Influence of Pubertal Stage on Local Sweating Patterns of Girls Exercising in the Heat

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The influence of puberty on sweating patterns of girls exercising in the heat is not known. Nine- to 17-year-old girls, representing 4 stages of breast development: T1 (n = 21); T2 (n = 22); T3 (n = 25); and T4 (n = 22), cycled for 20 min at 60% in 35 °C. The population density of heat activated sweat glands was higher in T1 vs T3 and T4 and in T2 vs T4. Sweat drop area was lower in T1 vs T3 and in T1 vs T4, T2 vs T4 and T3 vs T4. The proportion of skin covered by sweat was lower in T1 vs T4. Sweating patterns of girls exercising in the heat are influenced by pubertal stage.

Effective human thermoregulation in the heat requires the ability to evaporate sweat from the skin’s surface. The sweating response to exercise depends on several factors including environmental conditions and the relative intensity of exercise, as well as an individual’s level of heat acclimatization, with sweating rate generally lower in children than in adults (1,7,12). Several studies have also reported age-related differences in sweating patterns (1,13), with sweating patterns described by population density of heat activated sweat glands, sweat drop area, and the proportion of skin covered by sweat (2,6). To our knowledge, however, studies describing sweating patterns (i.e., population density of heat activated sweat glands, sweat drop area, and the proportion of skin covered by sweat) of children during exercise in the heat have included boys only. Investigations involving girls would help contribute to our understanding in this area and possibly provide information about sex-based differences in sweating mechanics.

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Shibasaki et al. (13) and Inbar et al. (8) reported a higher population density of heat activated sweat glands in prepubertal boys than in young or older men. In spite of this higher density of heat activated sweat glands, children have a lower sweating rate when compared with adults, suggesting that sweating mechanisms develop during puberty although few studies have examined the independent effects of puberty. The influence of pubertal stage on sweating patterns of boys exercising in the heat was investigated by Falk et al. (6) who found that population density of heat activated sweat glands decreased and sweat drop area, sweating rate, and sweat production per gland increased throughout puberty. While the sweat pattern was characterized by numerous, yet small sweat drops in the least mature boys, but fewer, yet larger sweat drops in the most mature boys, the proportion of skin covered by sweat was approximately the same. The lower sweating rates but similar proportions of skin covered by sweat of the least mature boys led the authors to conclude that the boys’ pattern of sweat distribution may provide for more efficient cooling (6). Indeed, Inbar et al. (8) concluded that a major advantage of the prepubertal boys in their study seemed to be related to “highly efficient sweat evaporation”, possibly due to the boys’ sweating characteristics, including higher population density of heat activated sweat glands and smaller sweat drop area. Falk et al. (6) and Inbar et al. (8) studied males only. Therefore, it is unclear whether the above difference in sweating pattern between prepubertal boys, pubertal boys and men is also characteristic of females.

Greater understanding of the sweating response to exercise in children, and the influence of pubertal stage, is important for several reasons. First, recommendations for fluid intake for active individuals are often based on sweat losses; thus, further investigation of the development of the sweating response may be important from a fluid balance perspective. Second, the mechanisms involved in the development of sweating patterns during growth are not well understood, and there remains a need to distinguish between quantitative (size-dependent) and qualitative (size-independent) factors. Third, it has been believed for many years that, in very hot conditions, children do not thermoregulate as well as adults; new information about puberty-related sweating patterns could help to clarify, in part, children’s capacity for heat tolerance. Finally, there is a complete lack of data regarding sweating pattern characteristics for girls exercising in the heat, and the effects of pubertal development.

For these reasons, the purpose of this study was to investigate the influence of pubertal development on sweating patterns of girls exercising in the heat. Using validated and reliable methods of analyzing the sweating response, as has been reported previously (6), we hypothesized that sweating patterns (i.e., population density of heat activated sweat glands, sweat drop area, and the proportion of skin covered by sweat) would be influenced by pubertal stage thereby indicating the effect of maturation on mechanisms of the sweating response.

Methods

Participants

Ninety-two, healthy 9- to 17-year-old girls volunteered for this study. Pubertal stage was self-assessed based on breast development and the criteria of Tanner
The following stages were represented: T1 \((n = 21)\), T2 \((n = 22)\), T3 \((n = 25)\), and T4 \((n = 22)\). Two girls self-assessed breast development as Tanner 5 and were excluded from the analysis to maintain group homogeneity, which has been lacking in previous studies on this topic. Thus, data from 90 girls were analyzed. Group characteristics are presented in Table 1. Thirty-two girls had started menstruating, based on a nurse-conducted interview: T1 \((n = 0)\), T2 \((n = 3)\), T3 \((n = 12)\), T4 \((n = 17)\). All testing took place during the summer months, therefore, it was assumed that all girls were naturally heat-acclimatized during the time of testing and had the same degrees of heat-acclimatization before testing. Written informed consent was obtained from the parent and verbal assent from the daughter. The study was approved by the McMaster University Research Ethics Board, conforming to the Declaration of Helsinki on the use of human subjects.

**Visit 1**

Each girl visited the laboratory on two separate occasions. During the first visit the purpose and procedures of the study were explained to both the girl and her parent. Height (Harpenden wall-mounted Stadiometer 2109; 0.1 cm accuracy) and weight (Ancaster electro-scale model UMC-600; 20g accuracy) were also measured. Adiposity was assessed using bioelectrical impedance method (BIA-101A, RJL Systems Inc.). On each occasion, the girls were asked to come to the laboratory well hydrated by drinking water until ~1 hr before arrival. Upon arrival, each girl emptied her bladder before the BIA analysis. Peak oxygen uptake \((\dot{V}O_2\text{peak})\) was measured using an open-circuit system \((V_{\text{max}}\text{ Series, Sensor Medics})\). The McMaster all-out continuous progressive cycling protocol performed on a Fleish-Metabo cycle ergometer was employed, as previously described (3). The test was terminated upon the girl’s volitional exhaustion or when she could no longer maintain the 50 rpm cadence despite encouragement from the investigators.

<table>
<thead>
<tr>
<th>Pubertal Stage</th>
<th>T1 ((n = 21))</th>
<th>T2 ((n = 22))</th>
<th>T3 ((n = 25))</th>
<th>T4 ((n = 22))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (year)</td>
<td>10.1 ± 1.2</td>
<td>11.3 ± 1.4*</td>
<td>13.0 ± 1.6*†</td>
<td>14.1 ± 1.3*†</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>33.0 ± 7.7</td>
<td>41.9 ± 7.3*</td>
<td>54.8 ± 10.9*†</td>
<td>62.2 ± 11.5*†‡</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>137.2 ± 6.7</td>
<td>149.4 ± 10.2*</td>
<td>158.4 ± 7.0*†</td>
<td>164.5 ± 7.2*†‡</td>
</tr>
<tr>
<td>Body Fat (%)</td>
<td>19.7 ± 6.6</td>
<td>20.0 ± 5.7</td>
<td>25.4 ± 8.0*†</td>
<td>26.1 ± 4.9*†</td>
</tr>
<tr>
<td>(\dot{V}O_2\text{peak}) ((\text{ml} \times \text{kg}^{-1} \times \text{min}^{-1}))</td>
<td>43.8 ± 7.6</td>
<td>41.8 ± 5.2</td>
<td>39.4 ± 6.5</td>
<td>37.0 ± 5.8*</td>
</tr>
<tr>
<td>BSA ((\text{m}^2))</td>
<td>1.22 ± 0.24</td>
<td>1.32 ± 0.19</td>
<td>1.52 ± 0.21*†</td>
<td>1.60 ± 0.23*†</td>
</tr>
</tbody>
</table>

Values are mean ± SD. T1, Tanner 1; T2, Tanner 2; T3, Tanner 3; T4, Tanner 4; \(\dot{V}O_2\text{peak}\), peak oxygen uptake; BSA, body surface area. *significantly different from T1, \(p < 0.05\); †significantly different from T2, \(p < 0.05\); ‡significantly different from T3, \(p < 0.05\).
Visit 2

The second visit (5–7 days later) took place in a climate chamber with environmental conditions resembling a warm summer day (35 °C, 50% relative humidity (RH) and air velocity of <0.2 m·sec⁻¹). Each girl exercised for 20 min on the same cycle ergometer at a power output equivalent to that which corresponded to 60% of her measured VO₂peak at Visit 1. Twenty min was chosen as this is sufficient time for the sweating response to manifest (6). The girls dressed in athletic shorts, a bikini top, socks, and sport shoes. During the exercise, the following variables were recorded every 4 min: heart rate (HR; Sporttester PE4000), skin temperature (Tsk) at the subscapula site (Mikron M102 infrared thermometer), and rating of perceived exertion (RPE; Borg 6–20 scale).

Sweating patterns were assessed using a photographic technique (5), as previously described (6). This method is reliable and reproducible in the assessment of population density of heat activated sweat glands, sweat drop area, and the proportion of skin covered by sweat (4). Two min before the end of exercise, a subscapular skin site (approximately 3 × 3 cm) was dabbed lightly with dry, sterile gauze to remove any sweat. A small amount (~0.5 ml) of a vaseline-bromophenol blue (BPB) mixture was applied with a tongue depressor to the photographic skin site. The thickness of the Vaseline-BPB layer was approximately 0.1 mm. Vaseline prevents epidermal hydration, promotes sweat beading on the skin, and slows sweat drop coalescence. BPB stains the sweat droplets dark blue, increasing sweat-to-skin contrast. Immediately after the exercise test, a picture of the skin site was taken using a Minolta X-700 camera with a set of extension tubes, a ring flash, and a specially constructed attachment with a linear scale touching the skin. Computer-assisted slide analysis using Microcomputer Imaging Device (Imaging Research Inc., St. Catherines, Ontario, Canada) allowed for the assessment of population density, sweat drop area, and the proportion of skin covered by sweat. The measurement site (photographed area) is ~250 mm², with the analyzed area ~1/3 of the photographed site.

Statistics

One-way analysis of variance (ANOVA) was used to compare group characteristics. In a previous study involving boys (6), BSA accounted for 42% of the variance in sweating characteristics, indicating an important influence of body size. To control for the influence of body size and fitness, we performed a 1-way analysis of covariance (ANCOVA), with BSA and fitness as the covariates, to compare sweating pattern variables between groups. A Tukey post hoc test was used, when indicated, to identify significance among means. To further confirm the effects of pubertal stage, we also compared girls of similar chronological age but different pubertal stage using analysis of variance. A Tukey post hoc test was used, when indicated, to identify significance among means. To confirm the relationship between body size and sweating pattern, we performed Pearson correlations of BSA with population density, sweat drop area, and the proportion of skin covered by sweat. The level of statistical significance was set at $p \leq .05$. Values are means ± SD.
Results

HR, RPE, and $T_{sk}$ were similar among groups at the end of exercise (Table 2). Sweating pattern variables are presented in Figure 1. Mean values for population density of heat activated sweat glands ranged from $124.7 \pm 5.7$ glands per cm$^2$ in T1 to $91.0 \pm 4.1$ glands per cm$^2$ in T4 (Figure 1A). There was a significant ($p < .05$) group effect on population density; post hoc analyses revealed significant differences between T1 vs. T3 and T1 vs. T4, and between T2 vs T4. Mean values for sweat drop area ranged from $0.046 \pm 0.003$ mm$^2$ in T1 to $0.081 \pm 0.005$ mm$^2$ in T4 (Figure 1B). There was a significant ($p < .001$) group effect on sweat drop area; post hoc analyses revealed significant differences between T1 vs. T3 and T1 vs. T4; between T2 vs T4; and between T3 vs. T4. Mean values for the proportion of skin covered by sweat ranged from $5.74 \pm 2.01$ mm$^2$ in T1 to $7.23 \pm 2.15$ mm$^2$ in T4 (Figure 1C). There was a significant ($p < .05$) group effect on the proportion of skin covered by sweat; post hoc analyses revealed significant differences between T1 vs. T4.

Pearson correlations were significant between BSA and population density ($r=-.41, p < .05$) and sweat drop area ($r=.31, p < .05$), but not the proportion of skin covered by sweat ($r=.01, p=.89$).

Discussion

In agreement with our hypothesis, the results of the current study confirm that sweating patterns of girls exercising in the heat are influenced by pubertal stage. Progressive changes in components of the sweating response with increasing pubertal stage in girls confirm that the sweating response matures during childhood. Even when BSA (a reflection of body size) and fitness were controlled for in the analysis, a significant influence of pubertal stage on population density of heat activated sweat glands, sweat drop area, and the proportion of skin covered by sweat remained, suggesting that the mechanisms involved in sweating are, in part, size-independent.

The majority of previous studies involving sweating responses in girls have focused on sweating rate (local and whole body) and sweat electrolyte concentrations (10,11,14). To our knowledge, however, this is the first study to investigate the effects of maturation on sweating pattern characteristics of girls exercising in the heat. Similar to previous studies involving boys (6,8,13), we found a higher

### Table 2 HR, RPE, and $T_{sk}$ Responses at the End of Exercise in the Heat

<table>
<thead>
<tr>
<th>Pubertal Stage</th>
<th>$T_1$ ($n = 21$)</th>
<th>$T_2$ ($n = 22$)</th>
<th>$T_3$ ($n = 25$)</th>
<th>$T_4$ ($n = 22$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HR (bpm)</td>
<td>176 ± 16</td>
<td>175 ± 14</td>
<td>177 ± 10</td>
<td>175 ± 13</td>
</tr>
<tr>
<td>RPE</td>
<td>17.5 ± 2.6</td>
<td>15.8 ± 2.6</td>
<td>17.2 ± 2.2</td>
<td>16.0 ± 2.5</td>
</tr>
<tr>
<td>$T_{sk}$ (°C)</td>
<td>31.4 ± 1.5</td>
<td>31.8 ± 1.4</td>
<td>31.1 ± 1.0</td>
<td>31.1 ± 1.1</td>
</tr>
</tbody>
</table>

Values are mean ± SD. HR, heart rate; RPE, rating of perceived exertion; $T_{sk}$, skin temperature
Figure 1 — Influence of pubertal stage on population density of heat activated sweat glands (PD of HASG, A), sweat drop area (SDA, B) and proportion of skin covered by sweat (%SkA, C) of girls exercising in the heat. Values are mean ± SD. Bars linked with lines are significantly different from each other (p < .05).
population density of heat activated sweat glands in the least mature vs. most mature participants. Other characteristics such as sweat drop area displayed a progressive increase with advancing pubertal stage and this finding is also consistent with the male response. Thus, the available evidence suggests that growth-related changes in sweating pattern characteristics are similar between boys and girls. A limitation with previous work has been the lack of distinct pubertal groups between which comparisons could be made to better understand changes in sweating patterns in relation to pubertal development. For example, Shibasaki et al. (13) and Inbar et al. (8) only compared prepubertal boys to adult men, and Falk et al. (6) grouped their boys as prepubertal (T1), midpubertal (T2–4) and late-pubertal (T5), which made it difficult to distinguish when during puberty changes were occurring. However, these authors speculated that changes in sweat drop area may occur toward the end of puberty, as no differences were detected between the prepubertal and midpubertal groups (6). Because our study was designed to test girls at distinct stages of puberty, we were able to determine that changes in sweat drop area occur early in puberty, at least for girls, as girls at T3 were already different than girls at T1.

The current study adds new information about sweating patterns in girls at different pubertal stages. While most sweating characteristics demonstrated progressive changes during puberty, the proportion of skin covered by sweat was different only between the least mature and most mature girls. This finding is in contrast to that of Falk et al. (6) who did not find differences across their pubertal groups, although that study reported more heterogeneous groups of pubertal stages. However, sweating characteristics reported by Falk et al. (5) and in the current study were assessed at the same skin site using an identical photographic technique. A lower proportion of skin covered by sweat in the least mature girls is due to both a smaller sweat drop area and higher population density of heat activated sweat glands (see Figure 1B). Because Tsk was the same between all the groups, a smaller sweat drop area may translate into a more efficient evaporative heat loss, although we did not measure this directly. Inbar et al. (8) suggested that children have “highly efficient sweat evaporation”, which could be due to characteristics such as smaller, less widespread sweat drops. It will be important to confirm our findings using a longitudinal study design, which would allow the same children to be followed and tested over time. The cross-sectional nature of the present investigation cannot preclude that different pubertal groups also differed in other genetic and environmental factors, which we could not measure.

More study of the sweating response to exercise in children is needed to elucidate the mechanisms involved in the development of sweating patterns during growth. A decrease in population density of heat activated sweat glands with advancing pubertal stage may not be surprising since increasing body size results in higher BSA. Indeed, a significant inverse relationship between population density of heat activated sweat glands and BSA exists in children and young adults of both sexes (1) and we confirmed this relationship in the current investigation. For this reason, we adjusted our statistical analysis for BSA by conducting ANCOVAs on the sweating characteristics, thereby controlling for differences in body size that existed between the pubertal groups (Table 1). Using this approach as well as controlling for fitness, we still found a significant influence of puberty, strongly suggesting that there are qualitative changes to the sweating mechanism that occur during growth.
Our study was strengthened by the number of girls in each group; however, we acknowledge limitations with our study, as well. One limitation is that we did not measure whole body sweat rate, nor did we examine sweating characteristics under more prolonged exercise conditions. Having measured sweating rate would have provided a more complete picture of the sweating response and allow us to combine quantitative (sweat loss) and qualitative (sweating patterns) results. We focused our investigation on the sweating characteristics apparent early in exercise and measured these after a single, 20-min bout of moderate intensity cycling. Another limitation is that we made measurements of the girls’ sweating pattern at a single site (subscapular). It could be argued that sweating patterns may vary at different sites on the body, and we can only assume that if such regional differences existed they would be consistent from one pubertal stage to another and there is evidence to support this idea of proportionality, at least in population density of heat activated sweat glands (6).

In conclusion, we found that sweating patterns of girls exercising in the heat are influenced by pubertal stage, independently of BSA and fitness level. Whereas population density of heat activated sweat glands progressively decreased, sweat drop area progressively increased with advancing pubertal stage from T1 to T4. Further evaluation of the mechanisms responsible for sweating strategies during growth is needed to fully understand thermoregulatory ability in children.

References