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Review article

Pre-pubertal children and exercise in hot and humid environments: A brief review

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Abstract
The ability of pre-pubertal children to regulate their body temperature under thermoneutral environments is similar to that of an adult albeit via differing routes. However, this ability is challenged when exposed to extreme environments. Thermoregulatory responses of pre-pubertal children differ from adults via adaptations that occur during growth and maturation and disadvantage children when exercising in hot and humid environments. When ambient temperatures exceed that of the skin, an influx of thermal energy from the environment increases thermal stress. When coupled with exercise, the increased thermal stress results in reduced physical performance and an increased risk of developing heat-related illness. Evidence suggesting the severity of heat-related illness is greater in pre-pubertal children than adults is inconclusive because age-related differences in thermoregulatory responses are attributed to either morphologic or functional changes. Additionally, the majority of research on pre-pubertal children exercising in the heat has been maturational or comparative studies with adults conducted in the near absence of convective cooling, complicating extrapolation to field-based environments. However, current consensus is that pre-pubertal children are disadvantaged when exercising in extreme temperatures and that care should be taken in preparing for and conducting sporting activities in hot and humid environments for pre-pubertal children.

Key words: Child, exercise, heat, body temperature regulation, heat stress disorders.

Introduction

Human thermal homeostasis is under constant threat from stressors such as exercise, illness and environmental conditions. Ambient environmental conditions induce regulatory modifications in addition to circadian and seasonal fluctuations. Fluctuations in metabolic activity also present a comparable threat to thermal equilibrium. When both internal and external sources of heat production are combined, the body may be placed under considerable stress, resulting in increasing body temperatures (Kenney, 1998). A combination of behavioural and physiological mechanisms are then employed to manage the thermal load and preserve core body temperature (T_C) in the optimal range of 36.5 - 38.5°C (Moran, 2001).

The transfer of heat through blood flow redistribution and regulation of the sweating response is controlled by the autonomic nervous system and ultimately the hypothalamus, by initiating the inhibition of cutaneous vasomotor tone and increasing sweat output (Fortney and Vroman, 1985). During exercise, heat passively flows along temperature gradients from the musculature to the core en route to the skin for dissipation. However, when exercising in hot and humid environments, the combination of ambient environmental conditions and physical activity can reduce the capacity to effectively dissipate thermal energy, resulting in progressive increases in T_C and skin temperature (T_{SK}) (Nadel, 1979; Barrow and Clark, 1998). Consequently, levels of thermal load associated with exercising in hot and humid environments parallel the risks of developing heat-related illness (Moran, 2001).

Heat-related illnesses and pre-pubertal children

Heat-related illnesses vary from relatively minor conditions such as heat rash and cramps to more serious and life threatening conditions such as heat stroke (Davis, 1997). The majority of heat-related mortalities in adults occur during heat waves where affected individuals such as the chronically ill or elderly lack the physiological capacity to adequately respond to acute heat exposure (McGeehin and Mirabelli, 2001). Pre-pubertal children may also be susceptible to developing heat-related illness due to the physiological restrictions discussed below. Individuals undertaking strenuous physical activities are also at an increased risk due to heat generated by muscular contraction (Shapiro and Seidman, 1990). Therefore, physically active pre-pubertal children are at the most risk of being affected by the development of heat-related illnesses such as heat exhaustion and exertional heat stroke (Davis, 1997; Shapiro and Seidman, 1990).

In functional terms, heat exhaustion represents an inability to continue exercising in hot environments due to hypohydration and cardiovascular responses being unable to cope with the exercise workload (Armstrong et al., 1996). Typically, heat exhaustion results in T_C >39°C but <40.5°C associated with heat stroke (Barrow and Clark, 1998; Davis, 1997; Khosla and Guntupalli, 1999). Additional symptoms of heat exhaustion are displayed in Table 1. Failure to discontinue the progression of these symptoms can lead to the onset of heat stroke, the most serious heat-related syndrome with loss of consciousness occurring in the majority of cases (Barrow and Clark, 1998; Shapiro and Seidman, 1990; Wexler, 2002). Heat stroke may be fatal if untreated and can be divided into two categories: exertional or classical. Classical heat stroke is a condition primarily affecting the elderly, chronically ill and very young (infants to preschool aged children) during heat waves and results from an inability to dissipate passive thermal loads (Davis, 1997). Exertional heat stroke develops as a result of excessive heat production from muscular contractions during strenuous exercise in hot environments (Davis, 1997). Unlike classical heat stroke, the onset of exertional heat stroke is predominantly sporadic and sudden (Shapiro and Seidman, 1990).

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Table 1. Signs and symptoms of heat exhaustion, classical and exertional heat stroke

Heat exhaustion	Classical heat stroke	Exertional heat stroke
Fatigue and weakness	*As with heat exhaustion and*:	*As with heat exhaustion and*:
Tachycardia		
Anxiety		
Muscle cramps	Cessation of sweating	Continuation of sweating
Headache	Hot and dry skin	Incoherent speech
Irritability	Seizures	Acute renal failure
Vertigo	Loss of consciousness	Lactic acidosis
Syncope	Death	Rhabdomyolysis
Prolific sweating		Hyperuricemia
Hypotension		Hyperkalemia
Nausea		Seizures
Cold, pale, clammy skin		Loss of consciousness
Chills		Death
Piloerection		
Mental deterioration		

Symptoms of classical and exertional heat stroke are displayed in Table 1.

Heat exhaustion can develop as a consequence of severe water loss (>3% body mass) resulting from prolific sweating in response to heat stress (Armstrong et al., 1996; Bross et al., 1994). The relative magnitude of water loss and potential for hypohydration are similar between pre-pubertal children (10 - 12 yr) and adults as both often fail to ingest sufficient fluids *ad libitum* during exercise (Bar-Or et al., 1980; Meyer and Bar-Or, 1994). Major consequences of hypohydration include accentuated reduction in blood volume (haemoconcentration) (Harrison, 1986), increased cardiovascular strain due to diminished cardiac filling resulting in reduced stroke volume (SV) and an elevated T_C (Sawka et al., 1992). One study found, elevated rectal temperatures (T_{RE}) correlated well (r = 0.65) with the hydration status of 10 - 12 yr boys during an intermittent cycle protocol (45% VO_{2max}) in 39°C and 45% relative humidity (%RH). In this study, the rate T_{RE} increased in the hypohydrated boys (0.28˚C) was similar to obese adults (~0.2˚C) but twice that of lean adults (~0.1˚C) per 1% initial body mass loss (Bar-Or et al., 1980). However, under greater thermal stress (41 - 43˚C and 18 - 20%RH), pre-pubertal children (9.1 - 12.2 yr) cycling at 50% VO_{2max} experienced greater increases in T_{RE} (0.7 - 0.8˚C) with smaller changes in body mass (0.09 - 0.29%) (Falk et al., 1992a; 1992b; Meyer et al., 1992).

Hypohydrated 10 - 12 yr boys (1 - 2% initial body mass) and girls (1.1 - 1.8% initial body mass) experienced reduced exercise tolerance when working between 30 - 45% VO_{2max} under hot, humid (35°C and 50 - 65%RH) (Drinkwater et al., 1977; Wilk et al., 2002) and hot, dry conditions (48°C and 10%RH) (Drinkwater et al., 1977). In adults, body mass loss of 1.9% can compromise athletic performance by up to 22% (Craig and Cummings, 1966) via reduced circulating blood volume, blood pressure, sweat production and peripheral blood flow (Armstrong et al., 1996; 1998). Further body mass losses may induce signs of heat exhaustion (5%), hallucinations (7%) and may result in heat stroke or death (10%) (Bar-Or et al., 1988). As pre-pubertal children experience a small absolute blood volume (Bar-Or et al., 1971) and greater reliance on peripheral blood flow for thermal load dissipation (Drinkwater et al., 1977; Falk et al., 1992b), they appear to be more prone to severe consequences of hypohydration compared to adults.

Thermal balance mechanisms

Homeostatic control over elevated body temperatures requires the human body to dissipate all additional heat produced or accumulated. Dry heat exchange resulting from radiation, conduction and convection throughout the body, and subsequently with the environment, account for ~75% of heat loss at rest under thermoneutral conditions (Fortney and Vroman, 1985). Dry heat exchange is dependent upon exposed surface area, passive flow along temperature gradients from hottest to coldest, and represents the dominant heat loss mechanism in pre-pubertal children (Bar-Or et al., 1971). The rate of heat exchanged is dictated by environmental characteristics including ambient dry-bulb temperature (T_{DB}), %RH, air movement and velocity as well as clothing, T_{SK} and skin wettedness (Pascoe et al., 1994).

Importantly, when ambient temperature equals or exceeds that of the skin, evaporation is the only mechanism for dissipating excessive heat loads (Berglund and Gonzalez, 1977). In contrast to dry heat exchanged via temperature gradients, the potential for evaporation is dictated by the water vapour pressure gradient between water amassed on the skin and that of the immediate ambient environment (Nadel, 1979). Wet bulb temperature (T_{WB}) and %RH represent the potential for evaporation to occur (Nadel, 1979). As T_{WB} approaches that of the skin or ≥60%RH, the potential for efficient evaporation diminishes (Brotherhood, 1987; Binkley et al., 2002). Additionally, the velocity of surface air movement and geometry of the surface area also determine the effectiveness of evaporation (Saunders et al., 2005). However, the water vapour pressure of the air layer closest to the skin surface is the most influential factor determining evaporation rates (Gleeson, 1998). If sweat amassed on the skin is unable to evaporate it will accumulate and eventually roll off the body, resulting in minimal heat loss (Gleeson, 1998).

Thermoregulatory comparison between pre-pubertal children and adult populations

The ability of pre-pubertal children to regulate body temperatures in thermoneutral environments is similar to that of an adult albeit via differing routes (Bar-Or, 1989; Falk, 1998). However, this ability is deficient when exposed to extreme environments (Bar-Or et al., 1988; Bar-Or, 1989; Haymes et al., 1974; 1975; Drinkwater et al., 1977; Falk, 1998). Thermoregulatory responses of pre-pubertal children differ from adults via several morphologic and physiological changes which occur during growth and maturation disadvantaging pre-pubertal children when exercising in hot and humid environments (Bar-Or, 1989; Falk, 1998). When compared to adults, pre-pubertal children have a greater surface-area-to-mass ratio (A_DM) (Bar-Or, 1989), differing body composition (Falk, 1998) and smaller absolute blood volume (Bar-Or et al., 1971; Drinkwater et al., 1977). Pre-pubertal children differ physiologically with a lower cardiac output ($\dot{Q}$) (Bar-Or et al., 1971), greater metabolic heat production per kg body mass during work (Astrand, 1952) and a less efficient sweating mechanism (Bar-Or, 1989). These characteristics will be discussed in more detail below.

Surface-area-to-mass ratio

Metabolic heat production is proportional to active musculature and body mass while heat transfer to the environment by dry heat exchange is dependent upon exposed surface areas. As pre-pubertal children have a smaller body mass and a larger surface area compared to adults, their larger A_DM allows for a greater reliance upon dry heat exchange when temperature gradients permit (Falk, 1998). However, a greater A_DM becomes a liability once ambient temperatures exceed that of the skin and the body absorbs heat from the environment imposing additional stress on thermoregulatory mechanisms (Falk, 1998). An inability to compensate for the additional thermal load may result in an increased T_C and potential development of heat-related illnesses. Typically A_DM continually decreases during growth and maturation (Bitar et al., 2000; Falk et al., 1992b) and is independent of gender (Drinkwater et al., 1977; Meyer et al., 1992).

Thermal influx resulting from dry heat exchange is similar for 11 - 14 yr boys (48%) and adult men (49%) exercising under hot, dry conditions (49°C) (Wagner et al., 1972) while 12 yr girls exhibited greater dry heat exchange under various hot conditions (28 - 48°C and 45 - 10%RH) compared to college-aged women (Drinkwater et al., 1977). Both maturation groups dissipate similar portions of thermal load although mechanisms differ in relation to A_DM and environmental conditions. For example, in 28°C ambient conditions, 12 yr girls rely more on dry heat exchange (Drinkwater et al., 1977). However, in 35°C and 48°C environments, thermal load dissipated by evaporation is proportional to adults (Drinkwater et al., 1977). A marked circulatory shift in blood volume to the periphery aids the dissipation of heat via dry heat exchange mechanisms. However it may also contribute to reduced heat and exercise tolerance in hot environments (Drinkwater et al., 1977; Wilk et al., 2002).

Sweating mechanism

Sweating can be an effective heat loss mechanism for pre-pubertal children during mild heat exposure but is less effective during periods of combined heat and exercise stress when compared to adults (Haymes et al., 1975; Drinkwater et al., 1977). For example, when running at 68% VO_{2max} for 60 min under thermoneutral conditions (21°C and <50%RH), pre-pubertal children (12.8 - 13.8 yr) have been shown to dissipate 44% of their metabolic heat production through dry heat exchange and 51% through evaporation compared to 65% in adults (Davies, 1981). In contrast, under hot conditions (47.7 - 49°C) pre-pubertal boys (11 - 14 yr) dissipated 87% of their thermal load by evaporation, compared to 89% for the post-pubertal boys (15 - 16 yr) and young men (20 - 29 yr) (Wagner et al., 1972) and similar to contributions from pre-pubertal (12 yr) females (88%) (Drinkwater et al., 1977). However, despite proportionally lower metabolic rates, the pre-pubertal boys were unable to regulate body temperature as efficiently as the post-pubertal boys and young men suggesting a reduced effectiveness of evaporative cooling during pre-pubescence.

When ambient temperatures exceed T_{SK}, evaporation is the major avenue for heat dissipation. Thermoregulatory responses of pre-pubertal children expose them to an increased risk of developing heat-related illnesses given that their sweat rates are less than those of adults relative to body surface area for any given environmental or metabolic load (Falk et al., 1992a; Meyer et al., 1992). Additionally, it is unclear whether regional output differences in the sweat production of pre-pubertal children potentially elucidates the suggested reduced effectiveness of evaporative cooling (Bar-Or, 1998; Drinkwater et al., 1977; Wagner et al., 1972).

Development in the secretory function of apoeccrine (found in the axilla) and apocrine (found in the axilla and pubis regions) sweat glands during puberty could also partially explain the variation in sweat rate. Apoeccrine sweat glands, which only develop during puberty, are capable of sweat rates seven times that of eccrine sweat glands (found all over the body) despite the latter being the most abundant and active from birth (Falk, 1998; Sato et al., 1987). Additional contributing factors to differing sweat rates between pre-pubertal children and adults include smaller sweat glands, lower sensitivity of the sweating mechanism (Falk, 1998) and reduced anaerobic capacity of sweat glands (Falk et al., 1991). Interestingly, the reduced sweat rate of pre-pubertal children occurs despite a higher population density of heat-activated sweat glands (Falk et al., 1992a; Falk, 1998). The absolute number of glands remains unchanged beyond 2.5 yr, varying inversely with body surface area (r = -0.59) (Bar-Or, 1989). Therefore, pre-pubertal children have a greater density due to a smaller surface area (Bar-Or, 1989; Wagner et al., 1972). However, research on sweat gland population density expressed as the area of sweat drops and sweat covered skin, demonstrated that pre-pubertal boys (10.8 yr) experienced more numerous but smaller sweat drops per unit of skin area compared to post-pubertal boys (16.2 yr) who had fewer but larger drops of sweat (Falk et al., 1992a). Despite differing distribution patterns, similarities in the resultant sweat covered skin could have resulted in similar evaporative potential between maturation groups assuming skin cooling was proportional to absolute volume of evaporated sweat (Falk et al., 1992a).

When expressed relative to body surface area, pre-pubertal boys (11 - 14 yr) have substantially lower sweat rates than men (Wagner et al., 1972) although differences between pre-pubertal girls (12 yr) and women is less marked (Drinkwater et al., 1977; Meyer et al., 1992). Also pre-pubertal boys (9 - 12 yr) have similar or marginally greater sweat rates (8.0 $g \cdot m^{-2} \cdot min^{-1}$ vs. 7.4 $g \cdot m^{-2} \cdot min^{-1}$) than pre-pubertal girls (9 - 11 yr) (Haymes et al., 1975). The size of sweat glands in pre-pubertal children are related to age (r = 0.77) and height (r = 0.81) (Falk, 1998). Given that sweat gland function increases as the size of the gland increases, sweat gland size could also explain smaller sweat rates in pre-pubertal children (Falk, 1998). Although a moderately strong correlation exists between body surface area and sweat rate per gland (r = 0.74 - 0.76), 66% of the variance in sweat rate per gland is explained by a combination of body surface area and physical maturation, thereby disadvantaging pre-pubertal children (Falk et al., 1992a). Qualitative changes in the functional capacity of sweat glands that occur during puberty might explain the increase in rate per gland with aging (Falk et al., 1992a).

An additional explanation of the variations in the sweat response between pre-pubertal children and adults could be an age-related increase in sensitivity of the sweating mechanism in response to enhanced cholinergic and adrenergic stimuli resulting in an augmented sweating response during maturation (Falk, 1998). Additionally, greater T_{SK} for pre-pubertal children compared to adults at a given thermal load suggest a delayed onset of the sweating response (Drinkwater et al., 1977; Wagner et al., 1972) which may reflect reduced sensitivity of the sweating mechanism to thermal stimuli (Wagner et al., 1972). Wagner et al. (1972) found that the threshold for sweating in relation to T_{RE} was higher in 11-14 yr boys (T_{RE} = ~38.9˚C) compared with 20-29 yr men (T_{RE} = ~38.2˚C) during work in a hot, dry environment (T_{DB} = 49°C, T_{WB} = 26.6°C). Although the cause of lower sweat rates in children is unknown, the majority of proposed mechanisms revolve around maturation-related changes that occur during puberty, thereby disadvantaging pre-pubertal children. Collectively, the above studies highlight the inefficient evaporative capacity of pre-pubertal children places them at an increased risk of developing heat-related illness during physical activity or exercise in hot and humid environments.

Body composition

Decreased adiposity, increased fat-free mass (FFM), growth spurts and variations in hormonal status are typical features of puberty (Falk, 1998; Bitar et al., 2000). However, pre-pubertal girls have a lower percentage body fat (%body fat) than adult females (Drinkwater et al., 1977) while pre-pubertal boys have a slightly higher level of adiposity than adult males (Falk, 1998). For individuals of similar body mass, greater thermal stress is required to elevate the T_C of individuals with lower adiposity levels compared to those with higher adiposity because of the respective specific heat of adipose tissue (1.67 $kJ \cdot kg^{-1} \cdot °C^{-1}$) compared to FFM (3.35 $kJ \cdot kg^{-1} \cdot °C^{-1}$)(Falk, 1998). Therefore, individuals with a higher %body fat are at a disadvantage during exposure to hot environments because less heat is required to be stored before T_C begins to rise (Haymes et al., 1975).

Girls undergo significant annual increases in fat mass and body mass between pre-pubertal (10.4 yr) and pubertal (12.8 yr) periods with increased body mass consisting of 95% and 85% FFM for boys and girls respectively (Bitar et al., 2000). Maturational comparisons between pre-pubertal girls (12 yr) and college-aged women indicated significant increases in height, body mass, body surface area, %body fat and a decreased A_DM (Drinkwater et al., 1977). The significantly lower %body fat of the girls, coupled with their higher T_{RE} and lower exercise tolerance times in 35°C and 48°C environments, suggested a greater thermal stress compared to their adult counterparts. A lower %body fat should facilitate heat tolerance by reducing the magnitude of peripheral circulation required to elevate T_{SK} and promote dry heat exchange (Drinkwater et al., 1977). This did not appear to occur as the girls had higher T_{SK} and attained 90% HR_{MAX} when their T_{RE} averaged only 38.3°C, indicating greater cardiovascular strain.

Studies examining the heat tolerance capabilities of various levels of adiposity in pre-pubertal children (9 - 12 yr) determined that heavier children exhibit greater physiological strain while exercising (48 - 52% VO_{2max}) in the heat on the basis of higher T_{RE} and HR (Haymes et al., 1974; Haymes et al., 1975). Furthermore, heavy girls exhibited lower tolerance times (43 mins) despite similar T_{RE} and HR compared to their obese male counterparts who completed the 60 min protocol which the authors attributed to motivation (Haymes et al., 1975). However, lean girls exhibited higher T_{RE} (39.0 vs. 38.6˚C) and HR (195 vs. 180 $b \cdot min^{-1}$) than the lean boys during the warmest environment (~39.0˚C) (Haymes et al., 1974; Haymes et al., 1975). The higher HR and T_{RE} for the girls were suggested responses to the greater relative workload (48 vs. 43% VO_{2max}) and lower sweat rate (7.4 vs. 8.0 $g \cdot m^{-2} \cdot min^{-1}$) experienced by the girls respectively (Haymes et al., 1975). Therefore, significant increases in body mass resulting from increased FFM should result in reduced thermal strain. However, enhanced heat tolerance may not occur and reduced tolerance times in pre-pubertal children with lower %body fat may be attributed to inefficient cardiovascular adjustments and diminished evaporative capacity (Drinkwater et al., 1977; Falk et al., 1992b).

Cardiac output and blood volume

Marked increases in T_C and T_{SK} in pre-pubertal children exercising in high ambient temperatures are indicative of reduced evaporative cooling or higher peripheral blood flow (Falk, 1998). As a consequence, elevated T_{SK} reduces the T_C-T_{SK} gradient thereby presenting greater thermal strain on the transfer of heat from the core to the skin surface for dissipation. An increased thermal strain is supported by research indicating greater heat storage per kg body mass in children when compared to adults (Drinkwater et al., 1977; Haymes et al., 1974; 1975). However, this previous research has only been conducted in relatively dry heat environments (10 - 65%RH) and minimal research exists where children are exposed to high ambient temperatures in conjunction with high %RH. However, effectively dissipating heat from the core during exercise is dependent upon the $\%\dot{Q}$ directed peripherally. This redirection of blood flow results in competition between exercising muscle and skin for adequate blood flow, competition which is exacerbated in the heat (Bar-Or, 1989; Harrison, 1986). Additionally, thermal stress and exercise, alone or in combination, induce haemoconcentration that may be exaggerated by further exercise or dehydration thereby reducing exercise capacity (Harrison, 1986).

The degree of haemoconcentration is heightened during dehydration in conjunction with thermal stress and exercise (Harrison, 1986). Reducing blood volume and/or impeding its redistribution may result in continually increasing T_C. When compared to adults, the athletic performance of pre-pubertal children is limited by a lower absolute blood volume and increased competition for blood flow between the skin and active musculature (Bar-Or et al., 1971; Maughan and Shirreffs, 2004). Pre-pubertal children have a smaller absolute and relative blood volume in relation to body mass and particularly body surface area when compared to adults (Falk, 1998). As a result, pre-pubertal children display limited potential for convective heat transfer and divert a larger portion of their blood volume to the peripheral cutaneous circulation to facilitate heat loss (Drinkwater et al., 1977; Falk et al., 1992b). Therefore, the thermoregulatory capacity of pre-pubertal children is impeded as a result of a smaller absolute blood volume that decreases during thermal stress, exercise and dehydration. This is particularly concerning given that T_C increases more rapidly in children than in adults (Bar-Or et al., 1980), thus placing the exercising pre-pubertal child at an increased risk of heat injury

The $\dot{Q}$ of pre-pubertal children (10 - 13 yr) is 1 - 2 $L{\cdot}min^{-1}$ lower than that of adults at any given metabolic level and the fact that the T_C of pre-pubertal children increases more rapidly than in adults when dehydrated is of particular concern (Bar-Or et al., 1971). However, pre-pubertal children (10 - 13 yr) exhibit proportional increases to those of adults in $\dot{Q}$, HR, SV and $(a\text{-}v)O_2$ in response to workload increases when exercising at 40 - 70% VO_{2max} (Bar-Or et al., 1971). Between genders, pre-pubertal girls (10 - 13 yr) have a significantly lower SV than boys of the same age (Bar-Or et al., 1971; Vinet et al., 2003). Furthermore, for a given absolute $\%VO_{2max}$, pre-pubertal boys display a lower $\dot{Q}$ and HR as well as a higher SV when compared to girls of the same age during sub-maximal (40%, 50% and $70\%VO_{2max}$) exercise (Bar-Or et al., 1971). The higher HR demonstrated by girls was seen as being a feature of intrinsic differences between the sexes or as a derivative of their lower SV (Bar-Or et al., 1971).

The $\dot{Q}$ of pre-pubertal girls (12 yr) exercising in a hot environment has been shown to be consistently lower than that of college-aged women (Drinkwater et al., 1977). HR was consistently higher for the girls while SV was significantly lower than that of the women. It was suggested that a greater A_DM required a greater percentage of the girls' $\dot{Q}$ to be redirected to the skin to facilitate an increased reliance upon dry heat loss. This view was derived from reduced heat tolerance times, resulting from reduced blood flow to exercising muscles and decreased central blood volume leading to higher HR and increased cardiovascular strain (Drinkwater et al., 1977). Insufficient blood flow to internal organs and exercising muscle was also proposed for the reduced heat and exercise tolerance of pre- (12.2 yr), mid- (13.6 yr) and late-pubertal (16.7 yr) boys in hot, dry environments (42°C and 20%RH), thus contributing to a greater cardiovascular strain when compared to adults (Falk et al., 1992b). However, recent research suggests the redirection of blood flow and dehydration have limited influence on exercise tolerance times of pre-pubertal boys (11.7 yr) performing endurance exercise (65% peak VO_2) outdoors under hot and humid (31°C and 57%RH) conditions (Rowland et al., 2007).

Acclimatisation

Although pre-pubertal boys (8 - 14 yr) display similar physiological responses during heat acclimatisation, the acclimatisation rate in pre-pubertal children is somewhat slower than adults (Wagner et al., 1972; Inbar et al., 1981). Research has investigated the acclimation of pre-pubertal boys (8 - 14 yr) via physical conditioning at 85% HR_{max} under dry heat (43.0 - 49.0°C and 21%RH) and thermoneutral (23˚C and 50%RH) environments (Wagner et al., 1972; Inbar et al., 1981) as well as via proposed passive thermal loading (Inbar et al., 1981). Pre-pubertal boys (8 - 10 yr) (Inbar et al., 1981) and adolescent males (15 - 16 yr) (Wagner et al., 1972) adjust at a slower rate than adult males as characterised by a reduction in HR, T_C and T_{SK} as well as an increase in sweat rate and SV (Shvartz et al., 1973). Adaptations have been seen following acclimation for 8 - 14 d (Wagner et al., 1972; Inbar et al., 1981) with 8 - 10 exposures of 30 - 45 min recommended on a daily basis (American Academy of Pediatrics, 2000). Limited between gender comparisons are available and further investigation into the acclimatisation of pre-pubertal children to thermal loads as well as to humid heat is required.

Gender differences

Much of the current literature has been centred around gender-specific maturational or physiological studies (Bar-Or et al., 1980; Falk et al., 1992a; 1992b; Haymes et al., 1974; 1975; Inbar et al., 2004; Rowland et al., 2007) as well as comparative studies between pre-pubertal children and adults (Drinkwater et al., 1977; Inoue et al., 2004; Wagner et al., 1972). Currently, a gap exists in the available literature comparing the thermoregulatory demands of pre-pubertal boys and girls exercising under a variety of extreme environmental conditions. A summary of the literature currently available is presented in Table 2. Gender differences in motivation (Sirard et al., 2006), anthropometric and body composition characteristics (Rowland et al., 2000; Vinet et al., 2003) as well as cardiovascular responses (Bar-Or et al., 1971; Vinet et al.,

Table 2. Differences in the thermoregulatory responses between pre-pubertal boys and girls exercising in hot and humid environments.

Response	Females	Males
Circulatory		
Cardiac Output ($\dot{Q}$)	Higher	Lower
Stroke Volume	Lower	Higher
Heart Rate	Higher or similar	Lower or similar
Skin blood flow	?	?
Blood pressure	?	?
Changes in blood volume	?	?
Temperature		
Core body temperature (T_C)	Higher or similar	Lower or similar
Rate of increase in T_C	Slower or similar	Faster or similar
Skin temperature	Similar	Similar
Heat loss (E)	Similar	Similar
Heat loss (R, K & C)	?	?
Fluid regulation		
Sweating rate	Lower	Higher or similar
Sweat electrolyte loss	Similar	Similar
Sweat gland size	?	?
Sweat rate per gland	Lower	Higher
Number of HASG	Similar	Similar
Metabolic		
VO_2	Similar	Similar

Abbreviations: ? = no available research, E = heat loss via evaporation, R, K & C = heat loss via radiation, conduction and convection, HASG = Heat activated sweat glands.

2003) have previously been reported for pre-pubertal boys and girls. However, the influence of these gender differences on thermoregulatory responses has yet to be determined and warrants further investigation. Future studies should also consider the interaction of gender and maturation (pre-pubescence through to adolescence) on exercise responses under various environmental conditions.

Conclusion

To date, most studies of pre-pubertal populations have examined either the effect of maturation within the same gender or comparative studies with adult responses to various environmental conditions. Additionally, the majority of studies of pre-pubertal children exercising under environmental heat loads have been conducted under controlled climatic conditions, such as in climate control chambers (Bar-Or et al., 1980; Drinkwater et al., 1977; Falk et al., 1992b; Inbar et al., 1981; Meyer et al., 1995; Wagner et al., 1972). Studies conducted indoors occur in the near absence of any airflow which importantly, would substantially influence convective and evaporative heat loss (Saunders et al., 2005) and ultimately influence heat storage and both skin and core body temperatures. Therefore, caution should be extended to comparisons or the extrapolation of results from indoor studies to outdoor activities, as core body and skin temperatures, HR, perceptions of exertion and sweat rates can all be significantly influenced by the velocity of circulating air (Adams et al., 1992; Saunders et al., 2005).

When ambient temperatures exceed that of the skin, pre-pubertal children are subjected to an influx of thermal energy from the environment. The thermoregulatory responses of children differ from adults via several morphologic and physiological adaptations that occur during growth and maturation and disadvantage pre-pubertal children when exercising in hot and humid environments. Pre-pubertal children have a greater A_DM, differing body composition and smaller absolute blood volume. They also differ physiologically with a lower $\dot{Q}$, greater metabolic heat production per kg body mass during work, and less efficient sweating mechanism. Therefore, particular care must be taken in the preparation for and conduct of sporting activities for pre-pubertal children in hot and humid climates. Future research should investigate gender differences and *in situ* thermoregulatory responses of pre-pubertal children exercising in a range of hot and humid environments.

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Key points

- Pre-pubertal children's ability to thermoregulate when exposed to hot and humid environments is deficient compared to adults.
- Research into the severity of heat-related illness in pre-pubertal children is inconclusive.
- Discretion should be used in applying findings from indoor studies to outdoor activities due to the influence of the velocity of circulating air on thermoregulation.

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