Thermoregulation in Humans: A Review of Developmental Changes

by

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A REPORT SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR
ADVANCED SCIENTIFIC RESEARCH

at

ISLANDS HIGH SCHOOL

Savannah-Chatham County Public School System

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Spring 2016
Introduction

Thermoregulatory homeostasis, while contributed to by multiple mechanisms, is ultimately controlled by the core temperature of the human body (Tc). The core body temperature, though difficult to accurately measure, remains at a general average of 37 °C with a safe range of variation of approximately 2°C (Brown et al. 1992). Therefore, the body must carry out automatic regulatory measures in order to maintain homeostasis, allowing it to stay within the safe ranges of human temperature.

A temperature below 35°C is considered hypothermic, and is defined as a state of the body in which heat loss exceeds the body’s ability to create heat. Hypothermia is a dangerous condition of the body, and can be controlled by behavioral thermoregulation, or conscious choices that minimize the exchange of heat from the body to the environment (Seely et al. 2008).

Hyperthermia occurs when the body is dissipating heat at a slower rate than it is being created, which results in overheating at extreme levels. Hyperthermia can also be controlled by a combination of behavioral and autonomic thermoregulatory functions.

In cold environmental settings, body heat is produced by the metabolism, thus placing those with higher metabolic rates, such as adolescents, at an advantage in cold climates (Inbar et al. 2004). While the production of this heat occurs within the metabolism, the heat is transferred by the blood vessels to the skin, consequently creating the skin temperature that is frequently used to gauge the thermal efficiency of humans under normal circumstances (Laakso et al. 2011). Skin temperature has a lower basal, or resting, temperature than the core of 34°C (Laakso et al. 2011). However, skin temperature also plays a significant role in thermoregulation, as the basis of thermal perceived comfort occurs due to the skin temperature and is therefore responsible for the induction of behavioral thermoregulatory measures.
The autonomic measures of thermoregulation fall into four categories: 1) radiation; 2) conduction; 3) convection; and 4) evaporation. Heat dissipation occurs primarily by evaporation via perspiration, but can also be accomplished with radiation, conduction, or convection. Alternatively, heat gain can be accomplished with metabolic heat generation or muscle contractions that cause heat, as well as with radiation, conduction, or convection measures (Seely et al. 2008).

The most common autonomic measures for maintenance of homeostasis are vasodilation and vasoconstriction, depending on the climate. Vasodilation occurs when the blood vessels are dilated, thus raising skin temperature by bringing warm blood to the surface of the skin in order to dissipate heat in warm environmental circumstances (Inoue et al. 2004). Vasoconstriction therefore constricts blood vessels in order to cool the surface of the skin to allow for less dissipation of heat in order to keep body heat in the body’s core in cold climates (Kurz et al. 1993). These functions both occur automatically by the activation of the trigger stimulus in times of thermal entropy.

Muscular activity also plays a role in thermoregulation, as there are certain involuntary functions that help to maintain thermal homeostasis. Shivering, for example, is an involuntary muscle contraction that is used as a thermal mechanism to generate muscular heat in cold environments (Ozaki et al. 1997). This is also why exercise causes overheating - the muscle heat generated by contractions during movement causes the body to warm, thus causing the warming of the body’s core (Araki et al. 1979).

An evaporative measure of cooling occurs in the form of sweat, but this method of heat dissipation can be problematic in humid environments or in people with underlying heart conditions such as low blood pressure or dangerously high heart rates (Inbar et al. 2004). This
method, in overly warm or humid environments, could lead to dehydration and, if extreme, heat exhaustion.

It is important to note that the temperature of the human body continues in a negative feedback loop. This means that, in accordance with the set point theory, the body cools beyond its optimal temperature, warms to bring the temperature back up, and then cools it yet again. Through this system, the result of one action prompts another that will cause the opposite result in a loop (Laakso et al. 2011).

**Infancy**

While the autonomic thermoregulatory activities of infants are ultimately similar to that of an adult, there are some thermoregulatory patterns that are unique to infants.

Despite the hypothesis that the thermal control of infants is unstable, evidence has been presented of temperature oscillations of an hour when measured continually during sleep (Tuffnell, 1993). Oscillation periods of one hour are ordinary in human thermoregulation during sleep, even for adults, due to the negative feedback cycle associated with the body temperature of mammals (Arons and Zhang, 2006). While the general pattern of the oscillations are the same between infants and adults, the differences in temperature of infants tend to be more extreme. In a sleep study, temperatures of infants ranged from 37.8 degrees Celsius to 36.3 degrees Celsius: this shows as much as a 1.3 degree variation from ordinary adult body temperature of 37.7 degrees (Brown et al. 1992; Seely et al. 2008).

It is generally accepted that newborn infants lose heat rapidly immediately after birth at a rate of nearly 3 degrees per minute if not assisted (Waldron and Mackinnon, 2007). It has been assumed that this is due to the large surface area to volume ratio relative to larger, adult humans (Smales and Kime, 1978). This is supportive of the hypothesis of instability of thermoregulation
in infancy; however, two or three days after birth, the metabolic rates of infants become adequate to regulate body temperature, thus establishing stability of body temperature patterns (Smales and Kime, 1978). After this short period of neonatal temperature instability, infants have shown an ability to maintain similar temperatures despite differing environmental conditions, thus presenting evidence of adequate homeothermy (Anderson et al. 1990; Tuffnell, 1993).

Though infants show proficiency at thermoregulation similar to that of adults, it is arguably more important to infant health that homeothermy is maintained, especially before the establishment of stable thermoregulatory patterns (Smales and Kime, 1978). While no single factor has been identified as the cause of Sudden Infant Death Syndrome (SIDS), it has been established that unordinary body temperature is a contributing factor in SIDS (Tuffnell, 1993). Practices to maintain infant body heat, like swaddling and the use of heat lamps, are necessary in the first two to three days of life due to the inability of infants to properly maintain body temperature, especially in premature infants (Stern, 1980).

**Childhood**

Under neutral environmental temperature circumstances, the thermoregulatory patterns of children show no difference from that of an adult (Araki et al. 1979). However, due to children’s higher surface-area-to-mass ratio relative to adults, certain differences in the exchange of heat between the body and the environment occur at extreme temperatures. There is a higher rate of exchange between children’s bodies and their environment than that of an adult, as their larger surface areas allow for faster acquisition of outside temperature conditions; this causes children to be less adaptive to climatic heat stress (American Academy of Pediatrics, 2000).

The thermoregulatory ability of children is generally considered to be inferior to that of an adult, as children exhibit lower evaporative heat loss due to lower heat transfer between their
internal organs and skin (Delamarche et al. 1990). This means that children seemingly have less ability to dissipate excess heat. However, children have shown no higher frequency in heat-related injuries than adults; consequently, it has been hypothesized that children dissipate heat with convective and radiative thermoregulatory strategies (Delamarche et al. 1990). Sweating rates increase after the age of 13, suggesting that sweating rates increase to levels similar to that of an adult after a child reaches puberty (Inbar et al. 2004).

Despite higher metabolic heat production in children, the rectal temperature both in neutral conditions and during exercise are the same between children and adults (Inbar et al. 2004). However, core temperature has been evidenced to be higher in children (Inoue et al. 2004).

Despite these differences and the tendency of children to perform athletic activities at the same intensity as most adults, there has been no evidence of higher rates of heat related injuries in children. (Delamarche et al. 1990).

**Adolescents**

Adolescents, as they have gained the sweating ability not seen in children, largely have the same thermoregulatory mechanisms as adults (Brokenshire et al. 2009). Adolescents are generally more involved in athletic activities, but no excessive heat injuries due to physiological inferiority have been evidenced. However, adolescents can have shortcomings in their behavioral thermoregulatory measures, as adolescents tend to be less responsible in hydration and nutrition without prompt (American Academy of Pediatrics, 2011). The criteria for efficient thermoregulation depend on the same risk factors as with adults, such as weather, exertion, level of fitness, and hydration, thus suggesting that adolescents have very little to no difference from adults in thermoregulatory mechanisms (Brokenshire et al. 2009).
Young Adults

As humans grow into young adults, their surface area to body mass ratio, which accounts for younger humans’ differences in thermoregulatory mechanisms, becomes equivalent to that of an adult and an elder, as there is no significant differences in the mean heights of young adults and the elderly (Direrro et al. 1999). Along with the similarity of young adults to both more developed humans, young adults exhibit similar rectal temperatures and sweating rates (Viveiros et al. 2011). Some characteristics are shared between the infantile, the young adult, and the elderly. In a study done by Inbar (2004) in which the thermoregulatory practices of three age groups were studied, all were similar in their dry heat gain, mass-related evaporative heat loss, and metabolic heat production (Inbar et al 2004).

Despite these similarities, young adults seem to present certain superiorities over other age groups in regards to thermoregulatory efficiency. For example, young adults were evidenced to have the highest rates of sweating sensitivity and sweating efficiency in comparison to children and the elderly, consequently causing their high rate of evaporative heat loss (Inbar et al. 2004). The higher rate of sweating sensitivity could be due to the suggested higher rate of skin-blood flow among young adults, as this could be a signal of a more efficient dispersal of heat (Viveiros et al. 2011).

Alternatively, it has been oppositely evidenced that young adults have a higher threshold for both vasoconstriction and heat production, thus showing signs of lower sensitivity to environmental temperatures (Frank et al. 2000). Foundings in another study, however, show a more immediate reaction of vasodilation in higher temperature than that of other age groups (Schellen et al. 2010).
There is also noted to be higher maximum intensity of temperature for young adults, which does support the hypothesis of the superior thermoregulatory methods of young adults (Frank et al. 2000).

Shortcomings of young adult’s high sweating sensitivity are also apparent, shown in the evidence in young adults of the highest thermal strain among age groups, possibly due to the higher amount of heat that requires dissipation in order for young adults to achieve thermal balance (Inbar et al. 2004).

**Adulthood**

As most general studies of thermoregulation occur on adult humans, the most information is available based on the thermoregulatory practices of adults relative to other age groups. However, effective and ethical ways to measure thermoregulatory responses of humans to thermal extremes and substances such as caffeine and alcohol are rare. To remedy this lack of ability to measure these responses, several thermal models have been developed in order to theoretically map the thermal responses to both thermal and nonthermal stimuli. These models include the Stolwijk model and the Fiala model (Laakso et al. 2011). The Stolwijk model is beginning to be replaced by the Fiala model, as the Stolwijk human thermal model is lacking in its accountability of blood flow, clothing, and conductive and radiative heat transfer (Foda et al. 2011).

The factors of thermoregulation that were most often attributed to thermal efficiency is skin blood flow, vasodilation, sweat rate, air movement, and clothing (Laakso et al. 2011). It has been considered that the autonomic thermoregulatory responses such as blood flow and vasodilation are more heavily affected by the core temperature (Tc), while the subjective comfort of the same person is affected more heavily by skin temperature (Tsk) (Frank et al. 1998).
The autonomic regulatory measures range in efficiency even between core and skin temperature. While peak skin temperature was most strongly affected by blood flow, it was least affected by sweat rate and vasodilation. The opposite is true, however, for core body temperature. Parts of this study data may be erroneous, as the model used for this study is unable to account for evaporative heat loss created by sweating due to lack of accountability for humidity and wind velocity. There is also a lack of accountability for the possibility of the heating of some tissues, as opposed to all or none, in extreme heat stress. (Laakso et al. 2011)

As there are four modes of thermal exchange; radiation, evaporation, conduction, and convection, there is a possibility of several outcomes that could be overlooked within the parameters of the conventional thermal study (Seely et al. 2008). For example, one study introduced the notion of body heat conductivity being largely attributed to the amount of chromosomal Q-heterochromatin in their genome (Ibraimov et al. 2007). This is a possibility that has not been explored much in other studies of its kind, as the hormones most frequently to thermoregulation is epinephrine and norepinephrine (Frank et al. 1998). Hormonal considerations such as these also create considerations of the differing hormone levels presented in age groups and genders, as with more specific research, connections could be found between these hormones, human characteristics, and thermoregulation could be established.

**Body Proportions**

Body proportions can also play a significant role in thermoregulation efficiency. However, contrary to conventional belief, there was an established decrease in skin temperature with increase in body fat, creating a negative correlation. This could be attributed to the higher surface area created by more skin exposure to air, thus allowing for effective dissipation of heat. Oppositely, there is a positive correlation between body fat and heat stress, which is likely
connected to core temperature. An increase in body fat contributes to change in the conduction and blood-flow related heat transfer with the environment, as fat requires less blood than an equivalent amount of muscle due to its lower density. (Zhang et al. 2001)

Despite body fat role in physical regulatory factors, it has little influence on basal metabolic heat and its production, though it is supposedly based upon height, weight, age, and gender (Zhang et al. 2001).

Outside of fat content, body proportions such as the relative length of limbs can play a role in heat transfer. A significant difference has been expressed between length of appendages such as legs (particularly the thigh) and effective dissipation of heat. Individuals with shorter limbs were shown to maintain their heat more effectively due to their lower relative surface area for heat exchange. (Tilkens et al. 2007)

**Elderly**

As humans age, their regulatory systems, including thermoregulatory mechanisms, peak in adulthood and begin to deteriorate afterwards. Therefore, the elderly are considered to be less efficient thermoregulators than adults (Kurz et al. 1993). In several experiments done by separately-operating researchers, older adults showed to be more hypothermic in a surgery situation when placed under anesthesia than a younger adult, and were cited to take an exceptionally long time to reach normal body temperature post-operatively due to their lack of heat-producing abilities (Ozaki et al. 1997; El-Gamal et al. 2000). This is partially attributed to a lower basal metabolic rate, and consequently lower resting temperature, as well as a slower rate of core heating, or, in the case of hyperthermia, heat removal (Ferrero et al. 2008). Older adults were cited to have required an extra 30 minutes to begin vasoconstriction as a warming mechanism in cold operating-room conditions as compared to younger patients, and had a lower
mean skin temperature when they did begin to warm (Ozaki et al. 1997). The impairment of organ and regulatory systems in elderly humans, such as muscular atrophy or dysfunctional cardiac systems, put seniors at a dangerously increased risk of hyper or hypothermia (Sato et al. 2009).

Not only does increasing age correlate with a decrease in thermoregulatory efficiency, but it also alters the methods of thermoregulation due to a shift in body mass, body proportions, neurotransmitter speed, and other differences in physiology (Inbar et al. 2004). Similar problems exists within the thermoregulatory systems of the elderly that exists for children; higher vulnerability to temperature extremes due to differences in both the efficiency and methods of temperature maintenance than that of an adult (Tsuzuki et al. 2002). For example, both children and seniors have a higher sweating threshold, meaning that their body core temperature must achieve a higher level to trigger the thermoregulatory mechanism of perspiring (Basu et al. 2002). This delayed response of sweating puts the affected age groups, seniors and children, at a higher risk of heat-related injury than an adult or adolescent.

Unlike children, however, the problems of the senior thermoregulatory system are concentrated in different areas. In staunch contrast to the heat production of children, older individuals have a lower rate of metabolic heat production as well as a lower rate of heat gain through the environment, thus yielding them less heat energy to produce necessary heat in circumstances of extreme cold (Sato et al. 2009; Inbar et al. 2004; Tsuzuki et al. 2002). This slowing of the basal metabolic rate of seniors can be at least partially attributed to the change that occurs in the production of thyroid hormones with age (Sato et al. 2009). These advantages that children have, considering their superiority over even adults in terms of metabolic heat
production, aid in the conclusion that the elderly are the most disadvantaged in regards to thermoregulatory methods apart from infants.

The metabolic limitations of the elderly lead to a higher risk of seniors acquiring hyperthermia or hypothermia in extreme temperature conditions (Ozaki et al. 1997). The slowing of metabolic rate with age not only affects the rate of metabolic heat production, but also limits the amount of lean body mass present in the body of the average senior (Frank et al. 2000). Seniors were shown to have the highest percentage of body fat on average, thus contributing to the lack of lean body mass presented by the elderly (Inbar et al. 2004). The higher fat content and consequent lack of lean body mass, in conjunction with the elderly’s reduced sensitivity to temperature extremes, causes a lack of shivering in the seniors that in turn results in less heat generation (Frank et al. 2000).

A general consensus of the researchers studying thermoregulation of humans relative to age is that the elderly population generally has a significantly lower threshold for thermal mechanisms such as vasoconstriction despite a diminished sensitivity to thermal discomfort (Frank et al. 2000; Inbar et al. 2004; Ozaki et al. 1997). The neurotransmitter norepinephrine, which controls the deployment of regulatory systems in response to thermal stimulus, has shown to be slower on the uptake in the elderly human’s nervous system (Frank et al. 2000; Thompson et al. 2004).

In conjunction, the maximum levels of elderly’s temperature gain is lower than a younger person’s, such as their mean skin temperature maximum and the maximum vasoconstriction intensity (Inbar et al. 2004; Frank et al. 2000). This lowered sensitivity is especially problematic for older people, as thermal regulatory mechanisms are triggered primarily by thermal comfort levels and strong emotion (Grassi et al. 2003).
Due to this, older people are slower to recover from periods of thermal stress in both overly warm and overly cool circumstances, including the influence of a drug such as anesthetic. In an anesthetic setting, elderly humans are more likely to become hypothermic due to an extremely high threshold for vasoconstriction, thus causing body temperature of seniors to remain cool during the presence of anesthesia in their bloodstream as well as take a longer time for temperature to rise back to ordinary levels (Kurz et al. 1993).

Despite lower thresholds for thermoregulatory action, however, impaired perception in the elderly reduces their sympathetic nervous system response to trigger vasoconstriction, or vasodilation in warm settings, due to a lack of sensitivity in the autonomic nervous system as a person ages (Khan et al. 1992). Even outside of thermoregulatory measures, a decrease in sensitivity to other bodily needs is evident through the tendency of seniors towards dehydration due to their diminished sensitivity (Takamata et al. 1999).

Oxygen consumption rate also has a lower peak than that of a younger person, which in turn leads to a lower skin blood flow and thus poor circulation of heat throughout the body of the senior (Okazaki et al. 2002, Thompson et al. 2004). This is hypothesized to be due to the aged skin, and therefore structurally compromised capillaries in the aged skin (Thomas et al. 1999). However, this can be improved by regular aerobic exercise, though this applies to all ages.

The differences in the thermoregulation of seniors even affects their vital signs, which are listed as the (1) respiratory rate, (2) pulse, (3) temperature, and (4) blood pressure (Chester et al. 2011). While the changes are not defined, it is implied within the study that the differences, while changed with age, also depend on outside factors such as lifestyle, weight, and diet. It is also considered that aging generally has a negative effect on plasticity that could hereby affect the vital signs.
Literature Cited


