 rpm for 5 min at four different exercise intensities. The heart rate (HR) was measured during the final minute of each exercise period. The $\dot{V}O_{2\text{max}}$ of each subject was estimated by extrapolating the relationship between the HR and the work rate to the estimated maximal HR for each subject.

Rectal temperature ($T_{re}$) was measured continuously with a rectal thermistor probe inserted 8 cm (for the boys) or 10 cm (for the men) beyond the anal sphincter. The skin temperature was measured with thermistor probes placed on the skin at nine sites (forehead, chest, abdomen, back, forearm, finger, thigh, lower leg, and foot). The mean skin temperature ($T_{sk}$) was calculated by weighting the nine sites as follows: forehead, 0.07; chest, 0.10; abdomen, 0.10; back, 0.15; forearm, 0.15; finger, 0.05; thigh, 0.18; leg, 0.13; and foot, 0.07 (Sasaki, 1981). The mean body temperature ($T_{b}$) was calculated by weighting $T_{re}$ and $T_{sk}$ as follows: $T_{re}$, 0.8; $T_{sk}$, 0.2 (Hardy and DuBois, 1937). The deviation of $T_{re}$ ($\Delta T_{re}$) and $T_{sk}$ ($\Delta T_{sk}$) during heat exposure from the baseline levels (measured at the end of the equilibrium period) was calculated every 5 min. The tympanic temperature ($T_{ty}$), which is sometimes more representative of core temperature (Cabanac, 1995), was measured using a tympanic thermistor (Takara Co., Ltd., Japan) only in the young men, because ethical considerations discouraged its use with the boys. All temperatures were recorded every minute by a computer-controlled data logger (model K722; Takara, Japan).

The skin blood flow on the forehead, chest, back, thigh, and finger (tip of middle finger) was monitored by laser Doppler flowmetry with identical instruments ($\lambda=780\text{ nm, fiber separation of 0.5 mm; Advance ALF-21, Japan}$) and expressed as laser Doppler flow (LDF; output range 0–2 V). Each probe was placed on a site on the skin near the respective sweating capsule (except for the finger) taking care to avoid placing the fiber optic ends directly over a superficial vein or hair follicle. Local sweating rates ($m_{\dot{w}}$) were measured on the forehead, chest, back, forearm, and thigh using the ventilated capsule method. Dry nitrogen gas was pumped through the respective capsules (7.54 cm²) at a rate of 1.0 l/min. The humidity of the nitrogen gas flowing out of the capsules was measured with a capacitance hygrometer (Vaisala HMP 133Y, Finland). The hygrometer and laser Doppler flowmetry output signals for $m_{\dot{w}}$ and LDF measurements, respectively, were sampled every 1.0 s and digitally converted. The mean $m_{\dot{w}}$ and LDF were calculated every minute by computer and expressed in mg·cm⁻²·min⁻¹ and mV, respectively. The systolic and diastolic blood pressures were determined every 10 min by brachial auscultation, using an autopsychomonometer (Speidel and Keller KG, Germany). Mean arterial pressure (MAP) was calculated as the diastolic pressure plus one-third of the pulse pressure. The cutaneous vascular conductance (CVC) was calculated by dividing LDF by MAP. In addition, the changes in CVC during heat exposure were normalized to 100% of the baseline levels [$\%\text{CVC}=(\text{CVC}/\text{baseline CVC})\times100$]. The HR was monitored continuously using a CM5 lead.

Thermal sensation was reported by each subject every 5 min using a nine-point scale: 1, very hot; 2, hot; 3, warm; 4, slightly warm; 5, neutral; 6, slightly cool; 7, cool; 8, cold; 9,
very cold.

Statistics

All of the data were expressed as means±SEM. An unpaired-t test was performed for the assessment of age-related differences in variables measured only once (e.g., subject characteristics, baseline values, \(T_b\) threshold for sweating onset). For the assessment of age-related differences in the time courses of variables, a two-way ANOVA with one between-subject factor (age: boys, men) and one within-subject factor (time points) was performed using data obtained every 5 or 10 min (\(T_{re}, T_{sk}, m˙_{sw}, \text{CVC}, \text{HR}, \text{and MAP}\)). For the two-way ANOVA, we assessed the data collected during the first half and the latter half of heat exposure separately, as the \(T_a\) exceeded \(T_{sk}\) at 31.0±0.8 min after the start of exposure in the boys and at 28.1±0.6 min in the young men, at which time \(T_{sk}\) was 35.73±0.18°C and 35.17±0.11°C, respectively. During the latter half of the heat exposure period, the boys had significantly higher \(T_{sk}\) than the men, but not during the first half of exposure. Similar differences between the two groups were observed for the skin temperature at each site except for the forehead (Fig. 2). There were no differences in \(\Delta T_b\) between the groups, even during the latter half of the heat exposure period (at the end of heat exposure: 0.64±0.06 vs. 0.52±0.06°C), although the boys had significantly higher \(T_{sk}\) during both the first half and the latter half of heat exposure.

Figure 1 shows the time courses of the \(T_{re}\), \(T_{sk}\), and \(T_b\) responses in the boys and young men as \(T_a\) increased linearly from 28°C to 40°C for 50 min and then maintained at 40°C for an additional 10 min. The \(T_{re}\) was significantly greater in the boys than in the men during the equilibration period (37.54±0.09 vs. 37.11±0.11°C for the boys and the men, respectively) and during heat exposure (at the end of heat exposure: 37.61±0.02 vs. 37.19±0.09°C), although the \(T_{re}\) did not change with increasing \(T_a\) in either group. \(T_{sk}\), which was measured only in the young men, increased significantly from 40 min after the start of heat exposure to the end of the exposure period (36.96±0.09, 37.06±0.09, and 37.18±0.07°C at the equilibration period, 40 min exposure, and 60 min exposure, respectively). Although there were no differences between the groups in \(T_{sk}\) during the equilibration period, \(T_{sk}\) increased significantly with increasing \(T_a\) in both groups. The \(T_a\) exceeded \(T_{sk}\) at 31.0±0.8 min after the start of exposure in the boys and at 28.1±0.6 min in the young men, at which time \(T_{sk}\) was 35.73±0.18°C and 35.17±0.11°C, respectively. During the latter half of the heat exposure period, the boys had significantly higher \(T_{sk}\) than the men, but not during the first half of exposure. Similar differences between the two groups were observed for the skin temperature at each site except for the forehead (Fig. 2). There were no differences in \(\Delta T_b\) between the groups, even during the latter half of the heat exposure period (at the end of heat exposure: 0.64±0.06 vs. 0.52±0.06°C), although the boys had significantly higher \(T_{sk}\) during both the first half and the latter half of heat exposure.

Figure 3 shows the CVC responses on the forehead, chest, back, thigh, and finger in the boys and young men as \(T_a\) increased. During the equilibration period, the boys had significantly greater CVC on the chest compared with the men,
but not at the other sites. The CVC increased significantly in both groups with increasing $T_a$. The boys had significantly greater CVC on the chest during the first half and on the chest and finger during the latter half of heat exposure; there were no differences in CVC between the groups at the other sites. The rate of increase in the CVC (%CVC) relative to the baseline on the forehead (at the end of heat exposure: $285 \pm 62$ vs. $159 \pm 15\%$) and finger ($141 \pm 13$ vs. $113 \pm 6\%$), but not the other sites, was significantly greater in the boys than in the men during the latter half of the exposure period.

Figure 4 shows the $\dot{m}_{sw}$ responses on the forehead, chest, back, forearm, and thigh in the boys and young men as $T_a$ increased. The $\dot{m}_{sw}$ increased significantly in both groups with increasing $T_a$. The time required for the onset of sweating tended to be longer for the boys, but not significantly so (forehead, $13.3 \pm 4.5$ vs. $9.8 \pm 3.2$ min; chest, $27.6 \pm 4.4$ vs. $20.9 \pm 2.9$ min; back, $28.9 \pm 4.7$ vs. $18.7 \pm 3.6$ min; forearm, $9.7 \pm 4.6$ vs. $20.7 \pm 3.2$ min; thigh, $30.0 \pm 4.3$ vs. $18.7 \pm 3.5$ min in the boys vs. the men, respectively). In both groups, the $\dot{m}_{sw}$ started significantly earlier at the forehead than at the other sites. The $T_b$ threshold for sweat onset was significantly greater at each site in the boys compared with the men (forehead, $36.97 \pm 0.03$ vs. $36.55 \pm 0.08^\circ C$; chest, $37.08 \pm 0.05$ vs. $36.65 \pm 0.08^\circ C$; back, $37.09 \pm 0.05$ vs. $36.63 \pm 0.08^\circ C$; forearm, $37.11 \pm 0.05$ vs. $36.64 \pm 0.08^\circ C$; thigh, $37.11 \pm 0.04$ vs. $36.63 \pm 0.08^\circ C$). The boys had significantly lower $\dot{m}_{sw}$ on the chest and thigh during the first half and the latter half of heat exposure. Similar tendencies that did not reach the level of significance were observed for $\dot{m}_{sw}$ on the back ($p=0.09$) and forearm ($p=0.09$) during the latter half of heat exposure, but not during the first half of exposure. The forehead $\dot{m}_{sw}$ in the boys increased remarkably during the latter half of heat exposure, as was also the case for the forehead CVC response, but no significant differences in the rate of increase were observed for the first half or latter half of the heat exposure period.

Figure 5 shows the HR and MAP responses and the thermal sensation in the boys and young men as $T_a$ increased. There were no differences between the groups in the HR during the equilibration period. The HR increased significantly in both groups with increasing $T_a$. The increase in HR relative to the baseline value was significantly greater in the boys than in the men during the latter half of the heat exposure period ($16.8 \pm 3.2$ vs. $10.4 \pm 1.4$ beats·min$^{-1}$ at the end of exposure), but not during the first half ($6.9 \pm 2.3$ vs. $3.3 \pm 1.3$ beats·min$^{-1}$ at 30 min after the start). The MAP was significantly lower in the boys than in the men both during the equilibration period and throughout heat exposure; however, the MAP did not
change during heat exposure in either group. The boys felt hotter during the latter half of heat exposure compared with the men (\(p < 0.01\)), but no differences in thermal sensation were observed between the groups during the equilibration period or the first half of the heat exposure period.

Discussion

It is well known that prepubertal children have an underdeveloped capacity to perspire owing to a lower sweat output per gland (implying that the sweat glands are smaller) (Falk et al., 1992a; Shibasaki et al., 1997a, b), and to a lower cholinergic sensitivity (Foster, 1969) and lower anaerobic capacity (Falk et al., 1991) of the sweat glands. In the present study, we also observed a higher \(T_b\) threshold for the onset of sweating and a lower \(m_{sw}\) in boys, which suggests underdevelopment of the sweating function. However, we did not observe a lower \(m_{sw}\) on the forehead, as the forehead \(m_{sw}\) in the boys increased rapidly during the latter half of heat exposure. The rapid increase in forehead \(m_{sw}\) corresponded to a similar response in forehead CVC. The existence of a selective brain cooling system in the human has been previously proposed (Cabanac, 1995). If the system is present, acceleration of heat dissipation on the forehead by increasing \(m_{sw}\) and CVC may contribute to cooling the brain. If so, our observations may support the interpretation that this system is activated earlier during heat exposure in prepubertal boys than in men.

Findings from the present study are in agreement with previous studies which showed that cutaneous vasodilation in response to heat stress was greater in boys than in young men (Drinkwater et al., 1977; Falk et al., 1992b; Shibasaki et al., 1997a, 1999). We observed higher CVC (at the chest and finger) and \(\%CVC\) (at the forehead and finger) in boys compared to young men. The age-related differences in the CVC response to heat stress observed at the forehead and finger were more marked during the latter half of the 60-min exposure period, during which \(T_s\) exceeded \(T_{sk}\), than they were during the first half of the exposure period. Considering the age-related differences in both \(m_{sw}\) and CVC responses, it seems that children may dilate more cutaneous vasculature to compensate for undeveloped sweating functions. However, in the present study, we did not observe higher CVC and \(\%CVC\) on the back and thigh in the boys compared with the men, even during the latter half of exposure. This finding supports a previous study that reported that age-related differences in cutaneous vasodilation may vary depending on the anatomical site (Shibasaki et al., 1997a).
Fig. 4  Local sweating rate ($m_{sw}$) on the forehead, chest, back, forearm, and thigh in prepubertal boys and young men exposed to increasing air temperatures. The values presented are means±SEM. The $p$-values presented are for the overall age effects during the first half and the latter half of the 60-min test.

Fig. 5  Time courses of heart rate (HR), mean arterial pressure (MAP), and thermal sensation in prepubertal boys and young men exposed to increasing air temperatures. The values presented are means±SEM. The $p$-values presented are for the overall age effects during the first half and the latter half of the 60-min test. * $p<0.01$ between groups during the equilibration period. A nine-point scale of thermal sensation was employed: 1, very hot; 2, hot; 3, warm; 4, slightly warm; 5, neutral; 6, slightly cool; 7, cool; 8, cold; 9, very cold.
Several factors may contribute to the greater cutaneous vasodilation observed in prepubertal boys, such as structural alterations in the cutaneous vasculature (Martin et al., 1995) or a greater withdrawal of vasoconstrictor tone or higher sensitivity of the cutaneous vasculature to active vasodilation systems (Shibasaki et al., 1999). Such age-related changes may not occur at uniform rates at all sites on the body surface. Although one review notes that functional nitric oxide (NO) is required for full expression of cutaneous vasodilation (Holowatz et al., 2007), there is no information as to whether maturation-related vascular changes in NO signaling contribute to greater cutaneous vasodilation in the boys.

We considered the possibility that the age-related differences in cutaneous vasodilation were attributable to differences in skin temperatures. However, age-related differences in the CVC response on the back and thigh were not observed, even though the skin temperatures were higher in the boys than in the men. When $T_a$ exceeds $T_{sk}$, the skin temperatures are modified by evaporative heat loss from sweating and by heat gain from the air to the skin, as well as the effects of cutaneous vasodilation (Bar-Or, 1989; Falk, 1998). Furthermore, the heat gain depends on the $A_{hy}$/mass; greater $A_{hy}$/mass ratios promote heat gain. We observed lower $m_\text{sw}$ and a greater $A_{hy}$/mass ratio in the boys. Therefore, the higher skin temperatures at the back and thigh in the boys may result from a combination of lower evaporative heat loss and greater heat gain from the air to the skin.

When $T_a$ is higher than $T_{sk}$, heat dissipation depends mainly on the augmentation in sweating. We observed that during the latter half of the 60-min heat exposure period the boys had lower $m_\text{sw}$ and greater heat gain from the air to the skin (as evidenced by higher skin temperature despite similar CVC levels on the thigh and back) compared with the men. In a test of responses to cold temperatures performed on the same levels on the thigh and back) compared with the men. In a test of responses to cold temperatures performed on the same levels on the thigh and back) compared with the men. In a test of responses to cold temperatures performed on the same levels on the thigh and back) compared with the men. In a test of responses to cold temperatures performed on the same levels on the thigh and back) compared with the men. In a test of responses to cold temperatures performed on the same levels on the thigh and back) compared with the men. In a test of responses to cold temperatures performed on the same levels on the thigh and back) compared with the men. In a test of responses to cold temperatures performed on the same levels on the thigh and back) compared with the men. In a test of responses to cold temperatures performed on the same levels on the thigh and back) compared with the men.

In conclusion, compared with young men, prepuberual boys showed more evidence of physiological strain, including higher CVC (%CVC), $T_{sk}$, thermal sensation, and HR, under the heat stress induced by $T_a$ exceeding $T_{sk}$. This greater strain is most likely attributable to a combination of lower evaporative heat loss as evidenced by lower $m_\text{sw}$ and greater heat gain owing to a greater $A_{hy}$/mass ratio. Age-related differences in sweating and cutaneous vasodilation responses might vary depending on the anatomical site.

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References


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