Review Article

Human Thermoregulation and Measurement of Body Temperature in Exercise and Clinical Settings

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Abstract

This review discusses human thermoregulation during exercise and the measurement of body temperature in clinical and exercise settings. The thermoregulatory mechanisms play important roles in maintaining physiological homeostasis during rest and physical exercise. Physical exertion poses a challenge to thermoregulation by causing a substantial increase in metabolic heat production. However, within a non-thermolytic range, the thermoregulatory mechanisms are capable of adapting to sustain physiological functions under these conditions. The central nervous system may also rely on hyperthermia to protect the body from "overheating." Hyperthermia may serve as a self-limiting signal that triggers central inhibition of exercise performance when a temperature threshold is achieved. Exposure to sub-lethal heat stress may also confer tolerance against higher doses of heat stress by inducing the production of heat shock proteins, which protect cells against the thermolytic effects of heat. Advances in body temperature measurement also contribute to research in thermoregulation. Current evidence supports the use of oral temperature measurement in the clinical setting, although it may not be as convenient as tympanic temperature measurement using the infrared temperature scanner. Rectal and oesophagus temperatures are widely accepted surrogate measurements of core temperature (Tc), but they cause discomfort and are less likely to be accepted by users. Gastrointestinal temperature measurement using the ingestible temperature sensor provides an acceptable level of accuracy as a surrogate measure of Tc without causing discomfort to the user. This form of Tc measurement also allows Tc to be measured continuously in the field and has gained wider acceptance in the last decade.

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Introduction

The ability to sense and regulate body temperature is a key feature of human survival. A deviation of ± 3.5°C from the resting temperature of 37°C can result in physiological impairments and fatality.[1] Some researchers suggested that heat could have played a central role in the synthesis and survival of the first unicellular organism on earth,[2,3] and the ability to sense and regulate body temperature contributed to the evolution of these unicellular organisms to multicellular cold blooded creatures (e.g., fishes, reptiles and amphibians) and warm-blooded mammals.[4] Organisms not endowed with thermoregulatory and protective functions and behaviours would have been eliminated through natural selection. Different strategies to regulate body temperature are used to maintain physiological homeostasis. For example, cold blooded animals regulate temperature by relying on external heat sources (ectotherms).[5] These animals are dormant at low body temperature and become active to seek food and shelter when their body temperature is raised by absorbing heat from the environment. Humans are endotherms because humans generate heat internally to regulate body temperature through a balance of heat production, absorption, and loss.

Like the first living cell on earth, thermo-sensitivity, thermoregulation, and thermo-protection remain a central part of physiological homeostasis and survival, and are necessary properties for living organisms to operate proficiently in their environment.[4] Physical exercise is one

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of the environments where human thermoregulatory functions are critical for survival and sustenance of physical work. During intense prolonged physical exertion (e.g., endurance races), body temperature can increase from about 37°C at rest to >42°C, where cellular cytoskeleton can be damaged[6] and the functions of organs and central nervous system can be impaired.[7] An understanding of thermoregulation during physical exertion is important in protecting athletes from heat injury and in managing physical performance under hot conditions. Advances in the related field of body temperature measurement have played an important role in human thermoregulation research, by allowing researchers to quantify and "see" body temperature. Although a variety of methods are available to measure body temperature, there are still challenges in measuring body temperature accurately, especially during exercise and sport participation. This review is aimed at providing a brief discussion on thermoregulation during exercise and sport participation and the measurement of body temperature in both the clinical and exercise settings.

Core and Shell Temperatures

In humans, body temperature comprises the temperatures of the core and shell. The core temperature (Tc) refers to the temperatures of the abdominal, thoracic and cranial cavities, whereas the shell temperature (Ts) refers to the temperatures of the skin, subcutaneous tissue and muscles.[4,5] Tc is regulated by the brain, at about 36.8°C during rest,[5] whereas Ts is influenced more by skin blood flow and environmental conditions.[4] For example, exposure to cold ambient temperature decreases Ts, but Tc may remain relatively constant. Although humans are regarded as homeotherms (able to maintain constant temperature) the dichotomy of body temperature into Tc and Ts is unique in that the Tc is endothermic, regulated by the brain, whereas Ts is ectothermic, being influenced by external environment. The human body is able to capitalise on the dual-thermic properties of thermoregulation by making the Ts slave to Tc. During heat stress, skin blood flow is increased, resulting in an elevated Ts and an increase in heat dissipation to the environment.[8] In contrast, cold stress reduces blood flow to the skin, leading to a decrease in Ts and conservation of heat in the body. The ectothermic properties of Ts and the endothermic properties of Tc function in synchrony to maintain thermal balance within the body.

Tc is essentially the temperature of the blood in the circulation, and the gold standard for Tc is taken to be the temperature of the blood from the pulmonary artery.[9-11] The pulmonary artery receives blood returning to the heart through the right ventricle, which is the blood that stores and transports heat to the skin and to the various organs in the body. Fluctuations in Tc can have significant implications on homeostasis in the body because Tc reflects the amount of heat the cells in the circulation and the cells and organs in the abdominal, thoracic and cranial cavities are exposed to.[5,10] Extremes in Tc (>42°C) can be detrimental to cellular and organ functions, which can threaten survival of the host.[12] Hyperthermia can impair the central nervous system and cause systemic inflammation, tissue necrosis and multiple organ failures.[7,12] Hypothermia (Tc <35°C) impairs cardiovascular, respiratory and central nervous system functions, which can lead to muscle damage, pulmonary oedema, hypotension, bradycardia, and renal failure.[13] The strong association between Tc and physiological homeostasis and disturbances makes Tc an important clinical and laboratory indicator of thermal strain in the body.

Temperature Regulation during Physical Exercise

During physical exercise, metabolic heat production can increase by 10- to 20-fold, but less than 30% of the heat generated is converted to mechanical energy.[8] Conversely, more than 70% of metabolic heat generated has to be transported from the peripheral compartments of the body to the skin to be dissipated to the environment. Heat starts to accumulate in the body when the heat dissipating mechanisms are unable to cope with metabolic heat production, leading to an increase in body temperature. For example, average gastrointestinal (GI) temperature increased from 37.6°C before exercise to 39.3°C after running for 45 min in the outdoor (Fig. 1). The highest individual GI temperature recorded was 40.3°C during the run. In addition, the mean GI temperature of soldiers marching for 12 km with the standard equipment and backpack increased from 37.5°C before the march to 39.4°C at the end of the march, and the highest individual GI temperature recorded was 40.4°C (Fig. 2). The duration and intensity of exercise, which drive metabolic heat production, contribute significantly to the amount of heat accumulated in the body during exercise.[14] The risk of heat injury during physical exertion is often underestimated during cooler conditions because metabolic heat production alone can generate sufficient heat to cause heat injury even in cooler conditions during intense exercise.[15,16] The "fire" starts from within the body in exertional heat injury, and heat casualties have been reported in ambient temperatures <20°C.[14-16] Athletes and coaches should continue to be vigilant about heat injury even when exercising in cooler conditions.

Heat transfer between the body and the external environment occurs through the processes of conduction, convection, radiation and evaporation.[5] Heat transfer through convection, conduction and radiation is bi-directional, where heat transfer between the skin surface and the environment is driven by the temperature gradient between the skin and the surrounding environment. Heat is

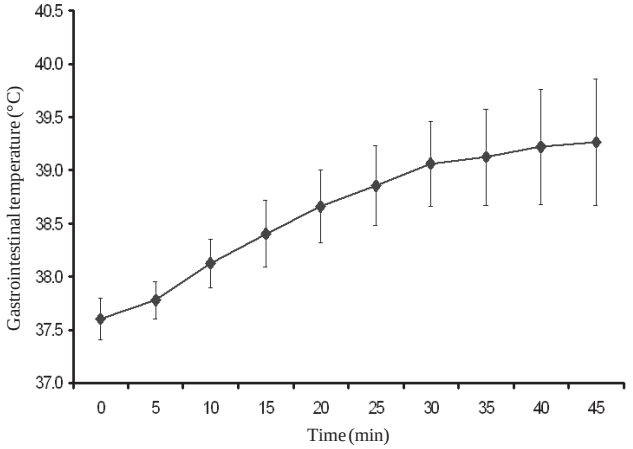

Fig. 1. Mean and standard deviation of gastrointestinal temperature during a 45 min outdoor run. Nine healthy male runners (20 to 24 years old) performed the self-paced run (5 to 6 min/km) in the outdoor, under an ambient temperature of ~30°C and relative humidity of ~65%. Core temperature was measured using the ingestible telemetric temperature sensor (VitalSense, Mini Mitter, Bend, OR) that was ingested about 8 h before the run.

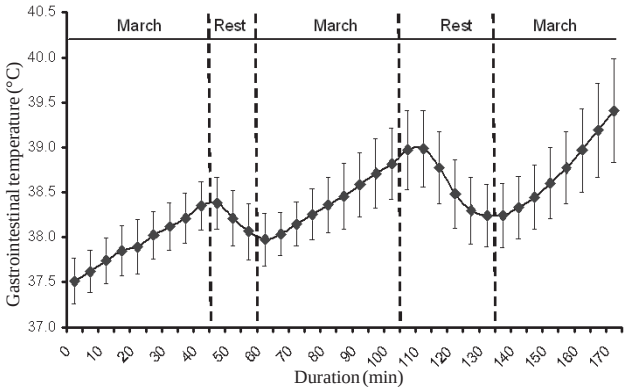

Fig. 2. Mean and standard deviation of gastrointestinal temperature during a 12-km march with the standard load and backpack for recruits in the Singapore Armed Forces. Ten male recruits (18 to 19 years old) from the Singapore Armed Forces performed the 12-km march carrying ~28 kg load under an ambient temperature of ~30°C and relative humidity of ~65%. The march was performed over 3 x 45 min of work intervals, and was interspersed with a 15 min and 30 min rest interval after the first and second work intervals, respectively. The recruits marched at a pace of ~5.3 km/h. Core temperature was measured using the ingestible telemetric temperature sensor (VitalSense, Mini Mitter, Bend, OR) that was ingested about 8 h before the march.

transferred from the environment to the skin if the ambient temperature is warmer than Ts and vice-versa. A fan blowing air that is warmer than the skin will cause heat to be absorbed by the skin. Based on these mechanisms of heat exchange between the skin and the surrounding environment, it is recommended that strenuous physical activities should be conducted during the cooler hours of the day and under the shade whenever possible. Organisers of sporting events should also be prepared to delay or cancel the event if the weather condition is hotter than anticipated.[17]

Unlike the other avenues of heat exchange, heat dissipation through evaporation is uni-directional, where heat is transferred only from the skin surface to the external environment.[18] Evaporative heat loss takes place when sweat changes from liquid to gaseous states. During physical exercise, >80% of heat is dissipated through evaporative heat loss, making it the primary means of heat removal from the body.[4] Therefore, the ability to sweat is very important for thermoregulation and the sustenance of exercise over long duration. About 1 litre of sweat is loss for each hour of exercise in hot conditions,[19] and higher sweat rates (>2 L/h) have been reported in well-trained athletes.[20] However, the propensity for sweat to be evaporated is inversely related to the amount of water vapour in the air. A high relative humidity inhibits evaporative heat loss whereas evaporative heat loss is promoted when the relative humidity in the air is low. Exercising under a warm and humid condition causes the body to lose fluid through sweat loss with minimal heat loss. Therefore, the common perception that exercising in the night hours lowers the risk of heat injury is not necessarily true in tropical climates, like in Singapore, where relative humidity is higher (>80%) in the night hours. Although the cooler temperatures at night may facilitate convective and radiative heat dissipation, evaporative heat loss is highly impeded by the higher relative humidity in the night. And since evaporative heat loss accounts for >80% of heat dissipation during exercise, the net result is an increase in heat storage in the body. The effects of water vapour content in the air on evaporative heat loss reiterate the need to be vigilant about heat injury even when exercising in cooler conditions.

Physiological Functions of Body Temperature

In humans, body temperature is regulated at the hypothalamus region of the brain,[21] which regulates body temperature to function within ±1°C of resting temperature over each 24 h cycle.[5] Deviation from resting body temperature affects various physiological systems in the body, which is indicative of the span of biological functions and dysfunctions that interact with the thermoregulatory mechanisms.[9] For example, fever has been a recognised feature of an infection since AD 64.[1] Besides providing a convenient symptom for the diagnosis of an infection, fever can also be therapeutic because an increase in body temperature may enhance the response of the immune system.[22] An elevated upper respiratory tract temperature may inhibit temperature-sensitive functions of pathogens.[23] Rhinovirus, which accounted for 40% of upper respiratory tract infections (URTIs) in adults,[23] functions within a strict temperature optimum of 33°C to 35°C.[24] An elevation of body temperature above the temperature optimum range would be inhibitory to the virus.

Hyperthermia may also function as the signal that triggers the central fatigue response during intense exercise.[25] Cyclists exercising in hot conditions on 3 separate occasions experienced volitional exhaustion consistently at an oesophageal temperature of 40.01°C to 40.02°C, regardless of the starting and rate of increase in oesophageal temperature.[26] Evidence from the same study suggests that the central fatigue mechanism inhibits exercise performance by limiting cardiac functions (i.e., stroke volume and cardiac output). The occurrence of central fatigue at a threshold temperature may serve to protect the body from overheating by "forcing" exercise cessation so as to prevent further increase in body temperature.[27] Hyperthermia may serve as a self-limiting signal to the central nervous system to protect the body against lethal heat stress.

A single bout of exposure to sub-lethal heat stress provides protection for subsequent exposure to lethal heat stress i.e., heat shock response.[28-30] Exposure to sub-lethal heat stress stimulates the synthesis and production of heat shock proteins (70 kDal molecular weight, HSP 70), which protects the cyto-skeletal structures of cells from denaturing under lethal heat stress.[30-33] In cells and whole animals (e.g., mice, larvae, pupae, embryos, bacteria cells, yeast cells etc), pre-exposure to a dose of sub-lethal heat stress conferred tolerance against a subsequent lethal dose of heat shock[34,35] and prevented phenocopy.[30-33] The increased thermo-tolerance is attributed to the synthesis of HSP 70 resulting from the sub-lethal heat exposure. This evidence suggests that temperature regulation plays an important role in the overall function of the body, and that the thermoregulatory mechanisms can adapt to thermal stress to confer a higher level of thermo-tolerance through the heat shock response.

Measurement of Core Temperature

Before the existence of the thermometer in the 18th century, physicians were skilled in assessing Tc by feeling skin temperature with their hands.[1] Although the scales to quantify temperature in Fahrenheit (1720 AD) and Celsius (1742 AD) were developed in the 18th century, the significance of thermometry for the clinical diagnosis of fever was only recognised in1868.[36] The gold standard for Tc is the temperature within the pulmonary artery,[9-11] but measurement of intra-pulmonary arterial (IPA) temperature is invasive, and is not suitable for non-surgical applications. In humans, non-invasive surrogate measurement of Tc is commonly taken at the sublingual site (oral temperature), the axilla, and the tympanic membrane.[4,5] Invasive sites for surrogate measurement of Tc include the rectum, oesophagus, and the GI tract.[4] Temperature readings from these Tc measurement sites are not uniformed because they represent the local temperature of the respective anatomical sites.[9] The site of choice for Tc measurement would depend on the type of instrument available and used, and the purpose of measurement. Sublingual, axilla and tympanic temperatures are commonly used in the clinical setting, whereas rectal, oesophagus and GI temperatures are most commonly used in the sports and exercise settings.

Oral Temperature

Oral temperature is one of the common sites for measuring Tc in the clinical setting. Oral temperature fluctuates about 0.4°C below IPA temperature.[37] The sublingual site is easy to access for taking oral temperature and oral temperature is responsive to changes in Tc.[1] However, oral temperature requires about 5 minutes to achieve a stable temperature reading[5] and its accuracy can be influenced by breathing rate, which makes it unfeasible to measure oral temperature during or immediately after physical exertion. Facial and head temperatures and the ingestion of beverages and food prior to temperature measurement can also influence oral temperature reading. Oral temperature measurement increases the risk of mouth-to-mouth cross infection and it is not suitable for young children (<5 years old) who have the tendency to bite the thermometer. Shivering, which occurs during fever and hypothermia, can cause biting and breakage of the thermometer and the risk of swallowing the mercury in the thermometer. Oral temperature may be a useful surrogate for Tc in the clinical setting, but care should be taken to mitigate the influence of environmental and behavioural factors that may affect the accuracy of the measurement.

Axilla Temperature

The axilla temperature is measured under the armpit, near to the brachial artery. Axilla temperature measurement is practical, non-invasive and safe, and is suitable for infants and younger children.[9] However, the inaccuracy and instability of axilla temperature makes it a poor choice for clinical and research application.[38] Although one study reported that axilla temperature is as accurate as rectal temperature in measuring Tc under stable ambient conditions in neonates,[39] there are conflicting reports of poor association between axilla temperature and other surrogate measurements of Tc in adults and children.[9] The sensitivity of axilla temperature to detect fever is poor, ranging between 27.8% and 33%.[40,41] Axilla temperature can be influenced by ambient temperature, sweat, humidity and the density of hair at the axilla, making it unsuitable for measurement of body temperature during sports and exercise participation.

Tympanic Temperature

Tympanic temperature is measured at the tympanic

membrane. Among the non-invasive sites for Tc measurement, tympanic temperature probably has the strongest association with Tc. The tympanic membrane receives blood supply from the internal carotid artery, which also supplies blood to the hypothalamus, the region of the brain that regulates temperature.[1] Tympanic temperature tracks Tc accurately for patients >3 years of age,[9] but there are concerns that the technology of infrared temperature scanners does not meet the healthcare industrial standards for temperature measurement,[42] and that the accuracy of the tympanic temperature measurement is highly dependent on the skill of the technician.[38,43] Compared with IPA temperature, using tympanic temperature resulted in 21.1% of the patients receiving delayed interventions and 37.8% of the patients receiving unnecessary interventions.[10] Only about 50.9% of tympanic temperature reading was reflective of Tc.[10] Tympanic temperature also underestimates Tc in patients under general and local anaesthesia.[38] The infrared tympanic thermometer does not measure temperature continuously, which makes it unsuitable for continuous temperature measurement during physical exercise.

Rectal Temperature

Rectal temperature is measured by inserting a thermistor rectal probe or a thermometer about 8 cm past the external anal sphincter. This is one of the most common methods for measuring Tc in the laboratory. Rectal temperature reading is stable and is not influenced by ambient conditions. However, the invasive nature of rectal temperature measurement can be traumatic for children and uncomfortable for adults. Using the rectal probe for research may discourage volunteers from participating in the study, especially if the task involves physical exertion. The principal author of this review measured ear canal temperature instead of rectal temperature in one of his studies because all the subjects that experienced the use of the rectal probe in the pre-intervention trial withdrew from the study without starting the post-intervention trial.[44] That particular study had to be done all over again using ear canal temperature as a surrogate for Tc measurement. Inconsistency in rectal temperature readings can result from the hot and cold areas along the rectum.[5] A key concern with the use of rectal probes is cross infection. Measuring rectal temperature resulted in an outbreak of salmonella cross infection in newborns.[45] The risk of cross infection can be removed by using disposable rectal thermometer probes. Although rectal temperature is a well accepted surrogate measurement of Tc,[38] recent evidence implies that changes in rectal temperature lags behind the changes in temporal artery temperature.[46] However, the validity of temporal artery temperature as an indicator of Tc has also been criticised.[11]

Oesophagus Temperature

Oesophagus temperature is measured by inserting a thermistor probe through the oral or nasal passages into the oesophagus. Once inserted, the probe is adjusted along the oesophagus to achieve the highest temperature reading, which is taken as the point that is proximal to the pulmonary artery.[47] Oesophagus temperature is about ± 0.1°C to 0.2°C of the IPA temperature, but oesophagus temperature measurement is avoided by some because of the difficulty and discomfort of inserting the thermistor probe through the nasal and oral passages.[9] Oesophagus temperature would be a preferred method of Tc measurement if patients and research volunteers are not adverse to the procedure of inserting the thermistor probe into the oesophagus.

Gastrointestinal Temperature

GI temperature is measured by ingesting a telemetric temperature sensor that transmits the temperature of the GI environment wirelessly to an external logger (Fig. 3). The idea of the telemetric temperature sensor was reported more than 30 years ago,[48] and telemetric temperature measurement was first used in animal studies.[5] The use of a telemetric temperature sensor to measure GI temperature in humans was reported only about 10 years ago,[47,49] and has gained wider usage since then.[50,51] The GI temperature performs as well as oesophageal and rectal temperatures in tracking Tc changes,[47,49,51,52] although GI temperature may respond slower to Tc changes than oesophageal temperature.[51] A meta-analysis on the agreement between GI, rectal and oesophagus temperatures by two of the authors, found better agreement between GI and oesophagus temperatures than between GI and rectal temperatures.[53] GI temperature responds slower to changes in temperature than oesophagus temperature at the beginning and end of

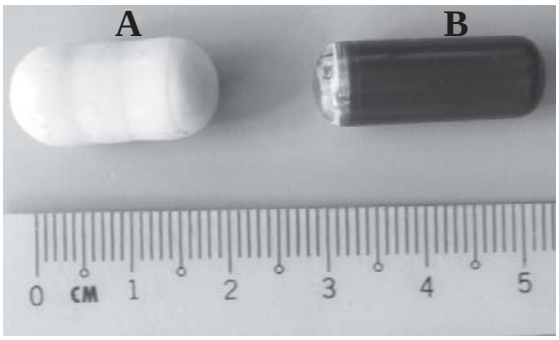

Fig. 3. The ingestible telemetric temperature sensors from (A) HQI Inc (Coretemp, Sarasota, FL) and (B) Mini Mitter (VitalSense, Bend, OR). These sensors are used to measure gastrointestinal temperature in humans. Following ingestion, the data measured by the sensors are transmitted wirelessly to a logger that stores and displays the temperature measured. The sensors are not digestible and they are expelled from the body through normal bowel movement. Details on the performance of the ingestible telemetric temperature sensor can be found in Byrne C, Lim CL. Br J Sports Med 2007;41:126-33.[53]

exercise and when there is a change in exercise intensity, but GI temperature responds faster than rectal temperature in the same instances of change in body temperature.[53] The key advantages of measuring GI temperature with the ingestible temperature sensor are the absence of discomfort to the user and the ability to track temperature continuously in the field. This advantage has allowed the authors and their colleagues to report continuous GI temperature, for the first time, in runners during a half-marathon.[50] Previously, studies measuring Tc in the field only measured a single point rectal temperature at the end of races.[54-56] One of the disadvantages of the telemetric temperature sensor is the difficulty in standardising the location of the sensor in the GI tract. To ensure that the temperature sensor is further down the GI tract, the sensor is usually swallowed 4 h to 8 h before measurement. However, as GI motility is different between individuals, the sensor may not be located in the same area of the intestine at the point of measurement. Those with faster gut motility would have expelled the sensor at the point of measurement. GI temperature reading can be influenced by water and food intake if the sensor is ingested too near to the time of measurement.[57] The telemetric temperature sensor has good potential as a surrogate of Tc measurement. Users need to gain sufficient experience with the system to better judge the suitable time to ingest the sensor so as to provide valid and reliable temperature readings. GI temperature measurement through the ingestible temperature sensor appears to achieve the best balance between practicability, comfort and user acceptance, and scientific validity and reliability.

Conclusion

The objective of this review was to briefly discuss the complexity of thermoregulation in humans, and the mechanisms that regulate body temperature during physical exertion. The intricacies of heat transfer between the skin surface and the environment were also discussed not only to educate readers on these issues, but also to highlight some common misunderstandings about thermoregulation during exercise and sports performance. Besides being an end-product of metabolism, heat also has therapeutic properties during an infection, and may serve as a self-limiting signal that triggers central inhibition of exercise performance. The ability to measure and quantify body temperature accurately is crucial in enabling research in thermoregulation. Current evidence supports the use of oral temperature for clinical setting, and GI temperature measurement through the ingestible temperature sensor has gained wider acceptance over the last decade for measuring Tc in the exercise and sport setting.

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Disclaimer

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