# Thermoregulatory responses of children exercising in a hot environment

*Respostas termorregulatórias de crianças no exercício em ambiente de calor*

*Respuestas termorreguladoras de niños en el ejercicio en ambiente de calor*

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## ABSTRACT

**Objective:** To review possible peculiarities in biological mechanisms related to responses of thermoregulatory and specific sweat glands in exercise performed by children in hot environments.

**Data sources:** Review of 47 articles published between 1960 and 2011 in the electronic databases MedLine and SciELO Brazil using the following key-words: 'children', 'heat', 'sweating', 'thermoregulation', 'sweat gland', and 'exercise', alone or in combination, in addition to a doctoral thesis about the subject.

**Data synthesis:** Pre-pubertal sweat rate during exercise is lower than among adults. Children have different thermoregulatory characteristics, with a small sweat output rate due to small sweat glands. High ratio between surface and body mass increases the absorption of heat during exercise under thermal stress in children, raising the risk of hyperthermia symptoms. However, great blood flow to skin contributes to the better control of thermal homeostasis in children. Small size of the gland, low cholinergic sensibility, low levels of circulating catecholamines during stress, and lack of androgenic hormone explain the occurrence of low elimination of sweat in exercises performed by children.

**Conclusions:** Children present immature sweat glands. Thus, physical activity combined with high temperatures is not well-tolerated by children and youngsters, with great vulnerability to thermal injury. In the heat, strict control of fluid intake and attentive monitoring of weather conditions should have especial attention for the safe practice of exercises.

**Key-words:** children; exercise; body temperature regulation; hyperthermia, induced.

## RESUMO

**Objetivo:** Revisar as possíveis peculiaridades nos mecanismos biológicos referentes às respostas termorregulatórias e sudorípara específicas no exercício realizado por crianças em ambiente de calor.

**Fontes de dados:** Foi feita uma revisão de 47 artigos publicados entre 1960 e 2011 nas bases de dados eletrônicos MedLine e SciELO Brasil, com a utilização dos seguintes descritores: 'crianças', 'calor', 'sudorese', 'termorregulação', 'glândula sudorípara' e 'exercício', sendo usados isoladamente ou em combinação, além de uma tese de doutorado sobre o assunto.

**Síntese dos dados:** Em pré-púberes, a taxa de sudorese durante o esforço é menor em comparação aos adultos. Crianças possuem características termorregulatórias diferenciadas, apresentando um débito de suor por glândula muito menor. A maior razão entre área de superfície e massa corporal faz com que crianças absorvam mais calor durante o exercício sob estresse térmico, elevando o risco de apresentarem sintomas de hipertermia. O maior fluxo sanguíneo para a pele contribui com um melhor controle da homeostase térmica de crianças. O menor tamanho da glândula, a menor sensibilidade colinérgica, os níveis baixos de catecolaminas circulantes durante o esforço e a falta de hormônio androgênico explicam a ocorrência da baixa eliminação de suor no exercício realizado por crianças.

**Conclusões:** Crianças exibem glândulas sudoríparas imaturas. Assim, a prática de atividade física combinada a altas temperaturas não é bem tolerada havendo maior vulnerabilidade às lesões térmicas. No calor, deve-se ter um controle rigoroso da ingestão de líquidos e um monitoramento atencioso das condições climáticas para maior segurança na prática de exercícios.

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Conflito de interesse: nada a declarar

Recebido em: 1/12/2011
Aprovado em: 4/4/2012

**Palavras-chave:** crianças; exercício; sudorese; termorregulação; hipertermia induzida.

**RESUMEN**

**Objetivo:** Revisar las posibles peculiaridades en los mecanismos biológicos referentes a las respuestas termorreguladoras y sudorípara específicas en el ejercicio realizado por niños en ambiente de calor.

**Fuentes de datos:** Se realizó una revisión de 47 artículos publicados entre 1960 y 2011 en las bases de datos electrónicas MedLine y SciELO Brasil, con el uso de los siguientes descriptores: "niños", "calor", "sudoración", "termorregulación", "glándula sudorípara" y "ejercicio", siendo usados aisladamente o en combinación, además de una tesis doctoral sobre el tema.

**Síntesis de los datos:** En pre-púberes, la tasa de sudoración durante el esfuerzo es menor en comparación a los adultos. Niños poseen características termorreguladoras diferenciadas, presentando un débito de sudor por glándula mucho menor. La mayor razón entre área de superficie y masa corporal hace que los niños absorban más calor durante el ejercicio bajo estrés térmico, elevando el riesgo de presentar síntomas de hipertermia. El mayor flujo de sangre para la piel contribuye con un mejor control de la homeostasis térmica de niños. El menor tamaño de la glándula, la menor sensibilidad colinérgica, los niveles bajos de catecolaminas circulantes durante el esfuerzo y la falta de hormona androgénica explican la ocurrencia de la baja eliminación de sudor en el ejercicio realizado por niños.

**Conclusiones:** Niños exhiben glándulas sudoríparas inmaturas. Así, la práctica de actividad física combinada a altas temperaturas no es bien tolerada por el público infantojuvenil, que presenta mayor vulnerabilidad a las lesiones térmicas. En el calor, se debe tener un control riguroso de la ingestión de líquidos y una monitoración atenta de las condiciones climáticas para mayor seguridad en la práctica de ejercicios.

**Palabras clave:** niños; ejercicio; sudoración; termorregulación; hipertermia inducida.

## Introduction

The most striking characteristic differing the thermoregulation of adults and children is the lower sweat production of these ones[1]. In pre-pubertal children, sweating rate during exercise rarely exceeds 400mL.h$^{-1}$[2]. Other studies[3-7] confirm the low sweat production in children, which decreases the ability of heat loss by the evaporation mechanism, predisposing them to an increased risk of thermal injury[8]. Thus, it is suggested that the low sweat production is related to the sweat gland immaturity[9,10].

Children have anatomical and physiological characteristics that differ from adults, such as distinct values of body composition, water, and bone density. Morphologically, children have a higher ratio between surface area and body mass, which leads to a more rapid increase in body temperature when it is thermally stressed by heat[1,10,11].

Differences between the circulatory system of adults and children may also influence the thermolytic response. Compared to adults, children have lower cardiac volume, lower plasma volume, and lower cardiac output to the same workload[1]. A lower cardiac output, in this instance, means that less blood is cooled by the body with thermoregulatory loss. However, when children exercise in heat, they deflect much of the cardiac output to the skin in an attempt to better control the thermal homeostasis[9,10].

There are few statistics on thermoregulatory accidents with children and adolescents. However, in a juvenile football tournament in the United States, held in hot weather, 34 players were hospitalized with symptoms of hyperthermia[12]. Thermoregulatory accidents can be avoided respecting most suitable times for exercise and offering good amount of fluids. In Brazil it is common to see juvenile soccer competitions held in the central hours of the day, exposing young children or young adolescents to critical thermoregulatory conditions.

Understanding biological phenomena related to children's body temperature control and their actual water requirement is extremely important for the pediatric exercise physiology, since an increasingly early entry of this population into the sports scene has been observed. The search for information in this area of knowledge guides hydration strategies in sport, especially for young athletes who exercise under thermal stress, and promotes a safer exercise practice for children and adolescents.

The aim of this study was to review possible peculiarities in biological mechanisms related to specific thermoregulatory and sweating responses of children when exercising in heat.

## Data sources

We selected articles published in indexed magazines between 1960 and 2011, in English and Portuguese, from electronic databases (Medline, SciELO Brasil and Google

Scholar), with the isolated or combined use of the following descriptors developed by Bireme: children, heat, sweating, thermoregulation, sweat gland and exercise.

The text was divided into two topics. The first one is about the control of thermal homeostasis in children when exercising in heat, emphasizing its main differences when compared to adults. The second topic addresses the physiology of children's sweat gland, focusing on their low sweat production.

### Control of thermal homeostasis in children when exercising in heat

The evaporative heat loss is crucial for the maintenance of thermal homeostasis regardless of age. In children, certain specific physiological, anatomical and metabolic characteristics provide differentiated responses to physical exercise. Traditionally, a particular lower efficiency regarding heat loss is attributed to this population[13]. This idea is confronted by thermoregulation studies that consider children as efficient as adults[1,6,7,10] on this matter, despite children's lower sweat production.

However, we observe that physical activity combined with high temperatures is not well-tolerated by children and youngsters, who show increased vulnerability to thermal injury[8]. In this sense, hydration strategies for children and adolescents should be guided by the main peculiarities of young athletes' thermoregulation, and it is also recommended avoiding activities in the hottest period of the day.

Thermoregulation is performed by a physiological control system consisted of central and peripheral thermoreceptors, an afferent conduction system, a central control for integration of thermal impulses, and an efferent responses system leading to compensatory responses[14]. This system regulates the balance between production (thermogenesis) and dissipation (thermolysis) of heat, in order to maintain the body temperature near a constant level of 36.5°C.

In the hypothalamus lies the central control system that regulates the body temperature by integrating thermal impulses from body tissues. When the integrated impulse exceeds or falls below the threshold temperature range, autonomic thermoregulatory responses occur in attempt to maintain adequate body temperature[14].

As observed, physical exercise associated with thermal stress by heat imposes a great challenge to children's thermal homeostasis, and could compromise not only their performance, but also their health.

Although physical mechanisms of heat loss are similar between children and adults, the rate of thermogenesis and thermolysis between these mechanisms are different. Humans lose heat by conduction, convection, radiation and evaporation. The sweat evaporation is the most important of these mechanisms and it is dependent on the sweat production. However, in pre-pubertal children this mechanism is immature[7,9]. Besides having a lower sweat production, children experience a more rapid increase in the core body temperature when exercising in heat, which can lead to hyperthermia[1,11,15].

Other peculiar characteristics related to children's thermoregulation should be highlighted. In children the metabolic heat of locomotion is higher than in adults, because children need more energy for activities such as walking and running[16,17]. In fact, children's energy requirement can be up to 30% higher than of adults, which may be attributed to low mechanical efficiency. Thus, the metabolic heat gain related to muscular work increases more in children.

There is another important factor related to low glycolytic metabolism in moderate-intensity exercise performed by children. Lower levels of lactate dehydrogenase and phosphofructokinase enzymes limits the speed of glycolysis[18,19]. Thus, the lower release of catecholamines, resulting from low anaerobic metabolism during exercise, limits the sweating rate in children, since the levels of circulating catecholamines increase the sweating rate by adrenergic betareceptors stimulation[20,21].

During physical exertion, young athletes have lower cardiac output compared to adults, deflecting much of this to the skin under high temperature[10,17], decreasing the central circulation and showing an increased cardiovascular work[22]. Thus, pre-pubertal children cool better by convection and radiation than by the evaporation mechanism[23,24]. This occurs mainly due to increased cutaneous vasodilation and increased blood flow to the skin[10,25], making it possible to control the temperature. Children have a relatively large outer surface per unit of weight, which makes their bodies absorb heat more quickly where the ambient temperature exceeds their skin temperature.

Children's skin temperature is higher when compared to adults subjected to physical exertion under the same environmental conditions[26]. A greater rise in children's skin temperature is observed probably due to increased blood flow and cutaneous vasodilation[10,27]. However, heat loss by cutaneous vasodilation cannot compensate the underdeveloped sweating function and, consequently, a rapid rise of the core temperature is verified[10].

Sweat evaporation is the main form of heat dissipation in humans. In hot weather conditions, lower production of

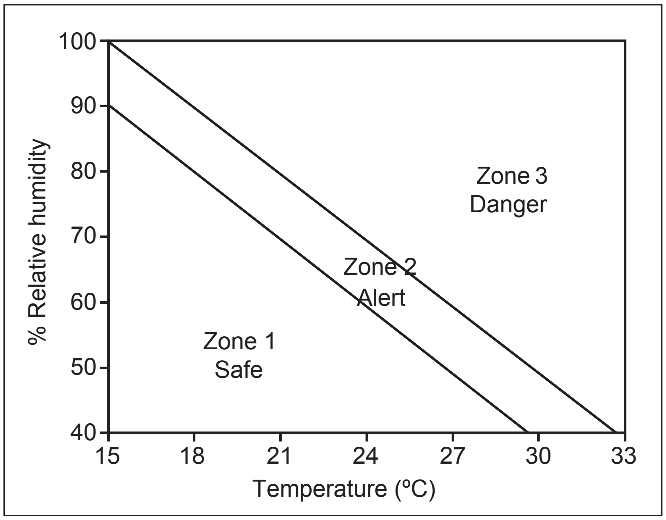


**Figure 1 -** Climatic guide divided into three security zones: 1 (safe) 2 (alert) and 3 (danger), adapted from the American Academy of Pediatrics

this fluid contributes to a faster heating of the body, which leads to lower exercise tolerance. However, Inbar *et al*[7] claim to be more heat loss by evaporation when it is corrected by body mass, which represents greater sweating efficiency (evaporation/total sweating), allowing a lower heat buildup in children during exercise.

Given that fact, it is advised to strictly monitor the temperature and relative humidity of the environment where the exercise will be performed, especially in warmer seasons of the year, in order to prevent symptoms of hyperthermia. Figure 1 provides a climatic guide prepared by the American Academy of Pediatrics (AAP) to prevent thermal injury caused by heat in active children during prolonged exercise.

## Children's underdeveloped sweating mechanism

The thermoregulatory system of pre-pubertal children is in development, impairing the body's ability to dissipate heat and protect itself from heat[7,28]. For a better understanding of the immature sweating mechanism of children, it is necessary to understand the physiology of the sweat gland, especially during events that trigger the sweat production.

Efferent signals from the pre-optic area of the hypothalamus via integumentary system and medullary raphe region reach the ventral branch of the spinal cord. This one communicates with the sympathetic ganglion via preganglionic fiber. The sympathetic postganglionic unmyelinated fiber passes through the communication with a gray branch, giving rise to the sudomotor nerve, which performs synapses directly in sweat glands of skin tissues[27]. Despite the sympathetic innervation, the sympathetic cholinergic system is the one responsible for the sweating, being acetylcholine the main neurotransmitter substance involved in the sweat output, showing numerous terminals[27].

When the acetylcholine binds to sweat gland muscarinic receptors, the intracellular concentration of calcium ions increases. High calcium concentration triggers increased permeability of $K^+$ and $Cl^-$, initiating, thereby, the release of the isotonic precursor fluid in its glandular portion[27]. Sweat is formed by active secretion of $Na^+$ and $Cl^-$ with a passive diffusion of water through the membrane. When passing through the duct, toward the pore, a decrease in concentration of constituent fluids occurs, mainly $Na^+$ and $Cl^-$, by means of $K^+$ exchange in the basolateral membrane. This mechanism is regulated by sodium-potassium ATPase pump[29].

Sweat is hypotonic in relation to blood plasma. In children and adolescents sweat is even more hypotonic, since they lose fewer electrolytes in perspiration[5,28]. This fact reduces the risk of hyponatremia or hypokalemia in children during exercise.

The sweat output occurs in a pulsatile form. The fluid output mechanism is regulated by a rapid hydrolysis of acetylcholine by acetylcholinesterase[30]. Acetylcholine induces the central sudomotor activity directly, by activation of muscarinic receptors, and indirectly, by activation of nicotinic receptors from the axonal reflex activity[31].

In humans, the number of sweat glands varies between 1.6 and 4 million, distributed throughout the body surface, showing a positive correlation between the number of sweat glands and sweating capacity[30]. Between two and three years of age, this number of sweat glands is fixed, and there is no further formation of new glands after this phase[30].

Changes in sweating rate can lead to changes in the density of sweat glands activated by heat and/or sweat output per gland during each sweat expulsion[26,30]. The effect of both growth and maturation as of heat acclimation is the increase of the sweat gland cholinergic stimulus. Moreover, it occurs concomitantly to the acceleration of stimuli toward the peripheral sympathetic nervous system[31].

With physical growth, especially of body surface area, a decrease in the density of sweat glands activated by heat is verified. This phenomenon does not favor increased perspiration, but, on the other hand, glands increase in size (hypertrophy), increasing the amount of sweating rate[9,10]. Growth and maturation provide increased ability to sweat glands, however, unevenly. This means that some areas may have a higher cholinergic sensitivity compared to other ones[10].

Sweating rate increases due to three factors: increased number of glands activated by heat, increased amount of sweat output per gland, and the combination of both[30,32]. Moreover, the dehydration inhibits perspiration primarily by central mechanisms, due to increased blood osmolality[30], which reduces the sensitivity of the sweat gland and compromises the ability to control the body temperature[33]. It is known that dehydration higher than 2% of the body weight affects performance in adults, however, in children, only 1% already compromises performance, besides increasing the risk of hyperthermia[34].

The smaller size of the sweat gland in children largely explains their sweat production, because the smaller the gland, the smaller its secretory portion[10]. Shibasaki *et al*[30] show that there is a positive correlation between the individual's sweat gland size and sweating rate. Corroborating this study, Falk *et al*[35] report that the individual's sweat gland size could be related to age and height. With growth and maturation, the sweat gland hypertrophy is associated with increased cholinergic stimuli. Therefore, responses of peripheral sweat glands are regulated mainly by cholinergic stimuli, although these glands may also respond to adrenergic stimuli[36].

Physical training and acclimation can modify sweating rate. A good fitness provides greater peripheral control, causing gland enlargement (hypertrophy) even in prepubertal children. Consequently, this leads to increased sweating rate[37].

Despite the greater density of sweat glands activated by heat due to their small size, children have a much lower sweat output per gland than adults[11]. On this matter, Sato and Sato[38] showed adults with precarious sweating function, with smaller gland size (hypotrophy) and lower sweat output per gland. Thus, studies involving children suggest that cholinergic sensitivity explains the low volume of sweat[9,10].

The action of androgen hormones may also modulate the sweating control mechanism. The increase of sweating rate that occurs during maturation may be related to increased release of masculinizing hormones[1,10]. Kawahata[3], in 1960, with the use of pharmacological injections, found that testosterone increases the sweating response, while estradiol inhibits it, suggesting a possible sexual difference in this matter.

Araki *et al*[39] showed a dramatic sweating rate increase after puberty. However, no differences between sexes was observed among children in this matter, being attributed to the lack of testosterone effects the low sweating rate in male and female pre-pubertal children. It seems to be no differences in sweating rate between boys and girls when they have similar levels of physical activity and are not acclimated[5].

Similarly, Inoue *et al*[10] refer to the lack of effects of certain androgenic male hormones as a cause of decreased sweat production in children. However, the role of testosterone in the sweating regulation is not firmly consolidated. With the arrival and advance of the pubertal period, several studies observed increased sweating rate[5,9,34]. Falk *et al*[40] found a lower glycolytic metabolism in children's sweat glands, suggesting that this fact relates to their low sweat production.

The release of catecholamines by adrenal glands can also modulate the sweating rate. The increase in the circulation of these hormones, especially adrenaline, stimulates sweat production by activating sweat glands' betareceptors[20,21].

Considering the action of the sympathetic autonomous system on physical exertion made by pre-pubertal children, low levels of circulating adrenaline during moderate-intensity exertion indicate less involvement of anaerobic glycolysis. Less adrenaline released decreases the activation of glands' adrenergic receptors[20]. On this matter, Tian *et al*[21] argue that although catecholamines are not a determining factor of sweating rate, they are necessary because they induce greater secretory responsiveness of sweat glands. In dissent, a recent study[41] using an animal model found that the local blockade of adrenergic betareceptors did not affect sweating rate during exercise.

In the attempt to develop a plan of fluid replacement for youngsters engaged in systematic and regular training, the need to individually quantify the water loss, mainly due to sweating rate during exercise, was verified[42]. Young athletes should be instructed to develop good habits of hydration[34,43]. However, there is still no consensus on the recommendation for physically active children and adolescents or young athletes hydration[44]. It is estimated that the daily water balance for a sedentary child is 1.6L[45]. Thus, active children should consume a value greater than this to ensure their proper hydration.

Despite lower values of sweating rate compared to adults, hydration strategies for children are no less important, since they usually do not adequately replace fluids[46-48] and may end up dehydrated.

## Conclusion

Children and adolescents show distinct thermoregulatory responses to physical exercise. Under thermal stress by heat, they show a more rapid increase in body temperature, which predisposes them to an increased risk of thermal injury.

Sweat evaporation is the main form of heat dissipation in humans. During exercise in heat, children show lower values of sweating rate compared to adults, mainly due to underdeveloped peripheral sweating mechanisms. Thus, among children, there is a lower sweat output per gland, which has a smaller size and a lower cholinergic sensitivity.

The lower release of circulating catecholamines during exercise performed by pre-pubertal children seems not to favor a high sweating rate. The lack of masculinizing hormones has been considered a cause of lower sweating rate in pre-pubertal children. However, this correlation remains unclear.

In sports, hydration strategies for young people under thermal stress should be developed according to distinct characteristics related to thermoregulation and exercise.

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