SUSTAINED EXERCISE PLACES high demands on body thermoregulatory mechanisms, especially in conditions of high ambient temperature (T_a) and humidity. For competitive athletes and active individuals, the effective dispersal of the heat load generated by contracting muscle bears particular importance. Failure of mechanisms to effectively remove body heat during strenuous exercise would result in substantial decrements in physical performance while posing risk for eventual circulatory collapse, brain dysfunction, and generalized organ failure (21).

The dynamics of heat flux during sustained exercise can be briefly summarized (34): heat liberated by contracting muscle fibers is transferred away by its surrounding blood flow, resulting in an increase in core body temperature [estimated as rectal temperature (T_re)]. In response, hypothalamic control centers and peripheral receptors trigger compensatory cooling mechanisms, principally 1) cutaneous vasodilatation to augment skin blood flow (SBF) for convective heat loss to the surrounding air and 2) increased rate of sweating (SR) via sympathetic cholinergic stimulation to dissipate heat by evaporation at the skin-air interface. The magnitude of convective heat loss is governed by the local skin-air temperature gradient as well as adequacy of cutaneous blood flow. This means of heat dispersal is thus most effective in conditions of moderate environmental temperature, and it becomes less so as T_a rises. Heat loss by evaporation is directly related to both rate of sweat production and the skin-air water vapor pressure gradient. In high T_a, then, body heat loss is effected primarily through sweating, particularly in conditions of low ambient humidity.

Many factors influence this basic scheme, including level of aerobic fitness, clothing, energy substrate utilization, body composition, and wind velocity. Highly critical, however, is the state of body hydration and plasma volume, because increasing levels of dehydration incurred via sweating during exercise are reflected in decreases in cardiac output, decrements in SR, and rise in T_re (48). In summary, then, thermoregulatory efficacy during exercise is most closely linked to 1) adequacy of circulatory responses, 2) rate of sweat production, and 3) maintenance of body fluid volume, all in response to exercise intensity (19, 47).

When these thermoregulatory patterns were initially studied in children, certain maturational differences became evident (5–7). Most particularly, the SR of prepubertal boys during exercise was observed to be significantly less, by almost one-half, than that of young men. Recognized, too, were features unique to the pediatric population that might be expected to negatively influence body temperature regulation during exercise, including a greater body surface area-to-mass ratio (BSA/M), a higher metabolic demand relative to body mass (lower exercise economy) during weight-bearing exercise, slow acclimatization to heat, and a reduced cardiac output at a given metabolic rate compared with adults. Based on these observations, prepubertal children have been traditionally considered “less effective thermoregulators than adults,” at increased risk for exercise-induced heat illness as well as with diminished tolerance for exercise in hot climatic conditions (7, 11). As a consequence of this concern, particular guidelines for...
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fluid intake and sports activities in the heat have been formulated for child athletes (2, 6, 36).

This view of physically active youth as an at-risk group for heat injury and exercise intolerance in the heat has been based on a group of early studies that often lacked direct child-adult comparisons, failed to match subjects by relative exercise intensity, or involved extremes of Tₐ. More recently, a number of studies have assessed maturational differences in thermoregulatory responses to exercise in the heat while avoiding these methodological difficulties (25, 40, 44, 50). This review will reassess thermoregulation during exercise in the heat by children in light of these more recent reports and examine implications of any maturational differences in respect to their effects on physical performance and risk of heat injury. Initial sections will examine evidence for child-adult differences in various factors that bear on thermal regulation during exercise. Following this, the discussion will focus on the “so what?” factor: what evidence exists that any physiological differences between children and adults in thermal regulation during exercise can be translated to maturational differences in core temperature response, exercise tolerance, and risk of heat injury?

In this discussion, references to data in “adults” will indicate postpubertal young and middle-aged individuals (excluding elderly subjects, who possess their own unique thermoregulatory responses to exercise). All reported Tₐ will be expressed as dry bulb.

MUSCLE HEAT PRODUCTION AND ENERGY ECONOMY

The energy required to perform a given amount of muscle work [as assessed by oxygen uptake (V̇O₂), adjusted for substrate utilization] at a given work rate during cycle exercise is similar in children and adults (46). That is, muscular efficiency is not influenced by biological maturation. This implies that children possess qualitatively and quantitatively the same energetics of intracellular energy transfer and contraction coupling as do adults. More pertinent to the present discussion, initial sections will examine evidence for child-adult differences in various factors that bear on thermal regulation during exercise. Following this, the discussion will focus on the “so what?” factor: what evidence exists that any physiological differences between children and adults in thermal regulation during exercise can be translated to maturational differences in core temperature response, exercise tolerance, and risk of heat injury?

In summary, when exercising at a work rate that is commensurate with body size, heat production per body mass is expected to be equal in prepubertal children and adults. By this argument, then, children should not be disadvantaged by excessive heat production during exercise relative to their body mass compared with adults.

BSA/M

The processes of sweat evaporation and convection eliminate body heat at the skin surface. Thus individuals with a greater body surface area (i.e., heat radiator) relative to body mass (reflecting muscle mass, the heat generator) should be expected to expedite heat dispersion, reduce heat storage, and facilitate thermoregulation during exercise. By geometric principles, BSA/M is inversely related to body mass. Small animals have higher values than large ones, and children are no exception. The BSA/M ratio of the average 8-yr-old is almost 50% greater than that of the young adult.

In the popular viewpoint, children suffer an increased heat burden during exercise because metabolic rate per body mass in this age group is greater than the adult exercising at the same speed (5–7). Yet, that adult-child levels of metabolic expenditure and heat production during exercise are instead more appropriately considered in terms of relative exercise intensity is indicated by the following: 1) thermoregulatory mechanisms respond to heat production during exercise in respect to relative (i.e., %V̇O₂max) rather than absolute workloads (19, 47), and 2) in the real world of sports play, children do not exercise at the same work rates as adults. Instead, they participate at lower levels of physical activity commensurate with body size (muscle bulk, leg length, etc.).

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The greater BSA/M in children should be expected to be advantageous to their heat loss and thermal homeostasis during exercise compared with adults. A number of studies performed in adult subjects have supported this concept (16, 30). For example, Marino et al. (30) showed that BSA/M was negatively correlated with heat storage during running in highly trained distance runners, even in Tₐ of 35°C.

Other authors have criticized this concept as being oversimplistic (22, 36). Havenith (22) argued that confounding factors such as body composition, fitness, sex, and type and duration of exercise influence the effect of BSA/M on heat loss and that in certain conditions a low BSA/M may even be associated with lower rather than higher heat strain during exercise.

It has been suggested that in very hot climatic conditions, when Tₐ exceeds that of the skin (e.g., with a reversal of the skin-to-air temperature gradient), a higher BSA/M would act disadvantageously to absorb body heat from the environment.
Several studies have presented skin-to-air temperature gradients for children performing steady-state submaximal exercise in hot climatic conditions (14, 18, 25, 39, 40, 53). These permit an estimation of the level of Ta that might be necessary before a reversal of temperature gradient would become a handicap to children with their higher BSA/M. Average gradients for individual studies are plotted in Fig. 1 against Ta. These data suggest that a reversal of skin-air temperature gradient would only be expected to occur at Ta exceeding 38°C (100°F). This implies that higher BSA/M would only become a potential liability in extremely hot climatic conditions, which are not encountered during sports play.

There exists no experimental evidence, however, that this actually occurs. Two studies have revealed no significant group differences when comparing skin temperatures of children and adults performing exercise in extremely high Ta (41 and 48°C) at the same relative intensity (14, 25). In these reports, then, children and adults had similar skin-air gradients when the BSA/M was on the average 34% greater in the youth. The change in T_re with exercise was similar between groups in both studies.

These data do not support a higher BSA/M as a liability for children at high ambient temperatures. Reversal of skin-air gradient during exercise occurs only at marked extremes of Ta and appears to be similar in prepubertal children and adults without consequence to dispersal of body heat relative to BSA/M.

**Sweat Production**

A diminished SR is the most characteristic feature that distinguishes thermoregulatory response to exercise of prepubertal boys from that of adult men. An early study by Kawa-hata (28) in resting subjects in conditions of 45°C and 97% relative humidity (RH) indicated that whole body SR of 9-yr-old boys (455 ml·m⁻²·h⁻¹) was approximately one-half that of men 21–27 yr old (815 ml·m⁻²·h⁻¹) (28). Subsequent studies during both low-grade and highly intense sustained exercise have confirmed the magnitude of this age effect (7, 25, 33, 50).

These investigations suggest that the greatest gains in rate of SR during exercise (in male individuals) coincides with the age of puberty (3, 17). Falk et al. (17) compared sweating responses in groups of pre-, mid- and late-pubertal boys who cycled at 50% V̇O₂max for two 20-min bouts in 42°C, 20% RH (17). Average SR for the three groups were 4.95 ± 0.23, 5.79 ± 0.20, and 6.70 ± 0.42 ml·min⁻¹·m⁻², respectively. Size of sweat drops (drop area) increased with greater pubertal stage. In a similar study, Meyer et al. (33) reported that SR of boys aged 9.1 ± 1.4 and 11.7 ± 0.7 yr while cycling in the heat were similar but were only approximately one-half that of men aged 21.4 ± 3.2 yr.

Based on such data, Inoue et al. (26) suggested that the lower SR in boys was related to lack of male hormonal effects that occur at the time of puberty. Supporting this, the studies assessing sex-related SR at rest have indicated no differences in young girls from either prepubertal boys or adult women (28, 38).

This sex-related pubertal effect implies that variations in androgenic stimulation are responsible for maturational differences in SR. Still, the role of testosterone in regulation of sweat production has not been firmly established (7). Inoue et al. (26) noted that the frequency in pulsatility of sweat production relative to rate of sweat flow was generally lower in boys compared with men, with no differences in SR in respect to mean body temperature. They concluded that the lower SR in boys relative to young men reflected underdevelopment of peripheral sweating mechanisms rather than any impairment of central-driven sudomotor function.

Regional body differences in SR are observed in children as well as adults. But Shibasaki et al. (50) found that local SR values in chest, back, and forearm sites were significantly lower in boys than young men.

The maturational differences in SR among males during exercise is not related to sweat gland number, which is fixed by age 3 yr. Instead, the diminished flow rate in pubertal subjects reflects a lower sweat output per gland as well as a decreased sensitivity of sweat gland output in response to a given Ta (5, 6). Inbar et al. (25) described sweating responses to three 20-min bouts of exercise at 50% V̇O₂max in prepubertal and young adult male subjects. SR was 327 ± 11 and 445 ± 30 ml·m⁻²·h⁻¹ in the two groups, respectively. Sweat production relative to change in T_re was greater in the adults (771 ± 104 vs. 385 ± 26 ml·°C⁻¹·h⁻¹) as was SR per gland (11.0 ± 0.7 vs. 2.8 ± 0.2 ml/h per gland). Similar differences findings were observed with increasing pubertal stage by Falk et al. (17).

Does the lower SR confer a thermoregulatory advantage or disadvantage to young boys exercising in the heat compared with their adult counterparts? The answer is not altogether clear. Compared with adults, children would be expected to be at decreased risk for sweating-induced dehydration, with its adverse effects on heat storage, fitness, and risk of heat injury. On the other hand, evaporative sweat is the principal means of heat dispersal during exercise in hot climatic conditions when a diminishing skin-air temperature gradient limits convective heat loss. Consequently, children might be expected to demonstrate greater increases in heat load and T_re when exercising in conditions of high Ta. As will be discussed in sections that follow, the issue may be moot, because neither of these positive or negative outcomes are, in fact, observed.
Davies et al. (13) estimated that average heat loss by evaporation, expressed as percentage of metabolic heat, averaged 65% in young men compared with 51% in children while running at 68% VO_2max in thermoneutral conditions (13). Subsequent studies suggested, however, that the diminished sweat capacity in young boys does not necessarily imply lower evaporative heat loss during exercise (17, 25). In their comparison of pubertal boys and young adult men, Inbar et al. (25) estimated that evaporative skin heat losses normalized to body mass were greater in the pubertal subjects (8.10 ± 0.13 vs. 6.80 ± 0.13 W/kg). They calculated that sweating efficiency (evaporative loss relative to total body sweat) was significantly greater in the boys (0.69 ± 0.02 vs. 0.60 ± 0.04 W·ml⁻¹·h⁻¹). They considered that these findings might be explained by 1) children having smaller, more diffusely spaced drops, which could result in higher evaporative cooling, and/or 2) the possibility that larger drops in adults are more likely to coalesce, providing less cooling.

CONVECTIVE HEAT LOSS

Early investigators who observed low SR in boys expected that children might compensate by demonstrating higher levels of convective heat loss during exercise compared with adults. In fact, studies that have examined changes in SBF as a surrogate marker of convective heat loss have generally found greater increases in flow at the left chest and back, but values were lower than the adults on the left forearm. Falk et al. (18) found that forearm SBF (by venous occlusion plethysmography) in prepubertal boys both at rest and during exercise in the heat was twice that of postpubertal adolescents.

Martin et al. (31) described age differences in maximal skin vascular conductance (FVC_max) at rest in the left forearm that had been sprayed with hot water to create a skin temperature of 42°C. Blood flow was measured venous occlusion plethysmography, and maximal flow was divided by mean arterial blood pressure to obtain FVC_max. FVC_max was inversely related to age, with steepest rate of decline between ages 5 and 17 yr. Mean values at age 10 and 30 yr were 30 and 21 ml·100 ml⁻¹·min⁻¹·100 mmHg⁻¹, respectively.

These limited data indicate a higher SBF rate, greater skin vascular conductance, and, by inference, larger rates of relative convective heat loss during exercise in children compared with adults. The mechanisms that might account for these developmental differences remain obscure.

DEHYDRATION

The low SR of children during exercise in the heat might be expected to beneficially limit body fluid losses. However, there exists no evidence that their levels of dehydration during such exercise are any different from that of adults. The only direct child-adult comparison of hydration status during exercise without fluid replacement is that of Drinkwater et al. (14). They found that percent weight loss, rate of weight loss, and change in plasma volume during walking in 28, 35, and 48°C conditions were similar in premenarcheal girls and young adult women.

In a review of six child-adult comparison studies, Meyer and Bar-Or (32) estimated levels of hypohydration that would have occurred if fluid replacement had not been given (taking in account body weight and SR). They concluded from these data that the magnitude of expected dehydration during exercise in the heat in these reports was similar in the children and adults.

Based on findings in two separate studies, Bar-Or (8, 9) suggested that at any given level of dehydration, a child's T„ sub will rise more rapidly than that of an adult (8, 9). Eleven 12-yr-old boys cycled with fluid intake at 45% VO_2max at 39°C and 45% RH (8). On the average, T„ rose by 0.28°C for each 1% increase in weight loss. In the second study, four young adults (2 men, 2 women) performed treadmill walking without fluid replacement in 38–39°C T„. The rise in T„ for each 1% increase in weight loss was 0.15°C (9).

Degree of dehydration during exercise is dictated by fluid intake as well as SR. No experimental data are available regarding maturational differences in thirst drive relative to dehydration thresholds. Limited information suggests, however, that voluntary drinking and dehydration during exercise in the heat is similar in children and adults. The eight boys and eight men studied by Rowland et al. (44) consumed an average of 5.1 and 5.3 ml/kg, respectively, when drinking cool water ad libitum during cycling in 31°C and 50% RH for 30 min.

The boys in the study by Bar-Or et al. (8) cited above reach dehydration levels of 1–2% after cycling for 80–100 min. Voluntary drinking amounted to 66% of fluid loss. The authors noted that comparisons with studies in adults was difficult because of different climatic conditions, exercise protocols, and type of ingested fluid. Illustrating this, Rivera Brown et al. (39) found that voluntary intake replaced fluid loss of 78% with water intake but over 100% with intake of a glucose and electrolyte solution in 12 boys cycling in 33°C 58% RH with ad libitum drinking.

CIRCULATORY RESPONSES

The cardiovascular system bears a heavy burden during exercise in the heat. While satisfying the blood flow demands of muscle metabolism, circulation must be provided to shunt heat away from contracting skeletal muscle and body core, augment cutaneous flow for convective heat loss, and provide a fluid supply for sweat production. The adequacy of these circulatory responses is defined largely by body fluid content and blood volume. When dehydration ensues from sweat loss during exercise, stroke volume, cardiac output, and blood pressure fall concurrent with increase in T„ and decline in work performance (20). In subjects who remain euhydrated by fluid intake, however, cardiovascular function is typically maintained (44, 48).

Findings from early studies suggested to investigators that children’s circulatory responses to exercise were inferior to those of adults. Specifically, children demonstrated values of cardiac output at any given level of absolute VO_2 that clustered at the lower limits of the normal range in adult subjects (45, 51). This “hypokinetic circulatory response” was considered to contribute to impaired thermoregulation of prepubertal subjects during exercise in the heat (6).

It has been argued, though, that this observation is “biologically spurious,” because children do not exercise at the same absolute VO_2 as adults (45). Instead, they participate in phys-
Several studies have compared cardiovascular responses of adults and children during exercise in heat. Drinkwater et al. (14) found no differences between eight boys and 6.81 \( \pm \) 0.27 kJ \( \cdot \) h \( \cdot \) kg \( ^{-1} \) in prepubertal boys and 6.81 \( \pm \) 0.27 kJ \( \cdot \) h \( \cdot \) kg \( ^{-1} \) in those who were postpubertal boys. The earliest reports of heat acclimatization were made by Drinkwater et al. (14) in 1992, describing findings in five nonacclimatized prepubertal boys and five college-aged women who walked at low intensity. In 1995 Armstrong and Maresh (4) compiled data from 8 studies indicating no group differences between children and adults in rise of \( T_{re} \) during exercise in the heat. Average increase was 1.24 \( \pm \) 0.40 and 1.21 \( \pm \) 0.39°C, respectively. They concluded that children's thermoregulatory response to exercise in hot ambient conditions is not dissimilar to that of adults. More recent investigations directly comparing children and adults have borne this out (Table 1).

Similar findings have been observed by those investigators who have assessed body heat load during exercise (Table 1). Among the earlier reports, Drinkwater et al. (14) reported an average heat storage of 16.8 and 19.7 kcal/m² in girls and women, respectively, while walking in 35°C conditions and 31.0 and 26.2 kcal/m² \( \cdot \) h \( ^{-1} \) in 48°C (14). Falk et al. (18) calculated heat storage of 5.53 \( \pm \) 0.44 kJ \( \cdot \) h \( ^{-1} \) \( \cdot \) kg \( ^{-1} \) in prepubertal boys and 6.81 \( \pm \) 0.27 kJ \( \cdot \) h \( ^{-1} \) \( \cdot \) kg \( ^{-1} \) in those who were postpubertal while exercising in 42°C and 20% RH ambient conditions.

No maturational differences have thus been observed in responses of \( T_{re} \) or accumulation of heat storage during exercise in hot climatic conditions. These findings imply that thermoregulatory outcomes in children and adults are the same, regardless of any physiological and anatomic features unique to prepubertal subjects.

**PHYSICAL PERFORMANCE IN THE HEAT**

The idea that children are more intolerant to exercise in the heat compared with adults stems principally from the study of Drinkwater et al. (14) of five premenarcheal girls and five young adult women walking on a treadmill in a climatic chamber (without fluid replacement). As noted above, while walking at the same low relative intensity (30% \( V_{O2} \max \)), subjects were asked to perform two 50-min bouts of exercise in

### Table 1. Recent studies assessing changes in rectal temperature and heat storage in children and adults exercising in hot climatic conditions

<table>
<thead>
<tr>
<th>Age</th>
<th>Sex</th>
<th>%( V_{O2max} )</th>
<th>( T_{a}/RH )</th>
<th>( \Delta T_{re} )</th>
<th>Heat Storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shibasaki et al. (50)</td>
<td>10–11 yr</td>
<td>M</td>
<td>40%</td>
<td>30°/45%</td>
<td>0.5°C</td>
</tr>
<tr>
<td>Inbar et al. (25)</td>
<td>21–25 yr</td>
<td>M</td>
<td>50%</td>
<td>41°/21%</td>
<td>0.9°C</td>
</tr>
<tr>
<td>Riviera Brown et al. (40)</td>
<td>29–34 yr</td>
<td>F</td>
<td>60%</td>
<td>33°/55%</td>
<td>0.9°C</td>
</tr>
<tr>
<td>Rowland et al. (44)</td>
<td>11 yr</td>
<td>M</td>
<td>65%</td>
<td>31°/53%</td>
<td>0.6°C</td>
</tr>
</tbody>
</table>

M, male; F, female; \%\( V_{O2max} \), percentage of maximal oxygen consumption; \( T_{a} \), ambient temperature; RH, relative humidity; \( \Delta T_{re} \), change in rectal temperature.
ambient conditions of 28°C and 45% RH, 35°C and 65% RH, and 48°C and 10% RH. All subjects were able to finish the first walking bouts at 28 and 35°C. In 48°C T_a, all women completed the first walk but four of the five girls were removed by the investigators because of high heart rates (>90% maximum), flushed faces, and “marked signs of distress.” In the second 50-min walk, all completed the 28°C condition, but only two of the girls finished the bout in 35°C (compared with all the women).

[Other studies that have been cited to support a decreased exercise capacity by children in the heat compared children and adults at the same absolute workload (23, 24, 53). In this situation, the children were working at a higher relative exercise intensity and would thus be expected to demonstrate inferior exercise tolerance.]

Two recent studies have indicated no child-adult differences in tolerance to exercise in the heat when subjects are cycling at the same relative intensity. In their comparison of men and adults in tolerance to exercise in the heat when subjects are cycling at the same relative intensity. In their comparison of men and boys performing steady-load cycling to exhaustion (~63% \( \dot{V}O_2 \text{max} \)), Rowland et al. (44) could find no significant group differences in endurance performance capacity in either hot or cool ambient conditions. In ~19.7°C and 60% RH, the boys endured for 41.38 ± 6.30 min and the men for 42.88 ± 11.79 min. In 31.1°C and 54% RH, the boys lasted 29.30 ± 6.19 min and the men lasted 30.46 ± 8.84 min. In the study of Rivera Brown et al. (40), exercise endurance time in 33.4°C and 55% RH at 60% \( \dot{V}O_2 \text{max} \) in acclimatized women (76.5 ± 9.9 min) was greater than in young girls (56.9 ± 6.3 min), but the difference between groups was not statistically significant.

**HEAT ILLNESS**

Children have traditionally been considered to be at increased risk for heat illness (heat stroke, heat exhaustion) during physical activities compared with adults, a supposition based on 1) their perceived inferior thermoregulatory mechanisms, and 2) a greater incidence of heat stroke in the pediatric age group recorded during times of heat waves (1, 6, 35). However, these reports of heat stroke have indicated an augmented risk restricted to infants and small children (<4 yr old), which has been ascribed largely to dependency factors (such as parent neglect) and preexisting chronic illness (54). How this vulnerability might be translated to child athletes or older children playing in the heat is not clear.

In fact, cases of serious heat illness in child athletes are conspicuously absent from the medical literature, and informal opinion suggests that such events are rare. Brun and Mitchell (10) were unable to find a single case of heat-related illness in a child athlete in their survey of 10 yr of medical records in a tropical region of Australia (Cairns).

**CONCLUSION**

The characterization of children’s physiological responses and performance outcomes during exercise in the heat is far from complete. However, contrary to earlier assumptions, current research information fails to indicate thermoregulatory differences in the heat between children and adults. Physiological and anatomic features that might potentially bear influence on dissipation of heat in youth do not appear to translate into differences between children and adults in accumulation of body heat, changes in \( T_e \), exercise tolerance, or vulnerability to heat illness. Attention to adequate fluid intake and prevention of heat illness in active youth are clearly important, but there exists no convincing evidence that the risk of exercising in high \( T_a \) is any greater than that of adults. (27)

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