Measurement and manipulation of body temperature in rest and exercise

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Voor Quirine

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ABBREVIATIONS

avg = average
BM = body mass
bpm = beats per minute
°C = degree Celsius
CBF = cerebral blood flow
CNS = central nervous system
Δ = difference
HR = heart rate
Hz = hertz
ICE = ice-slurry
IR = infrared
LoA = limits of agreement
MRI = magnetic resonance imagery
NIRS = near-infrared spectroscopy
p = statistical significance level
PO = power output
r = correlation coefficient
RH = relative humidity
RPE = rate of perceived exertion
RT = reaction time
SC = scalp cooling
SD = standard deviation
TC = thermal comfort
TS = thermal sensation
VO_2 = oxygen uptake
W = Watt
WBGT = wet bulb globe temperature
ZHF = zero heat flux

T_{ac} = aural canal temperature
T_{amb} = ambient temperature
T_{ax} = axillary temperature
T_{bl} = bladder temperature
T_{body} = mean body temperature
T_{ca} = temperature of the inner canthus of the eye
T_{core} = core temperature
T_{eb} = exhaled breath temperature
T_{es} = esophageal temperature
T_{fh} = forehead temperature
T_{gi} = gastrointestinal temperature
T_{np} = nasopharyngeal temperature
T_{or} = oral temperature
T_{pa} = pulmonary artery temperature
T_{pill} = temperature measured by telemetry pill
T_{re} = rectal temperature
T_{sk} = (mean) skin temperature
T_{tr} = temporal radiation temperature
$T_{ty\text{-}c}$ = tympanic temperature measured by direct contact
$T_{ty\text{-}ir}$ = tympanic temperature measured using infrared
T_{ur} = urine temperature
T_{va} = vaginal temperature
T_{zhf} = temperature measured using the zero heat flux technique

GLOSSARY OF TERMS[1]

Ambient temperature (T_{amb}): The average temperature of the environment surrounding a body (usually air or water), as measured outside the thermal and hydrodynamic boundary layers that overlay the body.

Body heat balance: The steady-state relation in which total heat gain in the body equals its heat loss to the environment.

Core temperature (T_{core}): Ideally, the mean temperature of the thermal core. In practice it is represented by a specified core temperature at the site of measurement.

Core, thermal: Those inner tissues of the body whose temperatures are not changed in their relationship to each other by circulatory adjustments and changes in heat dissipation to the environment that affect the thermal shell of the body.

Body heat content: The product of the body mass, its average specific heat, and the absolute mean body temperature.

Heat flow: The amount of heat transferred per unit of time between body parts at different temperatures, or between a body and its environment when at different temperatures.

Heat strain: In temperature regulators: 1. Any deviation of body temperature induced by sustained heat stress that cannot be fully compensated by temperature regulation; 2. Any activation of thermoeffector activities in response to heat stress that causes sustained changes in the state of other, non-thermal, regulatory systems.

Heat stress: Any change in the thermal relation between a temperature regulator and its environment which, if uncompensated by temperature regulation, would result in hyperthermia.

Homeostasis: General term characterizing the relative constancy of the internal environment of an organism as being maintained by regulation.

[1] Partly from: The Commission for Thermal Physiology of the International Union of Physiological Sciences. Glossary of terms for thermal physiology. *Jpn J Physiol* 2001; 51(2): 245-80.

Hyperthermia/hypothermia: The condition of a temperature regulator when core temperature is above/below its range specified for the normal active state of the species.

Mean body temperature (T_{body}): The total temperature signal generated by all thermosensors distributed in the core and shell.

Mean skin temperature (T_{sk}): The weighted average of a certain number of regional skin temperatures.

Precooling: The artificial reduction of body heat content prior to exercise.

Selective brain cooling (SBC): Lowering of brain temperature, either locally or as a whole, below aortic (arterial blood) temperature.

Shell, thermal: The skin and mucosal surfaces of the body engaged directly in heat exchange with the environment. In addition, those tissues under these surfaces whose temperatures may deviate from core temperature due to heat exchange with the environment and to changes in circulatory convection of heat.

Temperature regulation: The maintenance of the temperature or temperatures of a body within a restricted range under conditions involving variable internal and/or external heat loads.

Thermal comfort (TC): Subjective rating on how comfortable the thermal environment is experienced.

Thermal sensation (TS): Subjective rating on the sense of temperature.

Thermoeffector: An organ system and its action, that affect heat balance in a controlled manner as part of the processes of temperature regulation.

Thermography, infrared: The recording of the temperature distribution of a body from the infrared radiation emitted by the surface.

Wet bulb globe temperature (WBGT): a composite temperature used to estimate the combined thermal stress of air temperature, humidity, wind speed and solar radiation on humans.

Chapter 1

General introduction

Humans are equipped with an extensive thermoregulatory system to keep their body core temperature within a narrow range around 37°C (1). They can elevate and stabilize their core temperature above environmental temperature by adjusting metabolic heat production and heat loss mechanisms. As a result, humans are called endotherms, meaning they are able to maintain a constant temperature independent of external conditions.

Nevertheless, regularly conditions occur in which a constant core temperature is not maintained. This may be due to a pathological thermal state like fever, but environmental and behavioural factors may challenge the thermoregulatory system of healthy individuals as well. A combination of high climatic load, strenuous exercise and/or wearing protective clothing may for example impose uncompensable heat stress on athletes, firemen and soldiers. Therefore, reliable core temperature measurement in rest and exercise is of major importance to monitor subjects and take appropriate measures. Further, more knowledge on the way in which heat stress affects performance and on how this process might be manipulated, could optimize performance and decrease health risks.

This introduction will provide some background on both the issues of core temperature determination and the relation between heat stress and performance, the main topics of this thesis. But first some basic information on human temperature regulation is provided.

1.1 HUMAN BODY TEMPERATURE

Heat balance

Body core temperature is determined by the balance between heat production and heat loss. This heat balance can be captured into the following equation (2):

$$M \pm C \pm R - E = S$$

M represents metabolic heat production. Metabolically active tissues degrade a large part of their energy to heat, which contributes to the internal temperature.

C represents conduction and convection. Conduction means the transfer of heat from one material to another by direct molecular contact, for example from a body to clothes or air. Convection involves moving heat, for example by the movement of air or water around us. Conduction and convection work in common to lose body heat when the environment is cooler than the skin: conduction transfers heat from the skin to the surrounding air or water and convection sweeps away the warmed molecules. When the environment is hotter than the skin, the body gains heat by the reverse process.

R represents radiation, which involves heat transfer by infrared rays. In rest, this is the main mechanism to lose heat. At room temperature, about 60% of the excess body heat is lost by radiation (3). Again, net heat gain is also possible, when the temperature of the surrounding radiation source is higher than the skin. The C and R terms constitute the dry heat loss of the body and their contribution depends on the temperature difference between the body skin and the environment.

E represents evaporation, involving all heat that leaves the body in the form of water vapor. Sweating is the main example, but also some insensible water loss happens in the lungs and at the mucosa of the airways. During rest in room temperature, evaporation accounts for only 20% of body heat loss (3). However, evaporation becomes increasingly important (80-100%) when body temperature rises and/or when the ambient temperature is close to the body's skin temperature. Evaporation is also called wet heat loss. As its cooling capacity depends on water that is really evaporated (not dripped off), wet heat loss is dependent on the relative humidity of the surrounding air.

S represents net heat storage. When the body heat content remains stable, S will be zero. However, positive or negative heat storage means an increase or decrease in core and/or skin temperature.

Humans are capable of maintaining a stable heat balance in very diverse conditions; the world's lowest and highest measured ambient temperatures are -89.2°C (Antarctica, 1922) and 57.2°C (Libya, 1917), while additional variations in humidity, radiation, wind and precipitation occur. The next paragraphs describe the ways in which the body controls the heat balance, preventing large fluctuations in core temperature.

Body temperature regulation

Human body temperature can be divided in the core and the shell temperature. The core includes the abdominal, thoracic and cranial cavities and has a stable temperature due to its endothermic nature. The shell comprises the skin and subcutaneous tissue, which are influenced by the environment (4). More refined models define a third compartment for the muscles, but this will be left out of consideration here.

Because of this heterogeneity, not a single regional temperature measurement reliably reflects the mean body temperature (5). Therefore, mean body temperature (T_{body}) is determined by calculating a weighted average of core (T_{core}) and mean skin temperature (T_{sk}):

$$T_{body} = a*T_{core}+(1-a)*T_{sk}$$

in which *a* is dependent on T_{sk}: 0.6 (T_{sk}<31.5°C), 0.7 (31.5°C<T_{sk}<33°C) or 0.8 (T_{sk}>33°C) (5; 6).

The setpoint for core temperature is about 36.8-37.0°C with a circadian fluctuation of approximately 0.6°C (7). This temperature is tightly regulated using a servomechanism, depicted in Figure 1.1. The main thermoregulatory centre is housed in the hypothalamus (located in the diencephalon), although other unidentified structures in the central nervous system (CNS) may also be involved. The hypothalamus receives input from central and peripheral, cold and warm thermoreceptors. Central thermoreceptors are largely located in the hypothalamus itself, but also in the spinal cord, and deep abdominal and thoracic tissues. Their firing rate reflects the temperature of the local blood supply. Peripheral thermoreceptors are located in the skin and some mucous membranes, mainly responding to (changes in) the environment.

All afferent thermal input is integrated in the hypothalamus, which acts as a thermostat. The integrated signal is compared to a setpoint that may be modified by pyrogens, acclimatization and circadian rhythms (8). The hypothalamus controls several effector mechanisms to restore body temperatures to the desired value:

- *Vasomotor tone*: Constriction of the smooth muscles around skin arterioles and superficial veins reduces blood supply to the skin. This increases the insulating capacity of the shell and reduces dry heat loss from the skin. On the contrary, dilation of the skin arterioles increases blood supply to the skin when an increase in heat loss is required.
- *Sweat glands*: When body heat content is too high, sweat glands are stimulated to actively secrete sweat. Evaporation is very powerful mechanism; 1 L of sweat evaporation results in a heat loss of 2428 kJ (3).
- *Shivering*: When vasoconstriction is insufficient and more heat needs to be generated, the body starts shivering. Shivering involves rapid and involuntary contractions and relaxations with low mechanical efficiency. As a result it can increase metabolism up to 5 times the normal value (8).
- *Non-shivering thermogenesis:* This mechanism involves increasing the metabolic rate without muscle activation, presumably by the release of hormones (adrenaline, noradrenaline, thyroxine). Its exact mechanism and efficacy in humans is controversial, but recent research suggests that non-shivering thermogenesis is more important to generate heat in healthy men than was previously assumed (9).

Next to these physiological factors, there are also behavioural and physical factors that contribute in controlling the heat balance.

- *Behaviour.* In extreme conditions, behaviour is the main tool to prevent detrimental environmental impact. This includes wearing appropriate clothing, seeking a protected or artificially created microclimate and/or adjusting the activity level (i.e. metabolic heat production). On a longer term, increasing fitness and acclimatization level will improve temperature regulation (10; 11).
- *Body composition.* Subcutaneous fat is a great insulator, facilitating conservation of heat. Further the ratio of body surface area to body mass influences the rate of heat loss. A larger surface to mass ratio leads to an easier loss of heat (12). Therefore, tall and heavy individuals are more at risk for hyperthermia, whereas small and lean subjects may easier develop hypothermia (3).

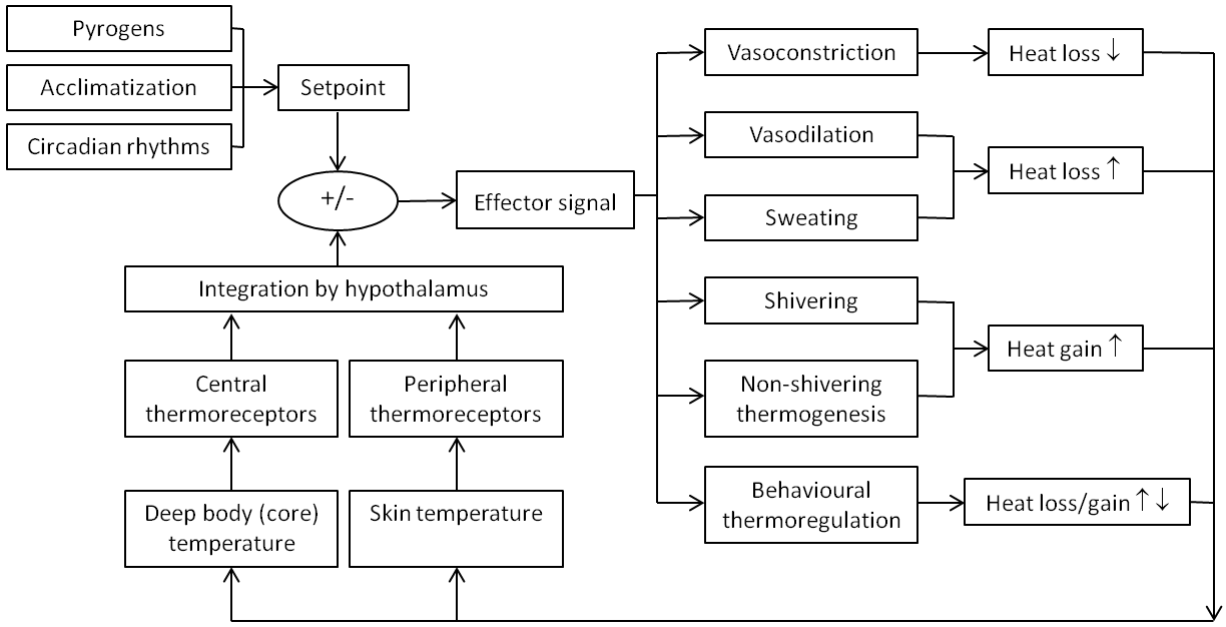

Figure 1.1. *Human thermoregulatory system, adapted from (13).*

Deviations in body temperature

Usually, core temperature stays within its normothermic range of 36.1-37.8°C (8), covering differences across individuals and measurement sites (1; 14). In addition, its specific value depends on the circadian rhythms, the menstrual cycle and small incidental fluctuations. Deviations outside the normothermic range are referred to as hypothermia and hyperthermia. Mild deviations may impair bodily functioning, performance and comfort, while more severe deviations (<33°C or >40°C) may have life-threatening consequences like cell damage, organ failure, systemic inflammation and CNS impairment (4) (Table 1.1).

It has to be noted that the reported thresholds are indicative and that exceptions occur. In well-trained athletes, core temperature may exceed 40°C without adverse events (15); at the low side of the spectrum it has been shown that survival occurs even when a core temperature of 13.7°C has been reached (16).

Table 1.1. *Classification of body core temperatures and its consequences, from (7).*

Temperature	Consequences
> 44°C	Denaturizing of proteins, death
40-44°C	Failure of thermoregulation
37.8-40°C	Fever, hyperthermia
36-37.8°C	Normothermia
33-36°C	Mild hypothermia
30-33°C	Hypothermia: reduced metabolism, depressed respiration and consciousness
27-30°C	Deep hypothermia: failure of thermoregulation, ventricular fibrillation
20-27°C	Apparent death, light rigid pupils, extreme bradycardia
<20°C	Asystole, death

There are a few main causes for deviations towards the hyper- or hypothermic range (8):

Illness

The most well-known illness related temperature deviation is fever. Fever is known as a symptom of infection since 64 AD (17) and is often operationally defined as a core temperature above 38°C. In fever, the setpoint for core temperature is increased due to pyrogens triggering the hypothalamus. Besides being a major diagnostic tool for infection, it may be physiologically functional by stimulating the immune response and inhibiting temperature-sensitive pathogens (4). Another temperature related illness is poikilothermia (18), the inadequate function of the thermoregulatory control centre. Because of this lack of control of the heat balance, core temperature can easily and unconsciously run outside the normal range.

Clinical treatment

During clinical treatments, core temperature may, deliberately or not, fall out of is normal range. Therapeutic hypothermia is being used during surgery or after ischemic insult to the brain (19) to improve chances on a positive outcome. It requires strict control of core temperature. On the contrary, perioperative hypothermia is a common unwanted thermal phenomenon after surgery that may increase the risk of complications (20).

Exercise

Exercise increases metabolic heat production and is therefore the most common way to actively increase core temperature. Several factors, including exercise intensity, environmental conditions, clothing, fitness level and hydration status determine the extent and the health risks of this so-called exercise hyperthermia. Paragraph 1.3 will discuss heat stress and exercise performance.

Extreme environments

In extreme environments it may become impossible to maintain the heat balance, resulting in negative of positive heat storage. Factors contributing to a positive heat storage are high ambient temperature, high humidity and little air flow, often in combination with exercise, protective clothing and/or dehydration. Negative heat storage particularly occurs in cold environments where wind and wetness are involved. When submerged into cold water, heat loss is about five times larger than in air of similar temperature. Alcohol and drug abuse may also increase the risk of hypothermia by disturbing the thermoregulatory system in the prevention of heat loss.

1.2 CORE TEMPERATURE DETERMINATION

Core temperature

The thermal core has been defined as “Those inner tissues of the body whose temperatures are not changed in their relationship to each other by circulatory adjustments and changes in heat dissipation to the environment that affect the thermal shell of the body” (21). This includes the CNS, central blood and thoracic and abdominal cavities. However, it is well-known that even inner tissues may be subject to slightly different temperatures and different responses to temperature changes (17; 22) (Figure 1.2). Therefore it can be stated that a single core temperature does not exist, core temperature depends on the location it is measured.

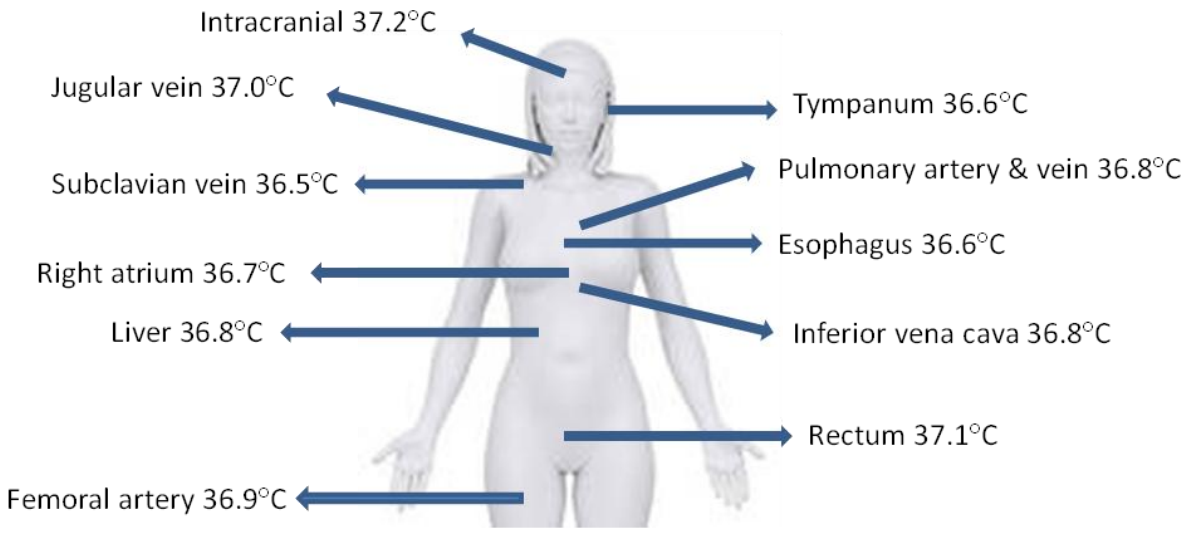

Figure 1.2. *Variation in core temperatures, based on (22).*

Further, inner tissues are often difficult accessible for measurement. As a result, core temperature is regularly estimated by measurements at surrogate locations. In combination with varying measurement methods and conditions, quite some sources of variation are introduced (23). So although the concept of core temperature is widely used, its interpretation and usability strongly depend on location, measurement method and measurement conditions.

Nevertheless, core temperature is an important parameter that is commonly referred to in clinical, occupational and forensic medicine, as well as in research and operational settings. Core temperature determination can detect illness at an early stage, prevent injury by heat or cold stress or guide a treatment. So research to good methods for core temperature determination is warranted.

Brain temperature

Brain temperature is one of the most interesting, but also one of the least known core temperatures of the body. Deep brain temperature is thought to be slightly higher than central blood temperature (~0.2°C) because of the high metabolic activity in the brain, producing an excess of heat. The extra heat is removed by the cooler arterial blood, whose flow is adjusted to the local metabolic rate. In that way, each part of the brain normally keeps a constant temperature above that of arterial blood (24). Some authors state that hypothalamic temperature may drop below heart temperature during

hyperthermia because of a so-called selective brain cooling mechanism (25). However, the existence of this phenomenon in humans is heavily debated (26-28). Paragraph 1.3 will discuss this issue more extensively.

Brain temperature is not an unambiguous concept. Direct recordings of intracranial temperature (29; 30) and theoretical modelling (31) indicated a substantial temperature gradient from inner to outer brain. Extracranial cooling by the environment would only be able to reach the superficial layers of the brain, the deeper layers being protected by the 'shielding effect of blood flow' (31). Differences between cortical and central branches of the cerebral arteries may also cause thermal gradients in the brain (32). Different temperature conditions in different parts of the brain might be functionally important. For example, temperature substantially affects hemoglobin affinity for O_2, the rate of chemical reactions and activation rate of membrane currents (31). So whenever analysing brain temperature, measurement depth and location should be considered carefully.

Unfortunately, possibilities to measure brain temperature are very limited. Invasive brain measurements are ethically not feasible except during surgery. As a result, non-invasive methods are required. Currently MRI seems most promising for this purpose, but is not sufficiently advanced for accurate measurements yet.

Gold standard

The previous paragraphs raise the question what temperature to use as a reference. There are two sites that are generally considered as 'gold standard' for core temperature: the hypothalamus and the pulmonary artery (33). The hypothalamus is an obvious location, because of its function as main thermoregulatory centre of the body. However, as just discussed, brain temperature can only be measured during specific surgery and is not a usable reference in practice.

The pulmonary artery contains a mixture of blood from all over the body, providing a valid measure for core temperature (34). A pulmonary arterial catheter is required for measurement, so again this method can only be used in certain clinical situations and is unsuitable in practice. The temperature in the distal esophagus reflects central blood temperature quite well (35; 36) and can be measured without clinical intervention.

Therefore T_{es} is often used as a substitute 'gold standard' for core temperature during scientific research.

Usually hypothalamic, pulmonary artery and esophageal temperatures are considered to be comparable, as blood from the heart is pumped to the hypothalamus through large arteries where cooling is minimal. There might be a difference during extracorporeal circulation when the brain is perfused, while the heart is not (37). Further, selective brain cooling may induce a deviation between trunk and brain temperature (24; 25).

Requirements

Obviously, measuring gold standard core temperature is, especially in practice, not ideal. So there is a need for alternative measures. Wartzek et al. (33) identified four main requirements for core temperature measurement:

Accuracy and precision

Accuracy refers to the systematic error or bias, precision to the random error (uncertainty) or standard deviation (SD). The total measurement error is usually expressed as bias ± 2 SD, determining the 95% limits of agreement (LoA) between a measure and its reference. The acceptable LoA depend on the purpose and conditions of the measurement. In general, a total measurement error below 0.5°C, resulting in 95% LoA of less than ±1.0°C is proposed as acceptable for spot checks like fever detection (33; 38). For establishing temperature patterns, bias is less important, but the SD should be below 0.3°C (33). In clinical practice, a temperature measurement method is suggested to be reliable when the SD is 0.3-0.5°C (39; 40). It is important to note that the accuracy and precision of a thermal sensor, as reported in its specifications, have usually been established in laboratory conditions. Regarding its validity for core temperature measurement in practice, a proper methodology is equally important.

Time

Instantaneous measurement during an emergency, a clinical routine or at home, requires a very short measurement time of <10 s. Decreasing measurement time may compromise accuracy. For long term monitoring several minutes to first measurement may be acceptable (33). Further, response time to changes in body heat content differs

per measurement method (location and sensor type). Its importance depends on the situation.

Operating range

The measurement range of human temperature should be between 25 and 45°C, although incidentally even lower temperatures are reported (33).

Handling

For the sake of valid and reliable measurements, as well as user acceptance, easy handling is essential. This implies that a measurement method should preferably be easy to use, safe and convenient for the subject (minimally invasive) and free of artefacts (33). For daily clinical routine and use at home, a low energy supply and affordable price are also required. For continuous monitoring, especially during exercise, a small, lightweight, wireless device is desirable, with extra protection against dislocation of the sensor.

The relative importance of these requirements depends on the application context, i.e. the environment (home, laboratory, field measurement, clinic), purpose (research, diagnosis, monitoring), subject (healthy subject, patient, newborn, worker) and required measurement (absolute, relative, gradient, continuous, spot check) (33). A wide array of measurement devices and body locations has been explored, each to a different extent fulfilling these requirements. The next paragraph provides an overview of current core temperature measurement methods. The appendix provides a more extensive discussion of the use, (dis)advantages, mutual agreement and contraindications of these methods.

Measurement methods

The thermometer is thought to be first invented by Galileo Galilei between 1592 and 1597. It was an air thermometer which only measured heat changes. This was followed by the development of the first liquid in glass thermometer in the seventeenth century (Duke Ferdinand II of Tuscany, 1654) and several temperature scales early in the eighteenth century (Fahrenheit, Reaumur, Celsius). Since Fahrenheit produced the first mercury in glass thermometer in 1713, it gradually displaced the palpation assessment in clinical practice (41; 42). For ages, that method has been used to determine fever in hospital and at home. However, mercury-in-glass thermometers are rather slow, hard to read and only usable at suboptimal body locations. Further, they have a limited

temperature range and breakage could result in mercury intoxication. The last decades, new methods to measure core temperature have been developed. They can roughly be classified into four groups:

Electrical resistance

The electrical resistance of a metal or semi-conductor changes with temperature. This mechanism actually succeeded mercury-in-glass as the standard way to measure temperature by direct contact. Most digital thermometers and thermal sensors make use of a semi-conductor resistance like a thermistor. In general a thermistor is accurate, reliable and can be made very small. A disadvantage may be that it requires direct contact with body tissue, posing the risk of inconvenience, injury and infection. Resistance thermometers are being used at a wide range of body locations with varying suitability to determine core temperature, as reviewed by several authors (e.g. 4; 17; 33; 37; 43).

Infrared (IR)

IR thermometry determines the radiant temperature of an object by measuring the infrared radiation from its surface. The real temperature can be calculated if the emissivity of the object is taken into account. The human skin has an emissivity of 0.98, independent of skin colour. IR thermometry is a non-invasive, convenient and safe measurement technique with little delay (44). However, it is a disadvantage that measurement results can be affected by the probe position regarding the measurement surface, heating of the detector or use of a probe cover (45). For core temperature determination, IR radiation is being measured at the tympanic membrane (35; 46; 47) and the temporal artery (48; 49). Recently, IR thermal imaging (50; 51) and near infrared spectroscopy (NIRS) are also being explored for this purpose.

Radio waves

Radio waves are a type of electromagnetic radiation with a frequency from about 300 GHz to 300 Hz. The frequency spectrum includes temperature dependent information. This mechanism is used in temperature pills, containing a quartz crystal that vibrates at a frequency relative to its surrounding temperature. The low frequency FM signal of the crystal is received outside the body (radio telemetry) and converted into a temperature value (52). Nuclear magnetic resonance (53; 54), microwaves (55; 56) and ultrasound

(57; 58) are other methods using radio waves to estimate temperatures. This allows for convenient non-invasive temperature measurement. However, the latter three are only at the initial stage of development for core temperature determination and have some practical drawbacks.

Heat flow

In the presence of a thermal gradient, heat will flow from a warmer to a cooler environment. The magnitude of the flow will depend on the magnitude of the thermal gradient and the thermal properties of the medium. This mechanism has been used to estimate core temperature at the skin, either by creating a zone of zero heat flow between core and skin (59-61) or by estimating core temperature mathematically from heat flow through a thermal bridge at the skin (38; 62; 63).

Figure 1.3. *Examples of electrical resistance, infrared, radio wave and heat flow thermometry.*

Table 1.2 provides an overview of the various measurement methods in each group, which have been reviewed in the appendix.

Table 1.2. *Overview of core temperature measurement methods, partly based on (33).*

Method	Reliability	Response time	Comfort	Non-invasive	Ease of use	Continuous field meas.	Issues
Electrical resistance							
Pulmonary artery	+	+	-	-	-	-	Only clinical, infection risk
Esophageal	+	+	-	-	-/o	-	Discomfort, gag reflex, interference by drinking
Nasopharyngeal	o	o/+	-/o	o	o	-	Discomfort and confounding factors
Forehead	-	o	+	+	+	o	Unreliable
Oral	o	o/+	o	+	o	-	Easily confounded: food/drink/exercise/saliva/position
Exhaled breath	-/o	o/+	o/+	+	o	-/o	Mask required, reliability unclear
Tympanic (contact)	o	o/+	-	o	-	-/o	Painful, tympanic perforation, dislocation
Aural canal	-/o	o	o	+	o	+	Influence of ambient conditions
Axilla	-	-/o	+	+	+	-	Unreliable
Rectal	o/+	-	-/o	o	o	-/o	Discomfort, delay time
Bladder	o/+	-	-	-	-	-	Only clinical, infection risk
Urine	-	-	o	+	-/o	-	Only during urination, delay time
Vaginal	o	-	-/o	o	o	-	No benefit over rectal, less acceptable
Infrared							
Tympanic (IR)	-/o	o/+	+	+	+	-	Easily confounded by improper measurement
Temporal artery	-	o/+	+	+	+	-	Unreliable
Thermal imaging	-/o	o	+	+	o	-/o	Superficial temperature, expensive camera
NIRS	-	NA	+	+	o	o	Not reliable yet
Radio waves							
Telemetry pill	o	-/o	+	+	+	+	Ingestion time, no standard location, expensive
MRI	-	+	+	+	-	-	Not reliable yet, complicated measurement, expensive
Microwave	-	NA	+	+	-/o	-	Poor resolution, electrical interference
Ultrasound	-	NA	+	+	-/o	-	Not reliable yet
Heat flow							
(Zero) heat flux	o	o/+	o	+	o	o	Start-up time, reliability in the cold

Core temperature measurement issues

Provided a measurement device is accurately calibrated and any systematic errors (offset) have been corrected in the device, deviations between different core temperatures are caused by external confounding factors or internal physiological phenomena.

External confounding factors

The first main external source of variation is the environment. Ambient conditions like temperature and wind can easily affect superficial temperature measurements that ought to predict core temperature. Particularly measurements at the ear (tympanum and aural canal) and skin (forehead, axilla, temporal artery, IR imaging, zero heat flux) seem substantially affected in cooler and unstable environments. In addition, oral, esophageal and intestinal measurements can be affected by external substances (food, drinks, ventilation), while cerumen or hair may confound in-ear measurements.

The second main external source of variation is inappropriate measurement (37). Large errors originate in incorrect procedures. Most well-known examples of error-prone methods are oral and tympanic measurements, the latter having the additional handicap of individual anatomical differences in the ear canal. All these errors cannot be corrected in the device and decrease its reliability, so care should be taken to minimize their influence. Multiple measurements by the same person may increase reliability provided only non-systematic errors are present.

Physiological phenomena

It is well-known that different body sites are subject to different temperatures and different responses to temperature changes. For example, T_{re} is generally 0.2°C higher than T_{pa} in rest, but may be significantly cooler than T_{pa} after 10 min of exercise, due to its delayed response. The brain belongs to the core, but its temperature depends on the depth and location of measurement. In addition, possible selective brain cooling may temporarily alter the relationship between trunk and brain temperature. These natural thermal differences should be appreciated when measuring core temperature. Both external confounding factors and physiological phenomena require to consider which measurement method is most suited for a certain occasion.

Concluding remarks

There clearly is a need for a reliable, fast, convenient and usable non-invasive method for core temperature measurement. However, this chapter indicated that core temperature is a complicated concept and it is still debatable how it should be measured. There is a bunch of measurement methods at numerous body locations, but each of them has its own drawbacks and confounding factors. As illustrated by Table 1.2, especially continuous monitoring of core temperature (changes) in an operational setting remains a challenge. This topic has been elaborated in four studies that are discussed in chapter 2 to 5 of this thesis.

Outline section 1

Section 1, including chapter 2-5 of this thesis, contains four studies to different practically applicable measurement methods for (continuous) core temperature determination during rest and exercise in the heat. Each study explores specific usability issues of one of these measurement methods, which have been equally selected from the classes defined in Table 1.2.

- *Chapter 2* focuses on a new zero heat flux device, which seems promising for clinical and at a later stage possibly field monitoring of core temperature;

- *Chapter 3* explores the potential of IR thermal imaging for monitoring core temperature;

- *Chapter 4* studies the limitations of temperature measurement in the aural canal at different ambient temperature and wind conditions;

- *Chapter 5* determines the relationship of intestinal telemetry pill temperature with esophageal and rectal temperatures during high rates of temperature change.

- The summarizing discussion in *Chapter 9* will provide the main conclusions of these studies and give an overview of the implications and future directions regarding core temperature determination.

1.3 HEAT STRESS & PERFORMANCE

Heat stress comprises any change in the thermal relation between a temperature regulator and its environment which, if uncompensated by temperature regulation, would result in hyperthermia (21). The deviation in body temperature and activation of thermoeffector mechanisms in response to heat stress, is referred to as heat strain (21). Although humans are quite well equipped to sustain heat stress, exercise in combination with a high climatic load and/or wearing protective clothing, elicits significant heat strain, performance impairment and health risks. Especially in occupational and endurance sports settings, this is a regularly occurring phenomenon.

Heat stress factors

Exercise

As about 80% of human's energy expenditure during exercise is converted into heat, the resting heat production (~1.5 W/kg body mass) increases by more than tenfold during heavy exercise. This imposes a considerable stress on the cardiovascular system and heat loss mechanisms of the body. Evaporation, extracting 2428 kJ/L evaporated sweat (3), may be able to compensate for high heat production in ideal conditions. However, heat production may easily exceed heat loss during strenuous exercise in less favourable evaporative conditions. If exercise intensity is maintained, this will result in uncompensable heat stress.

Climate

Climatic conditions are determined by several basic elements of the thermal environment: air temperature, humidity, radiation, air flow, precipitation and air pressure. Particularly the first four elements contribute to the level of heat stress imposed on a subject. High ambient temperatures (Figure 1.4) and relative humidity have for example been shown to increase thermal strain and impair exercise performance (12; 64-67). Wind on the other hand provides effective body cooling in warm conditions, attenuating thermal strain and extending time to fatigue (68; 69). Chapter 7 will provide further evidence on this topic. Conditions with high humidity and low air flow, in which heat loss mechanisms are compromised, are particularly hazardous.

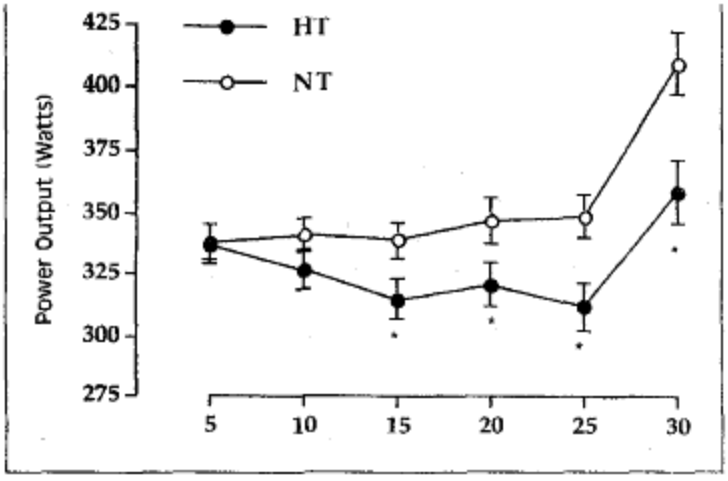

Figure 1.4. *Power output at a 30-min cycling time trial in 32°C (HT) and 23°C (NT) ambient temperature, from (67). * denotes a significant difference.*

Several methods have been tried to synthesize elements of the thermal environment into a single measure for heat stress. The wet bulb globe temperature (WBGT), invented in the 1950s to control heat illness in the US army, is the best-known and most widely used example (70). Safety guidelines for work intensity or continuation of events are often based on WBGT limits. However, WBGT has been criticized being not always representative for heat stress on the human body, especially in conditions of restricted evaporation (70-72). Further, physiological responses and safety limits strongly depend on factors like activity level and clothing.

Protective clothing

Clothing determines the microclimate around the body and thus has impact on all components of heat exchange with the environment. The thermal insulation value of clothing is represented by the clo-unit. The clo-unit depends on factors like water vapor transfer (breathability), liquid absorption and air flow around the body (73). Clothing with high clo-values impairs heat loss mechanisms and thus reinforces metabolic or environmental heat load. In that respect, strenuous activity in protective clothing imposes a particular risk. This is applicable to occupational settings like fire squads (74), sport settings like American football (75; 76) or ice hockey (77; 78) and extreme environments like polar expeditions (79). A warm environment may increase the impact of heat stress, but is not a prerequisite; heat strain has even been reported at

temperatures below 0°C during high intensity exercise in protective garments (79). Chapter 8 will elaborate on this topic by studying heat strain in ice hockey goalies.

Individual factors

The extent of the heat stress induced by exercise, climate and protective clothing is mediated by individual factors like body composition (12), fitness level (10) and acclimatization (11). As these factors are beyond the scope of this thesis, they will not be discussed further here.

Thermal strain

Temperature & fluid balance

A first obvious consequence of exercise-related heat stress is a rise in body heat content, increasing the core and/or skin temperature. The rate of temperature rise depends on exercise intensity, climate, training and acclimatization status, etc. At a certain individually specific threshold, heat loss mechanisms, like an increase in skin blood flow and the onset of sweating, are triggered to restore the heat balance. If heat loss mechanisms cannot sufficiently counterbalance heat production, uncompensable heat stress evolves. Then, maintenance of work load will eventually result in hyperthermic fatigue, exhaustion and/or heat related illness. Nevertheless, trained runners have been shown to attain intestinal temperatures of >40°C at the finish without any health problems (15).

Sweating is the most noticeable response to the increased body temperature, usually providing >80% of body cooling. Average individuals can sweat 1-1.5 L/h, while trained subjects may lose up to 3 L/h of sweat, with a maximum of 10-15 L/day. The actual cooling capacity of the sweat production is determined by the sweating efficiency, the fraction of produced sweat that is actually evaporated. Without sufficient replenishment, sweat loss easily leads to dehydration and electrolyte loss, increasing cardiovascular strain, performance impairment and health risks.

Central nervous system (CNS)

Heat stress and the subsequent hyperthermia affect several processes in the CNS, which may be associated with a decrement in both endurance and cognitive performance. In hot conditions β-waves in the brain are reduced, increasing the α/β brain wave ratio.

Being similar to sleep, this change might reflect a reduced state of arousal in hyperthermic subjects. In addition, hyperthermia has been reported to alter EEG activity. Although the exact meaning of this phenomenon is not entirely clear yet, EEG alteration appeared to be the best predictor of increased RPE during hyperthermia (80; 81).

The rise in brain temperature impairs the voluntary activation of skeletal muscle during fatiguing muscular work (64; 82). There is a progressive impairment in maximal voluntary contraction and central activation of several leg muscles when core temperature is increased and a return to baseline when the core is subsequently cooled (83-85) (Figure 1.5). This impairment seems to go beyond local temperature effects, although the peripheral muscles may contribute by imposing a need for increased central drive to maintain force production.

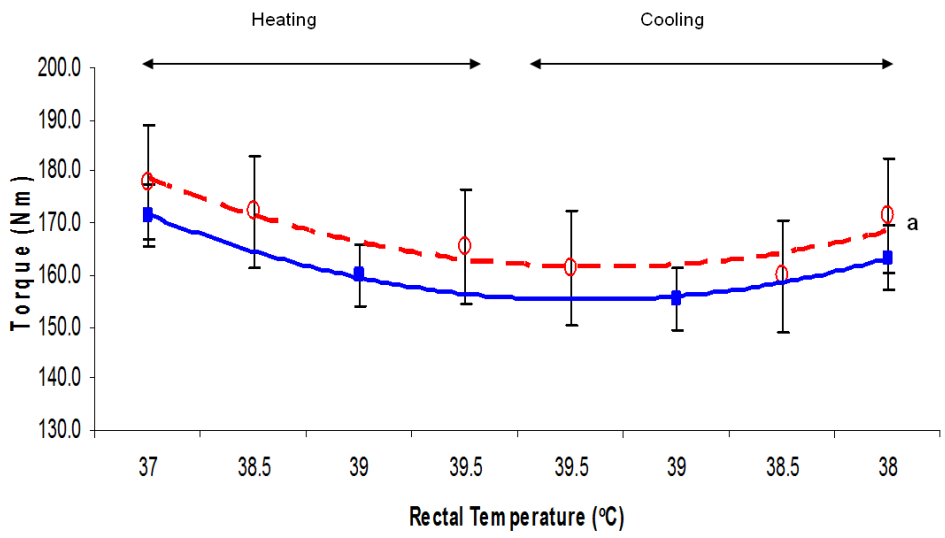

Figure 1.5. *Maximal voluntary contraction of a gradually heated/cooled leg (solid line) and the contralateral leg (dotted line). Both lines show a significant quadratic trend. From (85).*

The decrement in activation is likely to be caused by a reduction in brain impulses, but may also arise at the spinal level where motor neurons may be inhibited by sensory feedback from the contracting muscles. A reduction in brain impulses could be due to the mentioned reduction in β-waves accompanied by impairment in arousal/RPE, but also depletion of substrates and alterations in the level of certain neurotransmitters might play a role. Regarding the latter factor, dopamine and noradrenaline have been shown to affect performance of prolonged exercise, especially in the heat (86), while

serotonin might be linked to central fatigue as well (87). Further, B-endorphins and ammonia accumulation have been proposed to play a role in the fatigue process (87).

Perception

Thermal strain not only impacts physiological, but also perceptual parameters. The rating of thermal sensation indicates the subjective sense of temperature and is mainly determined by skin temperature (88; 89). The rating of thermal comfort indicates how comfortable subjects experience their thermal situation and is thought to be determined by both core and skin temperature (88; 89). Both perceptual measures have a strong link to microclimatic conditions like solar radiation, atmospheric pressure, maximum temperature, wind speed and relative humidity (90). Heat stress at similar levels of activity shifts both ratings upward to the warm and uncomfortable side (91-94). Skin wettedness (95) and mood state (90) may mediate the extend of this shift. Although thermal perception did not show to affect voluntary activation or MVC (83), it does seem to influence thermal behaviour and exercise performance. However, it is still debatable whether thermal perception per se mediates this effect or that an actual physiological change (in body temperatures) is required (91; 94).

Heat stress increases the rating of perceived exertion (RPE) during fixed intensity exercise (68). In addition, recent theories propose that the RPE is the regulated variable during self-paced exercise (96; 97). Tucker et al. (96; 98) developed a perception based model, which proposes that numerous afferent signals are subconsciously integrated into the RPE. Alternatively, Marcora (99; 100) suggested that the RPE is determined by a conscious sensation of thermal (dis)comfort. Either way, the RPE would mediate the regulation of exercise in an anticipatory way by adjusting motor unit activation, in order to prevent detrimental changes to homeostasis. This implies that self-paced work load has to be diminished during heat stress to maintain an acceptable RPE (101).

Cardiovascular strain

Heart rate and energy expenditure

To facilitate heat loss during episodes of heat stress, blood flow to the skin is increased. By enlarging the vascular bed, end diastolic volume and the subsequent stroke volume are reduced. To maintain a constant cardiac output during heat stress, heart rate is raised at any submaximal activity level. When exercising under heat stress, the

competitive blood flow demand of the muscles and the skin substantially increases the cardiovascular stress on the body. Increments in cardiovascular stress, as well as sweat rate, respiration and brain activity induce a higher oxygen uptake. Basal metabolic rate is 5-20% higher in a tropical climate (73) and 23% higher when core temperature is passively raised by 1.5°C (102). During exercise in the heat, when active muscles and skin vessels compete for the limited blood volume, a higher muscle glycogen breakdown and lactic acid production are observed (103). This adds to the increase in energy expenditure and reduction in gross efficiency (104).

Cerebral blood flow and metabolism

Hyperthermic exercise leads to hyperventilation and reduction in arterial CO_2 tension, which triggers cerebral vasoconstriction and decreased cerebral blood flow (CBF) (105). CBF keeps declining as long as core temperature increases, leading to impaired heat removal and significant changes in the cerebral heat balance (87). At severe hyperthermia, global CBF is diminished by 18%. Presyncopal symptoms or collapses in severely hyperthermic subjects could relate to cerebral perfusion limitations (106), especially during competition when athletes may push themselves beyond their limits. Despite the drop in CBF, cerebral metabolism does not decrease. During passive hyperthermia, cerebral oxygenation remains rather stable, possibly by increased cerebral O_2 extraction (107). During heavy hyperthermic exercise, intense neuronal activity even increases cerebral metabolic rate, indicated by a ~7% higher oxygen en glucose uptake (106). Because of reduced CBF and increased metabolic rate, cerebral oxygenation may be lowered and the local energy demand may be utilized to an extent that exceeds the cerebral energy supply and/or ATP resynthesis (87; 108). As a result, glycogen stores will be depleted and cerebral hypoglycemia may show up, deteriorating cerebral function.

The hyperventilation induced decrease in CBF, possibly accelerated by the competition for blood flow between muscle and skin, may cause local ischemia. Further, the increased local energy demand and hypoglycemia that accompany hyperthermia, impair neuronal and astrocytic function and may lower the activation level during the last part of a sustained contraction (87). Therefore, these mechanisms may precipitate hyperthermic fatigue. Glucose supplementation likely enhances performance by increasing or maintaining the supply of substrate to the brain. Glucose supplementation may also benefit by attenuating the exercise induced rise in ammonia (87).

Endotoxemia

Besides a reduction in CBF, cardiovascular strain during hyperthermic exercise also reduces blood pressure/flow to the gastrointestinal tract (109). The low blood flow compromises the integrity of the intestinal walls and endotoxins may ultimately leak into the circulation (110). The resulting endotoxemia triggers a cascade of detrimental responses such as free radical and cytokine release (5; 109). Free radicals impair contractile proteins of the muscle and cytokines impair the CNS, including a rise in setpoint and possibly inducement of central fatigue. In addition, cytokines cause hypotension and cerebral ischemia (109). Therefore, endotoxemia may both reduce the central neuromuscular drive and peripheral muscular activity.

Heat disorders

Heat strain can evolve into a heat disorder whenever the body is continuously unable to sufficiently control the heat and fluid balance. Extreme conditions are not required, as heat casualties have been reported under 20°C ambient temperature. There are several degrees with a different level of severity:

Heat cramps

The least serious heat disorder involves severe cramping of skeletal muscles, especially the most heavily used. It is thought to be caused by the loss of minerals and fluid as a result of profound sweating.

Heat exhaustion

Heat exhaustion arises when the cardiovascular system is unable to meet the demands of both the active muscles and the skin dissipating excess heat. Usually this happens when the blood volume has been reduced by fluid and mineral loss. It results in severe fatigue, dizziness, breathlessness, a pale and cool or hot and dry skin, weak rapid pulse and hypotension.

Heat stroke

Heat stroke is a life-threatening result of overheating, brought on by complete failure of the thermoregulatory system. It is characterized by a core temperature above 40°C, cessation of sweating, warm and dry skin, rapid pulse and respiration, confusion and unconsciousness. If untreated, heat stroke will end up in coma and death.

Structures that are most at risk during severe hyperthermia are the gut and the brain (5). The gut may suffer from endotoxemia and its detrimental consequences, as discussed in the previous paragraph. The brain is at risk for denaturation of proteins. Heat tolerance of the brain is dependent upon duration. Limits in brain temperature of a transient 44°C or 40-60 min in the range of 42-42.5°C have been reported (24).

Hyperthermic fatigue

Limitations in endurance performance

Numerous studies indicate that exercise hyperthermia can be a crucial limitation in human endurance capacity (e.g. 81; 111; 112). During maximal fixed paced exercise this is expressed in a reduced time to exhaustion, while during self-paced performance, work load is reduced to maintain an acceptable level of homeostasis. The exact link between heat stress, physiological strain and hyperthermic fatigue has not entirely been established though.

Originally it was thought that the performance limitation by exercise hyperthermia mainly had to do with the reduction in muscle blood flow (113), but this concept has been released. Further, glycogen content at the point of fatigue in the heat has been reported to be greater than at the point of fatigue in comfortable ambient conditions, indicating that glycogen depletion is not likely to be a cause of fatigue in the heat either (66; 114). Currently, hyperthermic fatigue is thought to be a complex phenomenon caused by several of the other homeostatic disturbances that have been described in the previous paragraphs. As pointed out by Cheung and Sleivert (109), both thermal strain, impairing arousal and voluntary neuromuscular activation, and cardiovascular strain, impairing blood pressure/blood flow to the brain and the splanchnic tissues, are likely contributors to hyperthermic fatigue. However, research separating thermal and cardiovascular effects by passive heating, revealed that cardiovascular strain was not a prerequisite for a reduction in voluntary neuromuscular activation (83). This led to the suggestion that a high core temperature per se is the primary factor inducing hyperthermic fatigue.

Performance regulation

In research on hyperthermic exercise, two concepts have been put forward on how performance is regulated toward voluntary exhaustion:

1. exhaustion occurs upon the approach or attainment of a critical internal temperature before the point of collapse in reached;
2. exercising humans anticipate the intensity of heat stress and seek to regulate their workload accordingly to prevent premature exhaustion.

Regarding the first concept, several studies found a consistent endpoint temperature at voluntary exhaustion, independent of starting core temperature, rate of heat storage, tolerance time, sweating rate, cardiac output, leg blood flow and substrate availability (64; 115; 116). This argues for a safety switch in organisms that elicits voluntary cessation of exercise at a critical internal temperature prior to catastrophic systemic damage from hyperthermia. A benefit of aerobic fitness is the ability to tolerate a higher core temperature at the point of voluntary fatigue. In fit subjects, the capacity for heat storage seems to be higher and the thermal setpoint for exhaustion is shifted upward.

Research supporting the second concept suggested there may be feedforward and feedback voluntary control of effort during heat stress, well before the attainment of physiological impairment of exercise (96; 97). This produces a work rate that permits completion of the task as efficiently as possible with the least risk of developing heat exhaustion. The self-selected pace might be modulated by the initial rate of heat storage (101). This notion was supported by the fact that subjects with a larger body mass appear to select a lower pace in the heat than lighter runners of the same level, in order to attain a similar manageable rate of heat storage (12; 117). Skin temperature and thermal perception at the start seem important as well. In a liquid-perfused suit that was heated or cooled during a time trial, subjects performed better when starting cool and finishing warm than vice versa (118).

It seems that studies applying fixed intensity exercise to exhaustion find evidence for the concept of critical core temperature, whereas studies on self-paced exercise rather point towards the anticipation concept. An interesting integration of these concepts proposes that the organism might use both systems: an anticipatory system to prevent excessive heat build-up and a safety switch to terminate exercise before collapse. In that way, both concepts serve complementary purposes (119).

Attenuation of heat strain

In view of the detrimental effects of heat stress on exercise performance, interventions that delay hyperthermia during heat stressed exercise have gained considerable interest. Nearly all the heat stress factors referred to in paragraph 1.3.1 can be alleviated by taking appropriate action. First, exercise-induced heat strain may be attenuated by adjusting the pacing pattern in order to prevent a high rate of heat storage at a premature stage. Second, environmental heat stress can be relieved by protection from radiation, using sun screens or specifically designed caps and helmets (120). Third, protective clothing should be lightweight, airy, breathable and/or easy to take off during breaks. And fourth, individual improvements in fitness and acclimatization attenuate heat stress.

But in addition to reducing heat stress, one can also diminish its impact by actively cooling the body. A recent review concluded that body cooling leads to a mean improvement in aerobic exercise performance of 4.25%, while the impact on anaerobic performance is more varied (121). Therefore, cooling manipulations before and during prolonged exercise have shown widespread application.

Precooling

Precooling refers to the reduction in body heat content prior to exercise performance in order to increase the heat storage capacity. This extra buffer for metabolic heat production is thought to delay or attenuate the discussed hyperthermia-induced mechanisms leading to performance decrement. In general, research demonstrated that precooling increases time to exhaustion during fixed paced exercise (122; 123). Further, it increases power output (124-126) and pacing stability (124) during self-paced exercise in the heat, providing most benefit for endurance exercise of over 30 min (127; 128). Remarkably, precooling benefits in thermal and cardiovascular strain are often mainly observed at the initial stages of a time trial, while the improved pace only becomes apparent at the final stages (124; 129) (Figure 1.6). In short explosive disciplines, precooling may be less effective as hyperthermic fatigue is not a limiting factor and lowering of the muscular temperature may decrease the contractile properties of the muscle (130).

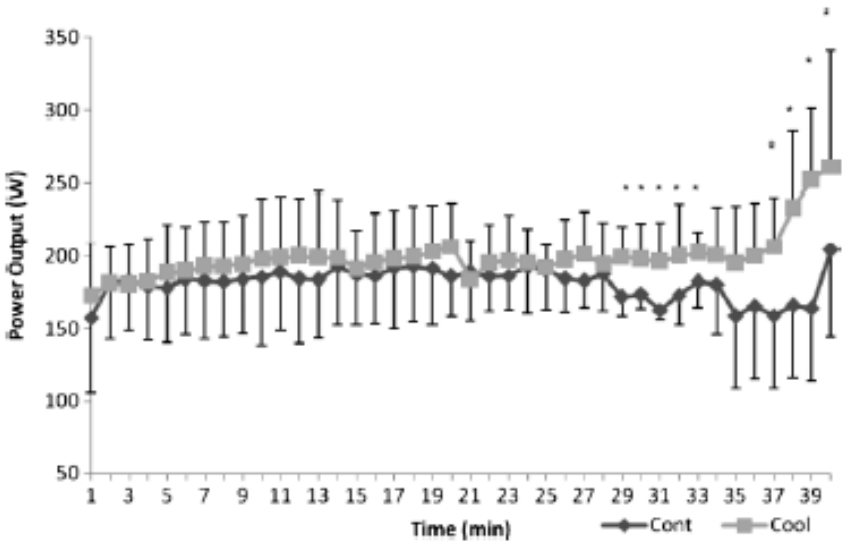

Figure 1.6. *Power output for precooling (Cool) and control (Cont) conditions during a 40-min cycling time trial in 33°C. From (124). * denotes a significant difference.*

Studies are widely varied regarding precooling and exercise methodology, as well as ambient conditions. Precooling methods have been focusing on the skin (ice jackets, ice packs, cool air flow), the core (ingestion of cold water/ice, cool air breathing, intravenous saline) or both the core and the skin (cold water immersion, cold room). Performance effects have been tested at intermittent and continuous protocols from 45 s to 60 min in both moderate and hot conditions. Despite the generally positive research results, especially on prolonged exercise bouts, methodological variation makes it difficult to establish general guidelines for optimal precooling application in practice (121; 127; 131). A recent meta-analytical review attempted to classify different precooling studies, comparing their relative performance effect (128). It confirmed that precooling was more effective in hot than moderate conditions (+6.6% and +1.4% for conditions above and under 26°C, respectively), more effective in endurance exercise (open end +8.6%, time trial +4.2%) than intermittent exercise (+3.3%) and short-term sprints (-0.5%) and more effective in subjects with high than moderate aerobic capacity (+7.7% and +3.8% for VO_{2max} above and under 65 ml/min/kg, respectively). Cold drinks or ice slurry ingestion was reported as the most effective method (+15.0%).

Nevertheless, there is a number of relevant issues for practical application that are sometimes overlooked in lab based experimentation. Substantial cooling (e.g. reduction of core temperature of >0.3°C) has to be achieved within a small time frame. The

method needs to be practical, logistically feasible in the field and sufficiently convenient for the subject. Further, research to an optimal combination with warming-up is warranted, as warm-up and precooling have an opposing effect on body temperature. Chapter 6 tries to contribute to this discussion. A cool core/skin with warm muscles has been suggested as the optimal combination. However, the beneficial effects of warm-up for prolonged exercise remain ambiguous (132); especially in the heat, precooling alone may be more effective. In that respect, it is relevant that precooling body parts with exercising muscles has been found not to result in a different gross efficiency during subsequent exercise than cooling other body parts (133). Finally it is worth noting that precooling may be extra useful for afternoon activity. Not only because ambient temperature tends to be higher at that moment, but also the diurnal core temperature rhythm reaches its peak in the afternoon, reducing the heat storage capacity (130).

Regarding practical application, ice slurry ingestion has been shown to be an effective and practical tool for precooling the core (129; 134). Ice vests and head cooling also seem useful alternatives, as they have been reported to lower the rise in core body temperature during an active and passive warm-up respectively, as well as to improve thermal perception (135; 136). Chapter 6 discusses both ice slurry ingestion and head cooling.

Cooling during heat stress

Cooling during heat stressed performance should logically be even more effective than precooling. Natural air flow by movement or wind and pouring cold water down the body are the most basic forms, applicable to many situations. But cooling modalities like cooling vests, cooling neck collars, hand-held heat exchange devices and head ventilation have also been explored. Although the latter modalities are prohibited in competitive sports and might be considered impractical to apply during work and exercise, these cooling interventions can provide considerable benefits in thermally demanding occupational settings, as well as during sports training or pre-event warm-up sessions.

Cooling during exercise appears to affect thermal perception and performance positively. Torso cooling by a cooling vest improved physiological parameters and performance in heat stressed pilots and additional head cooling had a positive effect on thermal comfort (93; 137). The latter was confirmed during fixed load exercise with face cooling by cold

water spray (92). Fixed load exercise with head ventilation has also been reported to significantly increase time to fatigue, up to 51% (68). Whole body wind application substantially increased evaporative capacity during prolonged fixed-paced cycling in the heat, reducing heat storage (Figure 1.7) and body temperature (69). The increased evaporative heat loss decreases skin temperature and may subsequently decrease core temperature as well (138).

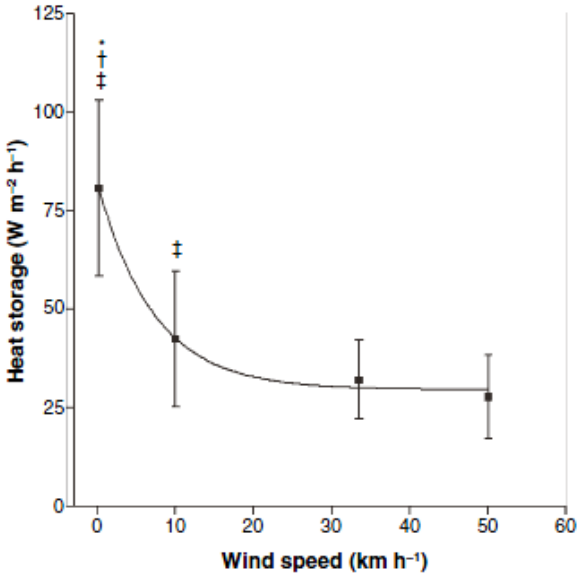

Figure 1.7. *Decrease in heat storage with increasing wind speed during 2 h ergometer cycling in 33°C and 59% RH. From (69).*

Self-paced exercise performance has also been shown to benefit from cooling applications; a heat exchange device applied at the palm of the hand improved cycling time trial performance (139), while neck cooling improved perceived thermal sensation and covered distance in a 15 min running time trial (140). Finally, it was shown that dilating the nostril flares during exercise decreases tympanic temperature (141). This could be explained by the stimulation of respiratory evaporative heat loss, which is in accordance with clinical findings (142; 143). Cooling the head and respiratory tract may be specifically interesting, as it might trigger selective brain cooling, an internal cooling mechanism of the brain. The next paragraph shortly discusses this phenomenon, of which the existence is still uncertain.

Selective brain cooling (SBC)

SBC refers to the lowering of brain temperature below central blood temperature and has been demonstrated in several homeotherms, especially in members of the order of

artiodactyls (144-146) (Figure 1.8). In situations like heat stress and dehydration, these animals make use of a vascular heat exchange system in their head, the carotid rete (24; 147; 148).

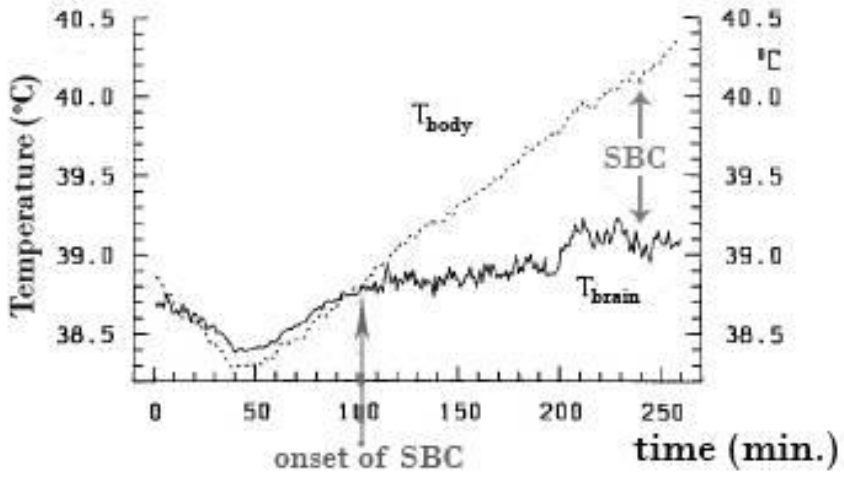

Figure 1.8. *Selective brain cooling as demonstrated in goats. From (146).*

It is a long lasting debate whether hyperthermic humans, for example during exercise, also demonstrate SBC (26-28). Humans do not possess a carotid rete, but might use a mechanism involving superficial cooling of venous blood at the scalp skin surface and the nasal mucosa. This would be transferred to the inner brain by countercurrent heat exchange, convection and conduction (24). The main purpose of SBC in humans would be to prevent heat induced damage of cerebral tissue, but could also be used to delay the onset of fatigue during prolonged exercise. If so, artificial stimulation of SBC would be an interesting tool to prevent detrimental effects of hyperthermia and/or enhance performance. Stimulation of SBC could be accomplished by face fanning, indirectly stimulating brain cooling by enhancing venous blood cooling in the superficial layers of the scalp (31). Another option is scalp cooling, which can be accomplished by packed frozen liquids or cooling helmets, as will be discussed in chapter 6.

Whether or not induced by artificial head cooling, the existence of SBC in humans is controversial. Numerous arguments for and against have been addressed in some interesting point counterpoint discussions (26-28). Research to the existence of SBC and the extent of its effect is complicated by the unclear temperature distribution in the brain and the difficulty to measure it in a reliable and valid way. The majority of the

experimental evidence comes from studies using tympanic measurements as a substitute for brain temperature (88; 149-153), most applying face fanning to trigger SBC. However, previous paragraphs already reported that there are many confounders in tympanic measurement, face fanning being one of them. So the small SBC effects that have been reported based on tympanic temperature are far from reliable. And even if a reliable tympanic measurement is obtained, it is still unclear how representative it is for average brain temperature.

Direct brain measurements during clinical interventions have provided indications that respiratory ventilation or head cooling may induce a slight decrease in subdural brain temperature during hyperthermia (154; 155). However, cooling appeared to be restricted to local and superficial layers of the brain. It is questionable if the term selective brain cooling is appropriate for a local artificially induced phenomenon. Neither brain stem measurements, nor cerebral arterial-venous temperature differences provided evidence that face fanning reduced average brain temperature below esophageal temperature (156; 157). So humans seem to have limited ability to selectively decrease average brain temperature below central blood temperature. Alternative brain temperature measurement methods like MRI could help to find more evidence on this issue.

Concluding remarks

Obviously, heat stress has considerable impact on performance and may impose health risks. However, the effects of specific conditions, the exact mechanisms linking heat stress to performance and the best ways to optimize performance and reduce health risks are still not fully unraveled. Gaining more knowledge on these topics could optimize safety, performance and well-being in occupational and sports settings. Chapter 6 to 8 of this thesis aimed to contribute to this purpose.

Outline section 2

In the second section of this thesis, including Chapter 6-8, three studies on the effects of (manipulation of) thermal stress are discussed. Each study focuses on one of the three main thermal stressors: exercise, climate and protective clothing.

- C*hapter 6* studies the effect of different preparation regimes on pacing during a 15-km cycling time trial in the heat. Preparation regimes involve warm-up, precooling by ice slurry ingestion and/or scalp cooling.

- *Chapter 7* first aims to establish the independent perceptual effect of wind cooling and its impact on performance when compared to windless climates inducing similar thermal strain. Secondly, the responses of temporary wind cooling during a self-paced time trial on thermal strain, thermal perception, pacing and performance are investigated.

- *Chapter 8* reports the amount of heat strain experienced by ice hockey goalies, wearing extensive protective clothing. In addition, heat strain related effects on performance are explored.

- The summarizing discussion in *Chapter 9* will provide an overview of the main conclusions of these studies, the additive value of this knowledge and directions for future research.

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Chapter 2

Non-invasive continuous core temperature measurement by zero heat flux

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ABSTRACT

Purpose

Reliable continuous core temperature measurement is of major importance to monitor patients. The zero heat flux (ZHF) method can potentially fulfil the requirements of non-invasiveness, reliability and short delay time that current measurement methods lack. The purpose of this study was to determine the performance of a new ZHF device on the forehead regarding these issues.

Methods

Seven healthy subjects performed a protocol of 10 min rest, 30 min submaximal exercise (average temperature increase about 1.5°C) and 10 min passive recovery in ambient conditions of 35°C and 50% relative humidity. ZHF temperature (T_{zhf}) was compared to esophageal (T_{es}) and rectal (T_{re}) temperature.

Results

T_{zhf}-T_{es} showed an average bias ± standard deviation of 0.17 ± 0.19°C in rest, -0.05 ± 0.18°C during exercise and -0.01 ± 0.20°C during recovery, the latter two being not significant. The 95% limits of agreement ranged from -0.40 to 0.40°C and T_{zhf} had hardly any delay compared to T_{es}. T_{re} showed a substantial delay and deviation from T_{es} and T_{zhf} when core temperature changed rapidly.

Conclusion

Results indicate that the studied ZHF sensor tracks T_{es} very well in hot and stable ambient conditions and may be a promising alternative for reliable non-invasive continuous core temperature measurement in hospital.

INTRODUCTION

Body core temperature (T_{core}) is one of the most common and important clinical measures. Substantial deviations from the normal T_{core} of around 37°C, especially in the brain and the gut, form a serious threat to a subject's health (1). Further, abnormal T_{core} can indicate illness at an early stage and guide appropriate action. Beside this, controlled T_{core} manipulation is used during surgery or as a therapeutic intervention the last few years. For example, mild therapeutic hypothermia is thought to improve the outcome of cardiac arrest and ischemic insult to the brain (2; 3). Therefore, reliable T_{core} measurement is of major importance to monitor patients.

T_{core} is actually not a single value and depends on the site of measurement (Pušnik and Miklavec, 2009). Two measures are accepted as gold standard for T_{core}: central blood temperature with a Schwan-Ganz catheter in the pulmonary artery and esophageal temperature (T_{es}) (4). As both are not acceptable in an operational setting, there has been a search for alternative non-invasive measures. However, current non-invasive measurement methods all have major disadvantages concerning reliability, delay time, convenience and/or usability (5-9). So there clearly is a need for a continuous measurement method that is reliable and has a small time delay. Further it needs to be safe, convenient and easy to use. The zero heat flux (ZHF) method may be a suitable method to fulfil these requirements. A ZHF sensor insulates the skin locally, ensuring the skin surface to be heated to deep body temperature and creating a region of zero heat flow from the body core to the skin (10). In that way, it allows measuring T_{core} at the skin surface. Typical body locations for ZHF sensors have low skinfold thickness and few large veins (11) like the sternum, forehead and occipital region of the head. Zero heat flux sensors are acceptable for subjects because of their non-invasive nature and quickly respond to temperature changes (4; 10).

In previous research, reliability and measurement location of ZHF sensors varied. Fox et al. (10) developed the first ZHF sensor for the sternum. They measured temperatures that were somewhat lower than rectal and ear canal measurements, but unfortunately exact numbers are not reported. Response time was rapid and differing skin temperatures appeared not to affect the measured value. In working condition and/or a cooler climate results were less satisfactory. Studies of Ball et al. (12) and Tsuji et al. (13)

showed rather large deviations from rectal temperature (T_{re}) with a ZHF device at the sternum (ΔT_{mean}: 0.54 ± 0.3°C) and the forehead (ΔT_{mean}: 0.9 ± 0.4°C) respectively. Togawa (14) got better results with a ZHF at the occipital region (ΔT_{mean}: 0.1 ± 0.2°C). This suggests that the occipital region is a reliable location, though it is not the most practical one. Unfortunately, in all studies T_{re} was used as a reference instead of T_{es}.

In the past few decades little has been published concerning T_{core} estimation by heat flux sensors, apart from the work of Gunga et al. (15; 16) and Kimberger et al. (17). However, they developed a heat flux device in which a heat element that compensates for changing internal and external conditions was omitted. Their 'double sensor' predicted T_{core} mathematically by considering skin temperature (T_{sk}), heat flux through the sensors and heat losses through the exterior surface. A benefit over a zero heat flux sensor is that the lack of requiring *zero* heat flux reduces measurement time. Whether the result is more easily affected by changing internal and external conditions has not been established yet (18). Kimberger (17) reported some good clinical results with perioperative and intensive care patients with quite stable T_{core} (98% of the heat flux measurement was within ±0.5°C of T_{es}). However, in their last report on healthy subjects during bed-rest, Gunga et al. (16) concluded that the sensor was not accurate enough for performing single individual core body temperature measurements under resting conditions at normal ambient room temperature (95% limits of agreement of −0.72 and +0.55°C).

Recently, Zeiner et al. (19) tested a new prototype non-invasive continuous cerebral temperature sensor (NICCT) using the ZHF method on the forehead. They monitored 19 patients undergoing mild therapeutic hypothermia after cardiac arrest. Compared to T_{es}, this resulted in reasonable 95% limits of agreement of -0.59 and +0.36°C. However, the study only investigated comatose patients in a temperature range of 33.5-36°C under clinical conditions. As justly brought up by Opatz (18), the device has not shown its capabilities under different ambient and physiological conditions. Therefore, the purpose of this study was to determine whether this device can also give a reliable estimation of T_{es} when T_{core} is stable, rapidly increasing or rapidly decreasing in the common human core temperature range of 36.5-38.5°C under hot ambient conditions. For that purpose we tested healthy subjects in rest, during exercise and during recovery after exercise in

an ambient temperature of 35°C. We hypothesized that the ZHF device would provide a good estimation of T_{es} with 95% limits of agreement within ±0.5°C.

METHODS

Subjects

Ten healthy and moderately fit subjects (six males and four females) with a mean age of 28.3 ± 5.3 years and a mean weight of 68.4 ± 9.3 kg participated in this study. Subjects were requested to follow their usual diets and lessen physical activities the last day before each trial. Each subject was fully informed of the purposes, protocol, experimental procedures and any associated risks and benefits before giving their written consent to participate. The experiment was approved by the institutional Ethics Committee at TNO.

Protocol

The test procedure consisted of two sessions on separate days, one preparatory session lasting about one hour and one experimental session lasting about three hours. The experimental sessions took place in a warm climatic chamber without any wind at TNO Soesterberg.

At the first meeting subjects completed an informed consent and anamnesis form. Then subjects tried to insert the esophageal probe. This probe had to be introduced via the nose and was then swallowed by drinking water to enter the esophagus. In case of severe gagging reflexes they were excluded from the study, after which ten subjects remained.

For the experimental session, subjects first redressed into sport clothes and inserted a rectal probe. Then a heart rate sensor and skin temperature sensors were attached. After that, the subjects started with a 20-min habituation period within the climatic chamber at 35°C. Ambient temperature during the entire protocol was maintained at 35°C and a relative humidity of 50%. At the start of the habituation period, the T_{zhf} sensors were attached to the forehead, giving them 20 min for stabilization. Then the esophageal probe was inserted and connected to the data acquisition system. After

habituation, the experimental protocol started with a 10-min rest measurement: 5 min in supine position and 5 min in erect position (offered in balanced order) to detect a possible effect of body orientation. Then a 30-min cycling trial was carried out. Subjects started at an intensity of 2 W/kg body mass. The purpose was to increase a subject's T_{core} by about 0.05°C/min, reaching an end temperature of around 38.5°C. T_{core} was monitored every 2 min during the trial. If a subject's T_{core} was increasing distinctly too slow or fast for two consecutive 2-min periods (>0.2°C deviation), intensity was adjusted by 20 W. After the cycling trial, subjects got a recovery of 10 min by sitting on a chair in the climatic chamber before the measurement ended.

Measurement methods and materials

Climatic chamber and cycle ergometer. Experiments were carried out in a custom made climatic room (Weiss Enet, Tiel, The Netherlands). Temperature was set at 35°C with 50% humidity. The 30-min exercise protocol was performed on a Lode Excalibur bicycle ergometer (Lode, Groningen, The Netherlands).

ZHF sensor. This study makes use of the ZHF method, measuring deep tissue temperature. In the human body, there is a natural heat flux from the body core to the skin surface as long as T_{core} is greater than T_{sk}. By locally insulating the skin, blocking all heat from going out, the temperature gradient between core and skin will decrease. T_{sk} directly under the insulated area will rise until it reaches equilibrium with the warmest region under the insulation (T_{core}). At that moment, zero heat flux is established and T_{core} can be measured at the skin. For the equations that base the ZHF method, see Zeiner et al. (19).

The ZHF system contains a prototype non-invasive continuous cerebral temperature sensor (NICCT, Philips, Eindhoven, Netherlands). This sensor consists of a patch (40x50x5 mm) that is placed on the forehead and comprises a layer of thermal insulation and electronics. A specific feature of the patch is its flexibility, which enables the sensor to follow the contours of the skin surface. This prevents the occurrence of air pockets between sensor and skin and optimizes thermal contact. Flexibility is ensured by choosing a flexible material (neoprene) for the thermal insulation. In addition, the electronics are mounted on a kapton® layer which is cut in a specific pattern to allow for deformation.

Two thermistors are placed at the top side of the insulation layer and one on the bottom side, continuously monitoring temperature on both sides of the sensor. The heat flux is defined as proportional to the difference between the average top temperature and bottom temperature. Heating elements are located at the top side of the sensor. The heating element is controlled by a proportional integral (PI) controller which is set to drive the heat flux to zero in order to eliminate heat loss from the skin. As heaters are adjusted in response to the continuously monitored temperatures, the sensor is shielded from external and internal influences.

Before the trials, two temperature probes were attached firmly to the skin just above the eyebrows by means of a dual-sided medical-grade adhesive tape (MP 597 MacTac 9710) and an adjustable headband. The second probe was added for testing an alternative sensor, but data from this probe was not used in the analysis. Wounded or inflamed skin at the measurement location was used as a contraindication. Several safety precautions have been built in, to prevent the patient's skin from overheating in case of technical failure. Further, there is no galvanic contact between the electrical circuitry of the temperature sensor and the skin. The probes were connected via a wired connection to a logging system which displayed and stored all measurements.

Esophageal, rectal and skin temperature sensors. T_{es} and T_{re} were measured using thermistors (Yellow Springs Instruments 400 and 700 series respectively, Yellow Springs, OH, USA). Thermistors were calibrated before data acquisition in a thermal water bath (TLC 15, Tamson Instruments, Bleiswijk, The Netherlands) using a Pt100 digital temperature indicator (P650, Dostmann Electronic, Wertheim-Reicholzheim, Germany) with resistance temperature probe (PD-13/S, Tempcontrol, Voorburg, The Netherlands). This certified combination of calibration instruments had an accuracy of ± 0.03°C. The subjects inserted the esophageal sensor themselves through the nasal passage. The insertion depth beyond the nostrils was determined according to the formula: insertion depth (cm) = (0.479 * sitting height (cm)) – 4.44 (20) assuring that the esophageal sensor was located at the level of the left ventricle. The rectal probe was inserted to a depth of ten centimetres beyond the anal sphincter and fixed with tape. Sensors were attached to a custom-made data acquisition system (VU, Amsterdam), consisting of a data logger with medical power supply and Labview software (National Instrument, Austin TX, USA). Sample frequency was 0.5 Hz.

T_{sk} was determined using iButtons (DS1922L, Maxim Integrated Products Inc, Sunnyvale, CA, USA) at eight locations, as described by ISO 9886 (21). The iButton on the forehead was placed between the headband and the hair line. A weighted average of the eight iButtons resulted in the mean T_{sk}. A sample frequency of 0.1 Hz was used.

Other measures. To get an indication of the intensity at which the subject was performing, heart rate was measured using a Polar Vantage NV sport tester (Polar Electro, Finland) at a 5 s interval. The mass of the subjects was determined on a weighing scale prior to exercise (Sartorius F300S, Göttingen, Germany) for determination of the initial power output at the ergometer.

Data analysis

T_{es} data were processed with a gating routine to remove the negative peaks due to swallowing relatively cool saliva. Then individual averages per 10 s, per 5 min and of the last minute of each trial phase were calculated for all temperature parameters, as well as 10 s group averages. These values have been used for statistical analysis in SPSS statistical software (SPSS 17.0, SPSS Inc, Chicago IL, USA). Concerning T_{sk}, both mean and forehead skin temperature (T_{fh}) were included in the analysis. T_{fh} was of particular interest in comparison to the ZHF sensor which was also located on the forehead. Besides, an elevated T_{fh} is often seen as an indicator of fever.

Differences. ANOVA for repeated measures was performed on each sensor's averaged temperature values of the last minute of a phase, to determine significant temperature changes in response to a phase transition. T-tests for paired comparison were performed on the 5-min averaged values to determine differences between temperature sensors at different intervals. Significance level was set at $p<0.05$. Further, bias may underestimate the real difference when a delta value crosses the x-axis. In that case, positive and negative values average towards zero. To check the relevance of this effect, root mean square (RMS) calculations were made in addition.

Bland-Altman diagram. To quantify the deviation between T_{re}-T_{es} and T_{zhf}-T_{es} a Bland-Altman diagram (22) was constructed for all individual 5-min values. In this diagram, the average value of two compared temperatures is depicted against their difference. It also

indicates the 95% limits of agreement (LoA) for these measurements at two standard deviations of the difference. We considered 95% LoA's of less than ±0.5°C as acceptable, as has been done in previous validation studies (16; 17; 23).

Cross correlation. All measurement methods have a certain time delay compared to T_{es}, i.e. it takes some time before a change in T_{core} will be detected by one of the alternative measures. Especially in changing conditions like exercise, it is important to keep the delay time as small as possible. Therefore cross-correlation on the 10 s group averaged values was used to figure out how much each temperature pattern must be shifted along the x-axis to make it maximally identical to the pattern of T_{es}. In fact, the formula slides the studied graph along the x-axis, calculating the integral of their product for each amount of sliding.

RESULTS

Seven subjects (four males, three female) finished the experimental protocol with a complete dataset and have been included in the statistical analysis. For three subjects, the ZHF data were unreliable due to technical problems.

Cycling intensity

Subjects started their cycling trial at an average intensity of 133 ± 27 W and finished it on average at 146 ± 40 W. One subject started her trial at 1.5 instead of 2.0 W/kg body weight because she had recently gone through a period of inactivity. Subjects cycled at an average heart rate of 152 ± 10 beats per minute (bpm) and reached an average maximum of 174 ± 11 bpm. For individual values see Table 2.1.

Absolute temperature patterns

An overview of the temperature patterns during the complete trial, averaged over seven subjects, is depicted in Figure 2.1. The first 10 min are in rest, followed by a 30-min exercise protocol and 10 min of passive recovery. There were no significant differences (p<0.05) in any parameter between the rest measurement in supine and erect body orientation. Average T_{es} in rest was 36.86 ± 0.13°C and rose during exercise significantly

Table 2.1. *Subject characteristics and intensity parameters. M = male; F = female; P = power output; HR avg = average heart rate; HR max = maximal heart rate.*

Subject	Gender	Age (yr)	Weight (kg)	P start (W)	P end (W)	HR avg (bpm)	HR max (bpm)
1	M	27	74	148	170	157	181
2	F	26	83	166	186	144	172
3	F	38	56	84	90	135	154
4	F	24	66	132	110	152	169
5	M	23	67	134	160	161	185
6	M	33	74	148	188	156	179
7	M	27	58	116	116	162	181

to 38.41 ± 0.41°C, so the manipulation to raise T_{es} about 1.5°C succeeded. T_{re} and T_{zhf} also increased significantly during exercise, but the increase in T_{fh} was not significant (p<0.05). T_{es} and T_{zhf} decreased significantly (p<0.05) during the 10-min recovery phase, but T_{re} and T_{fh} did not. Average T_{sk} during rest was 35.24 ± 0.56°C and increased till an average of 36.31 ± 0.42°C during the last minute of exercise.

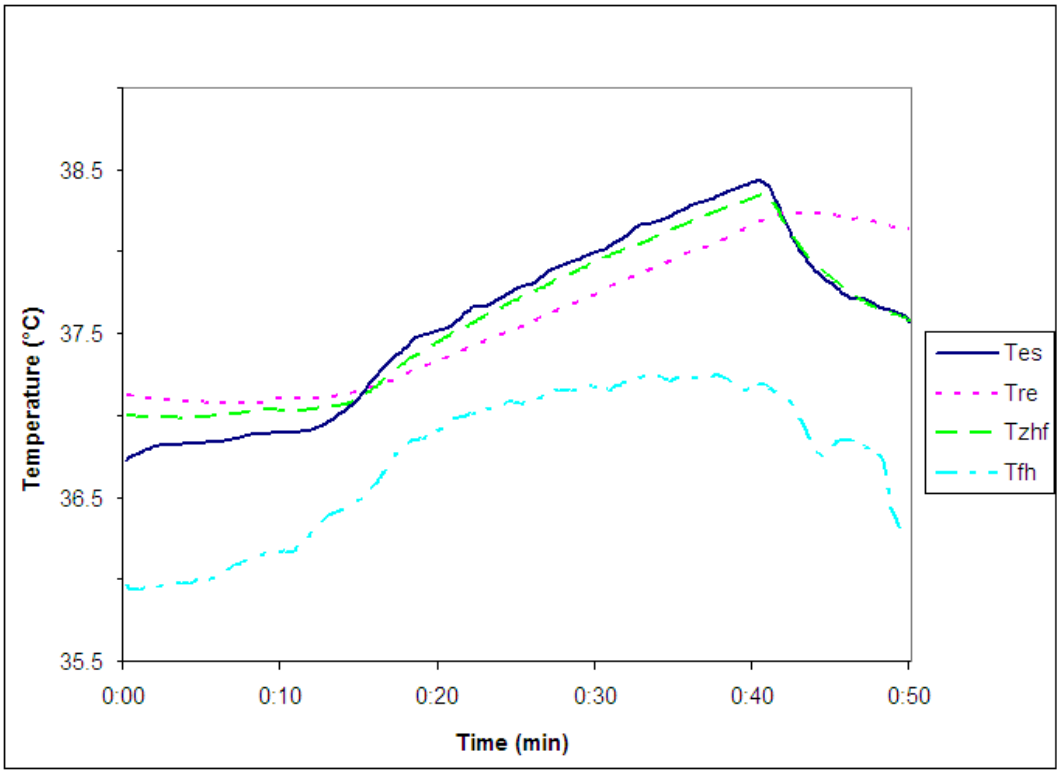

Figure 2.1. *Esophageal temperature (T_{es}), rectal temperature (T_{re}), zero heat flux temperature (T_{zhf}) and forehead skin temperature (T_{fh}) patterns during the complete experimental trial.*

Differences between measurement methods

Figure 2.2 shows the average temperature differences between measurement methods for each 5-min interval. At all intervals, T_{zhf} tracked T_{es} better than T_{re}. Especially during the recovery phase, T_{re} deviated considerably.

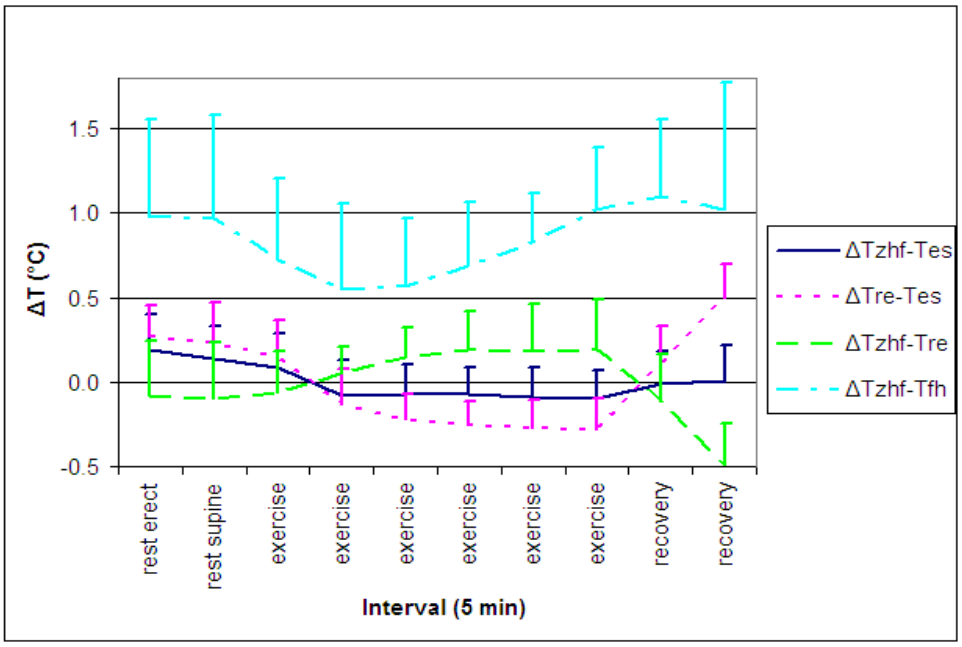

Figure 2.2. *Average temperature differences between different measurement methods - zero heat flux (T_{zhf}), esophageal (T_{es}), rectal (T_{re}) and forehead (T_{fh}) - during each 5-min interval of the experimental trial. For clarity of the graph, only positive error bars have been depicted.*

Table 2.2 gives the average temperature difference ± standard deviation (SD) between different methods for the three main phases: rest, exercise and recovery. T_{es} and T_{re} are in all phases significantly different, while T_{es} and T_{zhf} only differ during the rest phase (p<0.05). During the whole trial there is a large difference and a large variation between T_{zhf} and T_{fh}, while measuring temperature at the same location. The RMS values gave a similar impression and have therefore been omitted.

Table 2.2. *Average temperature differences (ΔT_{avg}) ± standard deviation, comparing different methods during rest, exercise and recovery.*

	ΔT_{avg} rest (°C)	ΔT_{avg} exercise (°C)	ΔT_{avg} recovery (°C)
T_{zhf}-T_{es}	0.17 ± 0.19*	-0.05 ± 0.18	-0.01 ± 0.20
T_{re}-T_{es}	0.25 ± 0.20*	-0.17 ± 0.23*	0.30 ± 0.29*
T_{zhf}-T_{re}	-0.09 ± 0.31	0.12 ± 0.24*	-0.31 ± 0.32*
T_{zhf}-T_{fh}	0.97 ± 0.58*	0.73 ± 0.42*	1.06 ± 0.60*

**significant difference (p<0.05)*

In Figure 2.3, Bland-Altman diagrams for T_{zhf}-T_{es} and, for comparison, T_{re}-T_{es} are depicted. The graphs show a mean difference of 0.00 ± 0.20°C and 0.01 ± 0.32°C respectively for all individual 5-min average values of the experimental trials. The 95% limits of agreement thus ranged from -0.40 to 0.40 for T_{zhf}-T_{es} and from -0.62 to 0.64 for T_{re}-T_{es}.

Delay time

Cross correlation analysis revealed a substantial delay of T_{re} compared to T_{es}. A maximal R value (0.914) was reached for a delay of 3.30-4.10 min. T_{zhf} did not show any delay compared to T_{es} (R=0.992).

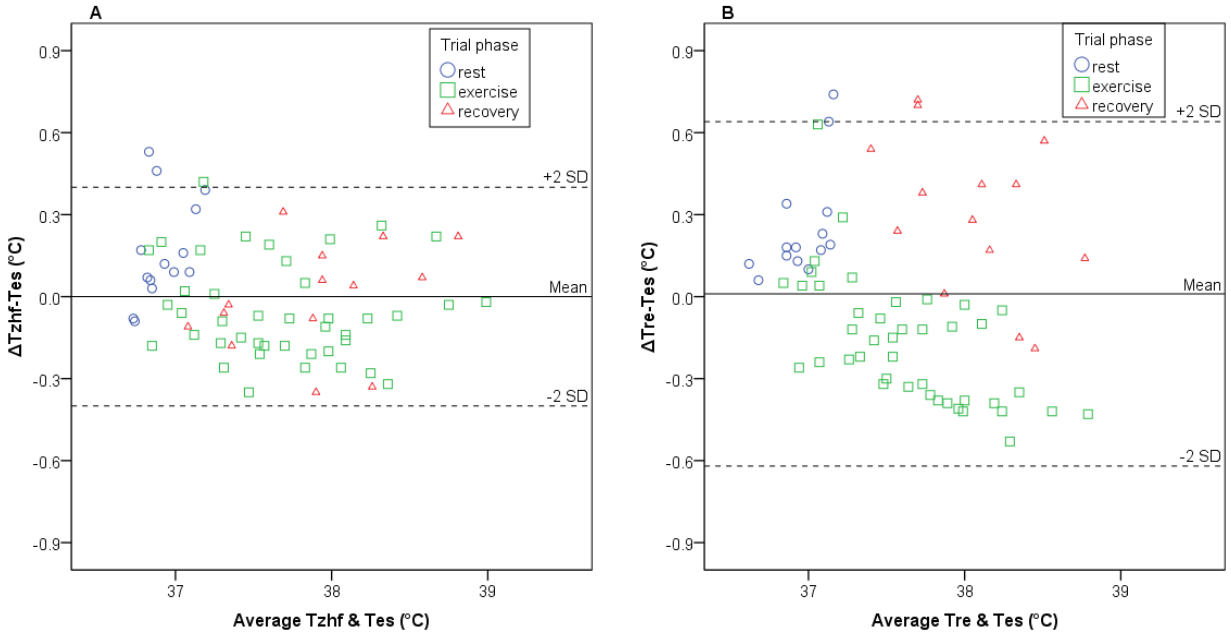

Figure 2.3. *Bland-Altman diagrams showing the differences of A) the zero heat flux and esophageal temperatures (ΔT_{zhf}-T_{es}) and B) the rectal and esophageal temperatures (ΔT_{re}-T_{es}). Both figures consist of all individual 5-min values for the rest phase (circles), the exercise phase (squares) and the recovery phase (triangles).*

DISCUSSION

The ZHF sensor used in this study gave a reliable estimation of T_{es} during both stable and changing body core temperature in a hot windless environment. The 95% limits of agreement of ±0.40°C are well within our acceptable level of agreement of ±0.5°C and the sensor showed no delay time at all compared to T_{es}. This indicates that the studied ZHF sensor has potential for reliable non-invasive continuous T_{core} measurement.

As the rectum is one of the most often used methods for T_{core} determination, as well in hospital, as in laboratories and at home, it is interesting to compare the results of T_{re} and T_{zhf}. At rest, T_{zhf} and T_{re} performed quite similar. In line with previous studies, T_{re} in rest was slightly higher than T_{es} (24; 25) and so did T_{zhf}. During exercise and recovery T_{zhf} tracked T_{es} in all intervals better and faster than T_{re}. The rectum is often used for T_{core} measurement because it consists of a large mass of deep body tissue and is not affected by environmental conditions (7; 26; 27). It can be a useful measure, as it reflects the local temperature in the vulnerable abdominal cavity (28). However, as blood flow to the rectum is low and the mass of organs in the body cavity is large, it requires a great amount of energy to change temperature (7; 26; 28-30). As a result, T_{re} is unreliable for monitoring quickly changing central blood temperature, reflected by T_{es}. This became most obvious in the recovery phase when individual differences between T_{re} and T_{es} rose up to 0.9°C. The time delay of about 4 min, calculated by cross correlation, was actually an underestimation of the real time delay in the recovery phase, as T_{re} had hardly started its decrease when measurements stopped. At that moment the gap between T_{es}/T_{zhf} and T_{re} was still widening as can be seen in Figure 2.1. This seems to support the suggestion that the time lag of T_{re} may rise up to 20 min, depending on environment, physical situation etc. (5). Especially in emergency situations where T_{core} may be fluctuating fast, this can have serious consequences. Proulx (30) already showed that it can lead to serious hypothermia during cooling procedures after heat stress. In this respect, T_{zhf} seems to be a promising alternative. In contrary to the statement of Yamakage and Namiki (8), T_{zhf} was still reliable at rates of change above 0.3°C/min.

Figure 2.3 shows that the deviation of T_{zhf} does not depend on trial phase, while the deviations of T_{re} are clearly grouped per trial phase, mostly as a result of the discussed delay. Nevertheless, in rest there was a significant difference between T_{zhf} and T_{es}, which was absent during exercise and recovery. This was largely due to two subjects with substantial average deviations in rest (±0.4°C). Individual analysis could not reveal a technical cause for this deviation, as temperatures seemed stabilized and the other phases looked normal.

Concerning limits of agreement, the current ZHF sensor seems to perform better than previous (zero) heat flux systems (12-16; 31). Previous studies are hard to compare though, as most studies measured under different ambient conditions and at different

locations. Most comparable was the set-up of Gunga et al. (15), as they estimated T_{core} with a heat flux device on the forehead during rest and exercise in 10, 25 en 40°C. However, this was not a *zero* heat flux device and T_{re} was used as reference. Our experiment shows that T_{re} has an inconsistent deviation from T_{es} when T_{core} is not stable. This may have caused the larger limits of agreement in their study, also in the warm and thus more comparable ambient temperature conditions (-0.08 ± 0.35 and -0.01 ± 0.37°C for work and rest in 25°C; -0.11 ± 0.34 and 0.10 ± 0.42°C for work and rest in 40°C (15)). The role of measurement technique remains unknown; the exact performance difference between heat flux and zero heat flux should be investigated further under different conditions with equal reference temperatures.

A possible pitfall in the analysis of temperature differences is underestimation of ΔT when averaging positive and negative differences. Therefore also RMS values were calculated on the temperature differences (10 s averages). Although this resulted in slightly higher deviations, differences of T_{zhf} and T_{es} were still within the set (acceptable) limits. In addition, as the upper limit of the 95% confidence interval of the RMS (0.41°C) for T_{zhf}-T_{es} was very similar to that of ΔT (0.40°C), the limits of agreement depicted in Figure 2.3 can be considered as a reliable reflection of the expected deviation.

Although there is a good match with T_{es}, the question remains which temperature the ZHF device actually measures. From comparison of T_{zhf} and T_{fh}, it is clear that T_{zhf} is not simply a reflection of T_{fh}, which even in a hot environment appeared to be a poor estimator of T_{es}. But viewing the size of the probe and the thermoregulatory mechanisms within the head, it is not likely either that the ZHF probe can penetrate to the deep cerebral structures. Yamakage and Namiki (8) assume reliable measurements to no more than 9 mm, but deduced this from a model using the thermal conductivity of unperfused tissue. Brajkovic and Ducharme (11) used ZHF to estimate muscle temperature and showed that the ZHF probe tracked the muscle temperature to a depth of up to 2 cm below the skin surface. As the probe surface was of similar size, one could assume a similar measurement depth, which would imply that it measures temperature just within the skull. A more precise estimation of measurement depth would be interesting though.

It must be acknowledged that current measurements took place under nearly ideal hot and stable ambient conditions. It is plausible that performance of the ZHF device of the

current size and configuration would deteriorate in more unfavourable conditions. The results of Zeiner et al. (19), who established limits of agreement of -0.59 and +0.36°C with the same ZHF device at a climate controlled intensive care unit (around 23°C, 40% humidity), suggest that the device still performs at an acceptable level near room temperature. However, it remains to be seen whether this also holds good for cooler conditions. Then the temperature gradient between core and skin becomes bigger and insulation of the skin more difficult. Also, the relatively cold shell becomes larger, requiring deeper measurement. Possibly a larger and more powerful ZHF sensor would be necessary. Further, windy conditions form a potential disturbance for the ZHF measurement. Unpublished results of the authors indicate that substantial wind (4 m/s) perpendicular to the sensor seems to double the standard deviation of ΔT_{zhf}-T_{es}.

Nevertheless, the studied ZHF sensor seems to have potential for practical applications, especially for clinical continuous T_{core} monitoring in stable ambient conditions. Currently, several non-invasive measurement methods like rectal, tympanic and oral are used in clinic. The latter two are known to be unreliable as they can easily be affected by external factors (24; 32-34). T_{re} has been shown to deviate from T_{es} during T_{core} changes (7; 30) and is regularly considered as uncomfortable. Besides, all of these methods are not suited for continuous measurement. For application during exercise, the ZHF method has in this study shown its merits under hot windless conditions in a lab. However, for operational application, there are several issues that need to be solved. A mobile ZHF system needs to be compact and wireless, while still providing sufficient energy supply. Further, performance in cold and windy conditions has to be optimized. And finally, for all applications a shortening of the 20 min stabilization period would be a big improvement. Comparison to a simple (non-zero) heat flux device would be useful in that respect.

Concluding, the studied ZHF device tracked T_{es} well with little or no time delay during stable, increasing and decreasing T_{core} in ambient conditions of 35°C without wind, estimating T_{es} better than the traditional rectal measurement. Therefore, the ZHF method may have potential for practical application, at least under warm and stable ambient conditions.

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Chapter 3

Infrared thermal imaging of the inner canthus of the eye as an estimator of body core temperature

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ABSTRACT

Purpose and methods

Several studies suggest that the temperature of the inner canthus of the eye (T_{ca}), determined with infrared thermal imaging, is an appropriate method for core temperature estimation in mass screening of fever. However, these studies used the error prone tympanic temperature as a reference. Therefore, we compared T_{ca} to esophageal temperature (T_{es}) as gold standard in ten subjects during four conditions: rest, exercise, recovery and passive heating.

Results and conclusion

T_{ca} and T_{es} differed significantly during all conditions (mean ΔT_{es}-T_{ca} 1.80 ± 0.89°C) and their relationship was inconsistent between conditions. Also within the rest condition alone, intersubject variability was too large for a reliable estimation of core temperature. This poses doubts on the use of T_{ca} as a technique for core temperature estimation, although generalization of these results to fever detection should be verified experimentally using febrile patients.

INTRODUCTION

The outbreaks of pandemic infections such as SARS in 2002/2003 have called for a method that allows mass screening for fever detection. Infrared thermal imaging is mentioned as an appropriate technique for mass screening of fever (1). The temperature of the inner canthus of the eye (T_{ca}) seems the most suited spot (2) although others argue that the average temperature of the face may be valuable as well, albeit in combination with other physiological parameters (3). A recent review observed a wide range in fever detection sensitivity from 4 to 90%, while specificity ranged from 75 to almost 100% (4). All studies in the review used (infrared) tympanic measurements as a reference. However, it is well documented that these measurements may deviate considerably from the core temperature as assessed using more reliable methods such as esophageal temperature (5). Therefore, this study aimed at determining the value of infrared measurements of the inner canthus of the eye (T_{ca}) compared to esophageal measurements (T_{es}). In order to obtain reproducible conditions, exercise and heat exposure were used to modify the body core temperature instead of fever.

METHODS

Subjects

Ten healthy and fit subjects (six males and four females) with a mean age of 25.8 ± 3.9 years and a mean weight of 72.3 ± 4.6kg participated in this study. Subjects were requested to follow their usual diets and lessen physical activities the last day before each trial. Each subject was fully informed of the purposes, protocol, experimental procedures and any associated risks and benefits before giving their written consent to participate. The experiment was approved by the Ethics Committee at TNO.

Protocol

The test procedure consisted of three sessions on separate days with at least one day in between: one preparatory session, one experimental session in which the subject was actively heated by exercise and one experimental session in which the subject was passively heated by a water perfused suit. The experimental sessions were offered in balanced order.

In the preparatory session subjects completed an informed consent and anamnesis form. Subjects not familiar with the esophageal probe tested their tolerance by inserting this probe. In case of severe gagging reflexes they were excluded from the study.

At the active heating session, subjects first redressed into sport clothes and inserted the rectal and esophageal probe. The heart rate sensor and skin temperature sensors were attached. After about five minutes, when the esophageal probe had stabilized, the measurement started with twenty minutes rest in the climatic chamber (30°C). This was followed by a ten minute submaximal exercise test that started at an intensity of 130W which was, if necessary, increased till subjects reached a heart rate of about 150 beats per minute. Then subjects got two minutes rest, before they performed a maximal exercise trial of eight minutes. They were instructed to cover as much distance as possible during these eight minutes. Hereafter, they got ten minutes of recovery (pedalling quietly at low intensity) before the experimental session stopped.

The passive heating session started with a rest measurement of ten minutes in the climatic chamber (30°C). Then the subject put on the water perfused suit which was set at a temperature of 45°C. The subjects sat down for forty minutes while their core temperature was increased passively. The complete experimental protocol is summarized in Table 3.1.

Table 3.1. *Experimental protocol of active heating session and the passive heating session. Sessions were offered in balanced order.*

	Time (min)	Activity	Intensity
Active heating session	0-20	Rest	
	20-30	Submaximal exercise	HR ~150 bpm
	30-32	Break	
	32-40	Maximal exercise	8 min self-paced
	40-50	Recovery	
Passive heating session	0-10	Rest	
	10-20	Putting on tubed garment suit	
	20-60	Passive heating (sitting)	T set at 45°C

Materials

Experiments were carried out in a custom made climatic room (Weiss Enet, Tiel, The Netherlands). Temperature was set at 30°C with 50% relative humidity. The 30-min exercise protocol was performed on a Lode Excalibur bicycle ergometer (Lode, Groningen, The Netherlands). To get an indication of the intensity at which the subject was performing, heart rate was measured using a Polar Vantage NV sport tester (Polar Electro, Finland) at a 5 s interval.

T_{ca} of the eye was measured using a FLIR ThermaCAM SC2000 PAL infrared camera (Flir, Breda, The Netherlands). The camera was positioned at about 1.5 m from the face. IR measurements were made at different time intervals during the active and/or passive heating sessions (Table 3.2).

Table 3.2. *Overview of infrared (IR) images made during the rest, exercise and recovery phase of the active heating sessions and during the passive heating sessions.*

Subject	Rest	Exercise	Recovery	Passive heating
1				X
2	X	X		
3	X		X	
4	X		X	X
5	X	X		
6		X		
7	X		X	X
8	X		X	
9			X	X
10		X	X	

T_{es} was measured using a thermistor (Yellow Springs Instruments 700 series, Yellow Springs, OH, USA). This thermistor was calibrated before data acquisition in a thermal water bath (Tamson TLC-15, Tamson instruments, Bleiswijk, The Netherlands) using a certified Pt100 calibration thermometer (P650, Dostmann electronic, Wertheim-Reicholzheim, Germany) with resistance temperature sensor (PD-13/S, Tempcontrol, Voorburg, The Netherlands). The subjects inserted the esophageal sensor themselves through the nasal passage. The insertion depth beyond the nostrils was determined according to the formula of Mekjavic et al. (6) based on sitting height. The T_{es} sensor was attached to a custom-made data acquisition system (VU, Amsterdam), consisting of a

data logger with medical power supply and Labview software (National Instrument, Austin TX, USA). Sample frequency was 1Hz.

Mean skin temperature (T_{sk}) of the body was determined by averaging the results of four iButtons (DS1922L, Maxim Integrated Products Inc, Sunnyvale, CA, USA) as described by ISO 9886 (7). See for an evaluation regarding the use of iButtons Van Marken Lichtenbelt et al. (8). A sample frequency of 0.1Hz was used.

Data analysis

Maximal T_{ca} on each image was determined with ThermaCAM Explorer software (Flir, Breda, The Netherlands). T_{es} data were gated to remove the negative peaks due to swallowing. Then T_{ca} measurements were matched with the T_{es} and T_{sk} measurements at the exact moment of the IR image. Averages per phase of the experimental sessions were calculated for T_{es}, T_{ca} and T_{sk}, as well as differences and standard deviations (SD) for each T_{es}-T_{ca} data pair.

A Bland-Altman diagram (9) was constructed for all data pairs to visualize the deviation between T_{es} and T_{ca}. In this diagram, the average value of two compared temperatures is depicted against their difference. It also indicates the 95% limits of agreement (LoA) for these measurements at two standard deviations of the difference.

RESULTS

Table 3.3 gives the measured values of T_{es}, T_{ca} and T_{sk} averaged over the different phases of the experimental sessions.

Table 3.3. *Values (± SD) of esophageal temperature (T_{es}), infrared canthus temperature (T_{ca}) and skin temperature (T_{sk}) averaged per phase of the different experimental sessions.*

Phase	N	T_{es}	T_{ca}	T_{sk}
rest	6	36.87 ± 0.29	35.60 ± 1.04	32.61 ± 1.01
exercise	4	38.35 ± 0.90	35.53 ± 0.43	33.67 ± 1.12
recovery	6	37.87 ± 0.33	35.87 ± 0.74	34.14 ± 0.82
passive	4	37.03 ± 0.30	35.75 ± 0.44	36.61 ± 0.42

The differences between T_{es} and T_{ca} at different trial conditions are shown in Figure 3.1. The differences were significant for all periods (p<0.05). The Bland-Altman plot (Figure 3.2) for all collected data points shows a mean difference of 1.80°C and a standard deviation of 0.89°C, resulting in 95% limits of agreement of 0.03 to 3.57°C.

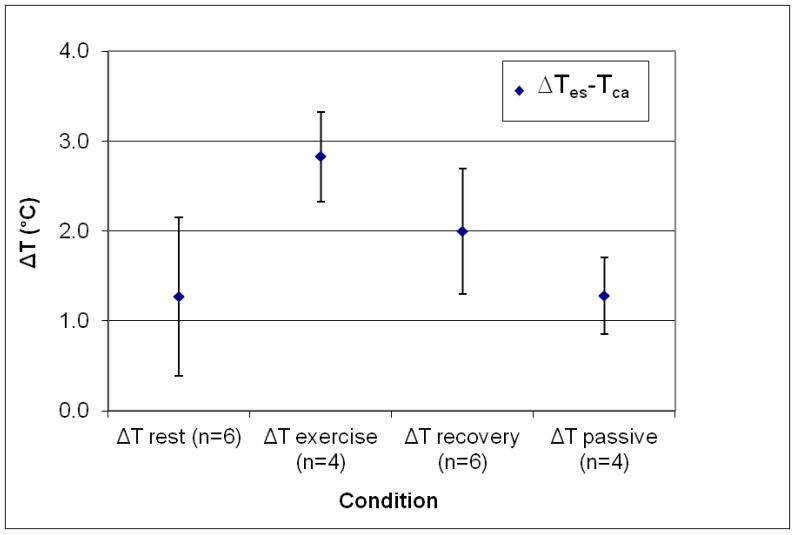

Figure 3.1. *Difference (± SD) between infrared temperature of the inner canthus of the eye (T_{ca}) and esophageal temperature (T_{es}) during rest, exercise and recovery of the active heating session and during the passive heating session in 30°C ambient temperature.*

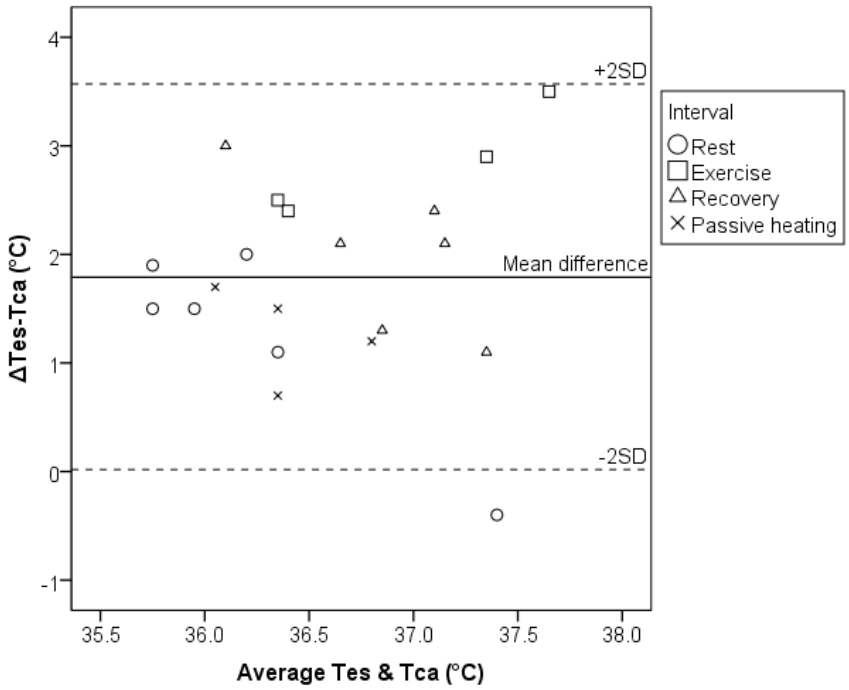

Figure 3.2. *Bland-Altman diagram for esophageal (T_{es}) and infrared temperature of the inner canthus of the eye (T_{ca}), showing the difference between T_{es} and T_{ca} (ΔT_{es}-ΔT_{ca}) as a function of the average of both temperatures. Symbols indicate during which intervals a measurement was made: circles for rest, squares for exercise, triangles for recovery and crosses for passive heating.*

In Figure 3.3, the same data points are depicted as a function of T_{es} only. The solid line is the linear fit which describes the relationship between T_{es} and the difference between T_{es} and T_{ca} (ΔT_{es}-T_{ca}). The dotted line shows the best fitting regression line with a fixed slope of 1.0. This line reflects the situation in which the change in T_{es} would be fully responsible for the change in ΔT_{es}-T_{ca}.

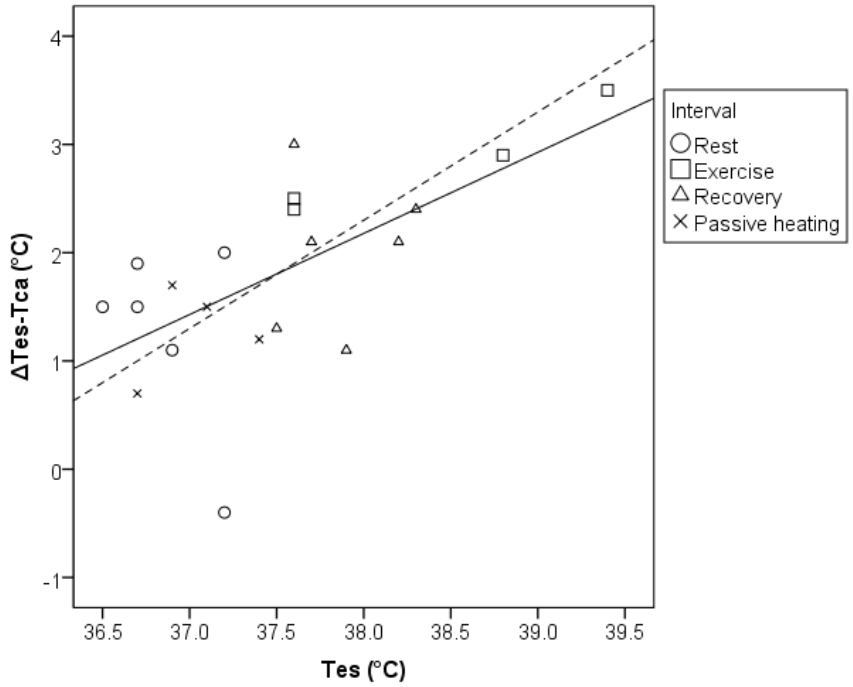

Figure 3.3. *Scatter plot for the difference between esophageal and infrared temperature of the inner canthus of the eye (ΔT_{es}-ΔT_{ca}) as a function of esophageal temperature (T_{es}). Symbols indicate during which intervals a measurement was made: circles for rest, squares for exercise, triangles for recovery and crosses for passive heating. The solid line shows the linear trend for all data points, the dotted line is the best fitting line of identity (slope=1.0) which would indicate that the increase in ΔT_{es}-T_{ca} is entirely due to the increase in T_{es}.*

DISCUSSION

The study shows that the radiant temperature of the inner canthus of the eye (T_{ca}) has a poor and inconsistent relation with esophageal temperature (T_{es}) during rest, exercise and recovery. In rest, T_{ca} was about 1.3°C lower than T_{es} (Figure 3.1). During exercise, the average difference between T_{ca} and T_{es} increased to 2.8°C. The increase in core temperature during exercise, as reflected by the rise in T_{es}, was largely invisible in T_{ca}. So ΔT_{es}-ΔT_{ca} increased almost proportionally to T_{es} (Figure 3.3), while a consistent

relationship between T_{es} and T_{ca} would have been reflected by a horizontal line. Therefore, it can be concluded that T_{ca} is not suited for estimating body core temperatures during exercise. Looking at the measurements in rest separately, adding a constant to T_{ca} does not yield a reliable estimator of body core temperature either, because of the large intersubject variation. The passive heating trials indicated that this variation was decreased when subjects wore a water perfused suit, which possibly created a more homogeneous temperature distribution among subjects. However, the standard deviation of 0.46°C does still not allow for reliable core temperature estimation. Unfortunately the passive heating protocol was not forceful enough to result in hyperthermic core temperatures, so a comparison with fever is not feasible.

Although exercise and fever both result in increased body core temperatures, one could argue that the measurements made during and after exercise are not representative for fever because of differing thermoregulatory mechanisms. In fever, the core temperature setpoint is increased due to pyrogens that enter the blood stream and trigger the hypothalamic neurons [10]. Therefore, thermoregulatory responses are directed at the attainment and maintenance of an elevated core temperature. In human exercise, it is generally believed that the increased body temperature results from a delayed onset of heat loss mechanisms and that the setpoint does not increase. After exercise, heat loss exceeds heat production and this induces a core temperature drop back towards the fixed setpoint (10; 11). The following considerations regarding this discrepancy between fever and exercise hyperthermia are relevant for the current experiment.

T_{ca} depends on the skin temperature (T_{sk}) of the inner canthus. If exercise and fever have a comparable effect on T_{sk} of the inner canthus, our results on exercise hyperthermia could presumably be generalized to fever hyperthermia. However, to our knowledge, inner canthus T_{sk} has not yet been determined during exercise and fever in the same subject. Mean T_{sk} data suggest that T_{sk} during fever may be higher than during exercise (12). Lenhardt et al. (12) induced fever (38.0-38.5°C) in eleven subjects during a control condition (supine position, only covered by a cotton blanket) and a self-adjust condition (subjects could control their warming themselves). In these conditions, skin temperatures started at a level comparable to the current study (32.5-33.0°C), but reached about 1 (control) to 2.5°C (self-adjust) higher peak values than during exercise/recovery of the current study. Considering these data, generalization from

exercise to fever seems unwarranted. Nevertheless, if T_{ca} really is a reliable, broadly applicable measurement method, it should reflect esophageal temperature for every thermal state of the body, regardless of the way this status is achieved (rest, exercise, passive heating or fever). This is not the case and therefore it poses serious doubts on T_{ca} as an estimator of body core temperature.

Further, as Cabanac (13) pointed out, there may not be a fixed setpoint in human thermoregulation. He argues that the setpoint is continuously adjusted, for instance for body fluid control. This makes fever and exercise hyperthermia more comparable in thermoregulatory aspects. In both cases an increase in body core temperature and skin temperature is observed. In addition, Kenny et al. (14) showed that whole body heat loss is rapidly reduced after exercise, despite the fact that body heat content, muscle temperatures and esophageal temperatures are still elevated (47% of the heat stored during exercise was not dissipated after one hour recovery, while heat loss mechanisms were back at baseline). Therefore, it is possible that a setpoint increase occurred during and after exercise, albeit of minor amplitude. In conclusion, T_{ca} is not a good estimator of core temperature during exercise and recovery hyperthermia. Possibly, this conclusion extends to fever as well, but experimental verification using febrile patients is necessary.

In many studies concerning fever screening with infrared imagery, (infrared) tympanic temperature has been used as a reference to establish the validity of the method. However, the use of (infrared) tympanic temperature as a reference during fever is not acceptable, since tympanic temperature is error prone and dependent on variables as ambient temperature and ear canal morphology (5). For properly establishing validity, it is therefore recommended that future studies use a reliable method, such as esophageal or intravenous temperature measurements.

Unfortunately, it was not feasible to measure T_{ca} for each subject for each thermal condition. However, in mass screening, also many different people in different physical states pass the system. Therefore, a consistent bias for different physical states with a small intersubject variation is a prerequisite. This study suggests that infrared imagery may not fulfil this prerequisite. Future studies should provide more insight into this issue, varying external and internal conditions for larger groups of subjects and structurally using reliable core temperature references.

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Chapter 4

Limitations of temperature measurement in the aural canal with an ear mould integrated sensor

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ABSTRACT

Purpose

Aural canal temperature measurement using an ear mould integrated sensor (T_{ac}) might be a suited method for continuous non-invasive core temperature estimation in operational settings. We studied the effect of ambient temperature, wind and high intensity exercise on T_{ac} and its ability to predict esophageal (T_{es}) and rectal temperatures (T_{re}).

Methods

Seven subjects performed a protocol of rest in 21, 10 and 30°C, followed by exercise and recovery in 30°C. Subjects performed the protocol twice: with and without face-wind from halfway the 30°C rest period. Extra auricle insulation was applied at one side.

Results

Ambient temperature changes affected T_{ac} significantly, while T_{es} and T_{re} remained stable. Insulating the auricle reduced but not abolished this effect. Wind had an immediate cooling effect on T_{ac} independent of auricle insulation. During exercise and recovery in 30°C, T_{ac} provided acceptable group predictions of T_{re} in trials without wind (bias -0.66 ± 0.21°C covered, -1.20 ± 0.15°C uncovered). Bias was considerably higher with wind, but variability was similar (-1.73 ± 0.11°C covered, -2.49 ± 0.04°C uncovered). Individual predictions of T_{es} and T_{re} showed more variation, especially with wind.

Conclusion

We conclude that T_{ac} may be used for core temperature assessment of groups in warm and stable conditions.

INTRODUCTION

Both in clinical and in operational settings, there is a need for continuous non-invasive temperature monitoring to quantify hyper- and hypothermia. The tympanic membrane is potentially a good location to accomplish this. It is located close to the hypothalamus, the main human thermoregulatory node, but still easily accessible. Further, it is well perfused with blood vessels circulating to and from the brain (1; 2), suggesting the tympanum might reflect core temperature. However, there are two major problems with tympanic temperature (T_{ty}) measurement. First, T_{ty} may be affected locally by ambient conditions like temperature, wind and local cooling/heating of the head (2; 3). Second, it is difficult to measure tympanic temperature properly, especially concerning continuous measurement in an operational setting.

T_{ty} has been compared regularly to esophageal temperature (T_{es}), which is often considered as gold standard for temperature measurement. In studies, measuring T_{ty} by direct contact, a reasonable agreement with T_{es} has been found during rest in stable conditions (4-7). However, significant deviations have been reported during passive heating, active heating and/or facial cooling (4; 6; 8-11), although Sato et al. (12) reported similar values for T_{ty} and T_{es} after slight rotation of the probe. It remains uncertain to which extent ambient conditions confounded these measurements. The deviation may also reflect a real difference between brain and trunk temperature. It is reported that in some mammals during heat stress, brain temperature levels off while trunk temperature continues to rise, a phenomenon often referred to as selective brain cooling (13-15). Further, the deviation might be caused by wrong thermocouple positioning. T_{ty} should be measured at the lower anterior quarter of the tympanum to obtain reliable measurements (16). Nevertheless, if measured accurately at the right spot, directly contacting the tympanum with a temperature sensor seems the most reliable method to measure T_{ty} (16). It is not a safe and comfortable method though. The tympanum may be damaged and a slight touch of the skin at the end of the aural canal, which is richly innervated with pain sensors, may cause severe pain. Therefore, direct tympanic measurements may be considered unsuited for practical application in an operational setting.

T_{ty} can also be measured indirectly by detecting the emitted heat from tympanum and aural canal with an infrared (IR) sensor. This method is safer, more comfortable and more acceptable for subjects (17) and is therefore frequently used in hospitals and at home. Again, results concerning the relationship of T_{ty} and T_{es} are conflicting and mostly not convincing (18-32). A major concern is the fact that the shape of the aural canal, poor aiming and/or limited insertion depth may prevent a proper view at the tympanum (1; 20). In addition, by a lack of insulation, environmental influences can cause an inconsistent relationship between T_{es} en T_{ty} over subjects and over time (2). Further, in-ear IR is not suited for continuous measurement, as heating of the IR sensor itself and condensation of sweat on the lens cause serious technical problems (33) unpublished observations by the authors).

An alternative in-ear method to estimate core temperature is measuring temperature in the external aural canal (T_{ac}) or against the wall of the aural canal. This method seems more suited for operational application than contact and infrared measurements. However, a strong relationship between core temperature and T_{ac} is not well established (34). Ambient conditions affect accuracy of T_{ac} measurement even more than T_{ty} unless appropriate insulation is applied (35). Daanen and Wammes (36) measured T_{ac} at several locations in the ear and observed, even at room temperature, a temperature difference of >1°C for two points that were 9 mm apart. So for proper measurement, a small temperature sensor has to be placed close to the tympanum and sufficient insulation is required to prevent environmental influences. House (37) indicated that measuring T_{ac} with an individualized ear mould could provide a stable measure of core temperature in several different conditions, at least relatively. Recently Nagano et al. (38) presented T_{ac} measurements with a thermocouple inserted in a sponge-type ear plug. Subjects performed a 120-min protocol with intermittent rest (15 min) and exercise (20 min, 75 W) periods in 25, 30 and 35°C. T_{ac} deviated 0.45 ± 0.08°C, 0.36 ± 0.11°C and 0.30 ± 0.12°C respectively from T_{re}.

Although this is a promising result for continuous operational measurement, it has only been obtained in warm and stable ambient conditions. It is not clear yet whether an ear mould (and additional auricle insulation if necessary) can provide sufficient protection to maintain reliable estimations of core temperature in cool or windy conditions. Further, in the study of Nagano et al. (38) core temperatures changed only gradually and over a

rather small range (about 0.8°C), while in operational settings, detection of rapid increases in core temperature is of major importance. Therefore this study aimed to get insight into the behaviour of T_{ac}, measured with an ear mould integrated sensor (EMS), during ambient temperature changes, wind application and high intensity exercise performance. For that purpose, we developed individual silicon ear moulds with a thermistor at the proximal side. In that way the thermistor could be brought close to the tympanum in a comfortable way, while the earplug insulated the aural canal. T_{ac} was measured in rest in different ambient temperatures, during heavy exercise in a hot environment, with and without wind application. To study the indirect effect that wind might have by conduction via the auricle and other surrounding tissue, or possibly via selective brain cooling, one ear was protected from the environment by an insulating ear cover. T_{es} was used as reference for body core temperature. We hypothesized that external conditions would still affect EMS measured T_{ac} significantly compared to T_{es}, although less pronounced for the ear with the covered auricle. Further, based on the results of Nagano et al. (38), we hypothesized that T_{ac} would track T_{es} properly during exertional hyperthermia.

METHODS

Subjects

Seven healthy and fit subjects (five males and two females) with a mean age of 25.4 ± 1.8 years and a mean weight of 72.3 ± 5.2 kg participated in this study. Subjects were requested to follow their usual diets and lessen physical activities the last day before each trial. Each subject was fully informed of the purposes, protocol, experimental procedures and any associated risks and benefits before giving their written consent to participate. The experiment was approved by the institutional Ethics Committee.

Protocol

The test procedure consisted of one introductory and two experimental sessions on separate days with at least one day in between. At the two experimental sessions, subjects performed an identical protocol of rest and exercise in the climatic chambers at TNO. In one of the experimental sessions, wind was applied during the second half of the trial. Body core temperature was measured with ear mould-integrated thermistors in

both ears, with one auricle protected from the environment, and compared to esophageal, rectal and skin temperatures.

Introductory session. At the first meeting subjects who were not familiar with the esophageal probe, tested their tolerance. The probe had to be inserted via the nose and was then introduced into the esophagus by swallowing the sensor with water. In case of severe gagging reflexes subjects were excluded from the study. For the seven subjects who passed this test, silicon ear moulds for both auditory canals were made. Before the experimental sessions, a thermistor was mounted in the ear mould to measure the temperature of the auditory canal.

Experimental sessions. First, subjects redressed into sport clothes and inserted the rectal and esophageal probe themselves. Heart rate and skin temperature sensors were attached and the ear moulds were inserted. After about 5 min, when the esophageal probe had stabilized and the ear moulds were largely habituated to the environment, the measurement started with ten minutes rest at room temperature (~21°C), followed by 10 min rest in the cold (10°C) and warm (30°C, 50% relative humidity) climatic chamber. Then subjects stayed in the warm chamber and in session 2 the wind tunnel was turned on, before another 10-min rest measurement was being done. This was followed by a 10-min submaximal exercise test that started with an intensity of 130 W, which was, if necessary, increased till subjects reached a heart rate of about 150 beats per minute (bpm). After 2 min rest, the subjects performed a maximal exercise trial of 8 min. They were instructed to cover as much distance as possible during these 8 min. Each session ended with 10 min of recovery (pedalling quietly at low intensity). Sessions were offered in balanced order. The experimental protocol is summarized in Table 4.1.

Measurement methods and materials

Climatic chamber, cycle ergometer and wind tunnel. Experiments were carried out in a custom made climatic chamber (Weiss Enet, Tiel, The Netherlands). In the cold chamber, temperature was set at 10°C, relative humidity was not controlled. Temperature in the warm chamber was set at 30°C with 50% humidity. The 30-min exercise protocol was performed on a Lode Excalibur bicycle ergometer (Lode, Groningen, The Netherlands), which was placed in a wind tunnel (DCTLL 850-8, Ziehl-Abegg, Künzelsau, Germany). Wind speed was measured with a flow meter (LV110, Kimo Instruments, France).

Table 4.1. *Experimental protocol. T_{amb} = ambient temperature.*

	Time (min)	Activity	T_{amb} (°C)	Wind	Intensity
Session 1	0-10	Rest	21	No	
	10-20	Rest	10	No	
	21-31	Rest	30	No	
	31-41	Rest	30	No	
	41-51	Submaximal exercise	30	No	HR ~150 bpm
	51-53	Rest	30	No	
	53-61	Maximal time trial	30	No	8 min self-paced
	61-71	Recovery	30	No	
Session 2	0-10	Rest	21	No	
	10-20	Rest	10	No	
	21-31	Rest	30	No	
	31-41	Rest	30	4 m/s	
	41-51	Submaximal exercise	30	4 m/s	HR ~150 bpm
	51-53	Rest	30	4 m/s	
	53-61	Maximal time trial	30	4 m/s	8 min self-paced
	61-71	Recovery	30	4 m/s	

Ear moulds and thermistors. An individualized ear mould was made for each subject. First, the aural canal was inspected with an otoscope for suitability (no injury, inflammation or severe obstruction and tympanum looks normal). In case of doubt a doctor checked the aural canal and if necessary cleaned it. Then a small wad of cotton was brought into the aural canal just beyond the second turn to protect the tympanum. Subsequently, the subjects' aural canals were filled with a silicon ear impression material (Addition Ultra, Detax, Ettlingen, Germany) that cured within a few minutes. When solid, the ear print was removed from the ear and a small canal was drilled through the mould. Before each trial a thermistor (P-8432, ICBT, Tokyo, Japan) was mounted into this canal and fixed with tape, with the tip just sticking out of the mould at about 5 mm from the tympanum. In one of the moulds (balanced left or right) a small hollow tube (2 mm) was inserted next to the thermistor channel (Figure 4.1). This open connection to the environment functioned as an air channel to keep sufficient audibility. Just before the experimental trials, the ear moulds were reinserted into the subjects' ear. In addition, the ear with the mould without air channel was extra protected from the environment with a cotton patch covering the complete auricle (Figure 4.2).

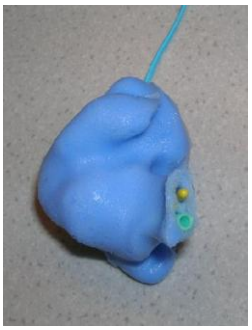

Figure 4.1. *Ear mould with thermistor and air channel*

Figure 4.2. *Insulating patch covering the auricle.*

Esophageal, rectal and skin temperature sensors. T_{es} and T_{re} were measured using thermistors (Yellow Springs Instruments 400 and 700 series respectively, Yellow Springs, OH, USA). Thermistors were calibrated before data acquisition in a thermal water bath (TLC 15, Tamson Instruments, Bleiswijk, The Netherlands) using a certified Pt100 digital temperature indicator (P650, Dostmann Electronic, Wertheim-Reicholzheim, Germany) with resistance temperature probe (PD-13/S, Tempcontrol, Voorburg, The Netherlands). Accuracy of the calibration instruments was ± 0.03°C. The subjects inserted the esophageal sensor themselves through the nasal passage. The insertion depth beyond the external nares was determined according to the formula of Mekjavic et al. (39) based on sitting height. The rectal probe was inserted to a depth of 10 cm beyond the anal sphincter and fixed with tape. The esophageal and rectal sensors as well as the other thermistors were attached to a custom-made data acquisition system (VU University Amsterdam, The Netherlands), consisting of a data logger with a medical power supply and Labview software (National Instrument, Austin TX, USA). Sample frequency was set at 1 Hz.

Mean skin temperature of the body was determined by averaging the results of four iButtons (DS1922L, Maxim Integrated Products Inc, Sunnyvale, CA, USA) placed on the neck, scapula, hand and shin, as described by ISO 9886 (40). See for an evaluation regarding the use of iButtons Van Marken Lichtenbelt et al. (41). A sample frequency of 0.1 Hz was used.

Other measures. To get an indication of the intensity at which the subject was exercising, heart rate was measured using an Equivital Life Monitor (Equivital Hidalgo Ltd, Cambridge, UK) at 15-s intervals. The mass of the subjects was determined on a weighing scale prior to exercise (Sartorius F300S, Göttingen, Germany) and used to calculate the initial power on the ergometer.

Data analysis

T_{es} data were processed with a gating routine to remove the negative peaks due to swallowing. Then individual and group averages per 30 s were calculated for all temperature parameters, as well as individual averages per 5 min. These values have been used for statistical analysis in SPSS statistical software (SPSS 17.0, SPSS Inc, Chicago IL, USA).

T-tests for paired comparisons were performed on the 30 s and 5 min averages to calculate bias and standard deviation between the T_{ac}, T_{es} and T_{re} sensors for different intervals. ANOVA for repeated measures was used to determine significant temperature changes of all sensors in response to a phase transition. For that purpose the final 30 s of a trial phase was compared to the final 30 s of the next phase. A 2x2 ANOVA for repeated measures was applied to discover a possible interaction between wind application and wearing an ear cover on T_{ac}. Significance level for all tests was set at $p<0.05$.

In view of the different response times of the different temperature measurement locations, cross-correlation on the 10-s averaged values was used to figure out how much each temperature pattern must be shifted along the x-axis to make it maximally identical to each other.

RESULTS

All seven subjects finished the experimental protocol with a complete dataset and have been included in the statistical analysis.

Average temperature patterns

In Figure 4.3, the different average temperature patterns are depicted for the entire trials. The upper panel A contains the trials without wind, panel B contains the trials where the wind tunnel was turned on at 31 min.

Clearly, both the covered and uncovered T_{ac} values (T_{ac_c} en T_{ac_unc} respectively) differed significantly from T_{es} in each phase (p<0.05). The absolute difference varied considerably depending on ambient temperature, wind and activity. Except for the rest period at room temperature, T_{ac_unc} differed also significantly from T_{ac_c}, especially in the cold room. Changes in ambient temperature while subjects were in rest induced both T_{ac} values to change in an exponential way as a result of the cooling and heating of the ear mould and aural canal. Both core temperatures remained stable. Also note the quick decrease in T_{es} during the break between the exercise bouts in the wind condition (Figure 4.3B).

T_{ac} response to phase transitions

The uncovered ear had a much stronger ΔT response (and larger standard deviation) to transitions in ambient temperature than the covered ear (Figure 4.4). Further, wind had a significant effect on T_{ac} of both ears. When no wind was present during the second 'rest 30°C' phase, T_{ac} continued its significant increase (Figure 4.4, left panel). When wind was turned on at the start of the second 'rest 30°C' phase, the increase in T_{ac} stopped instantly (Figure 4.4, right panel). All other phase transitions produced a significant change in T_{ac} values of both ears, except for maximal exercise to recovery.

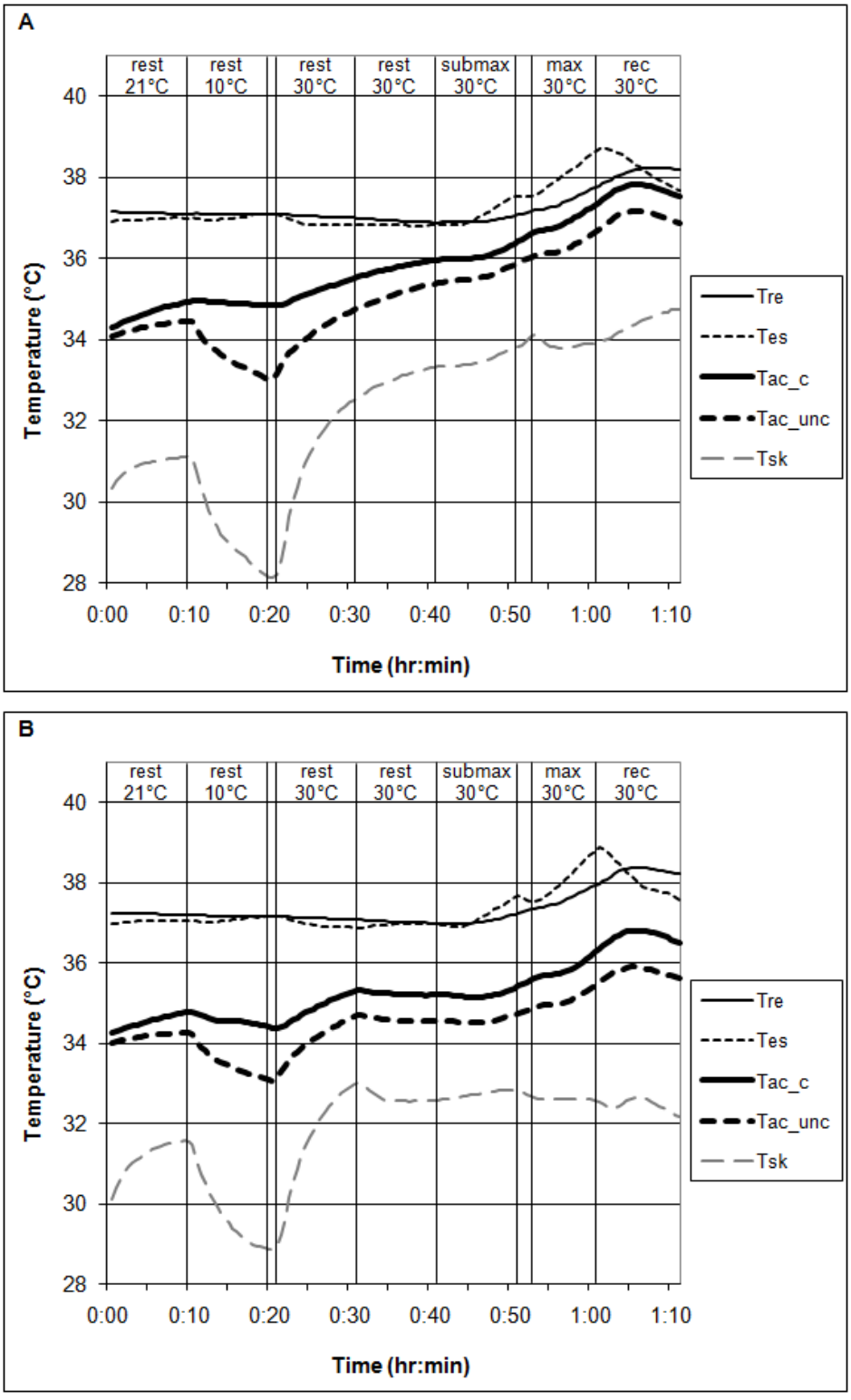

Figure 4.3. *Average rectal (T_{re}), esophageal (T_{es}), aural canal covered (T_{ac_c}), aural canal uncovered (T_{ac_unc}) and skin (T_{sk}) temperature patterns during the 71-min trial. Panel **A** shows the protocol entirely without wind, panel **B** shows the protocol in which the wind tunnel is turned on at 31 min. Vertical lines indicate transitions in protocol phase. The short intervals at 20-21 and 51-53 min are transfer time and exercise break respectively. Submax = submaximal exercise; max = maximal exercise; rec = recovery from exercise.*

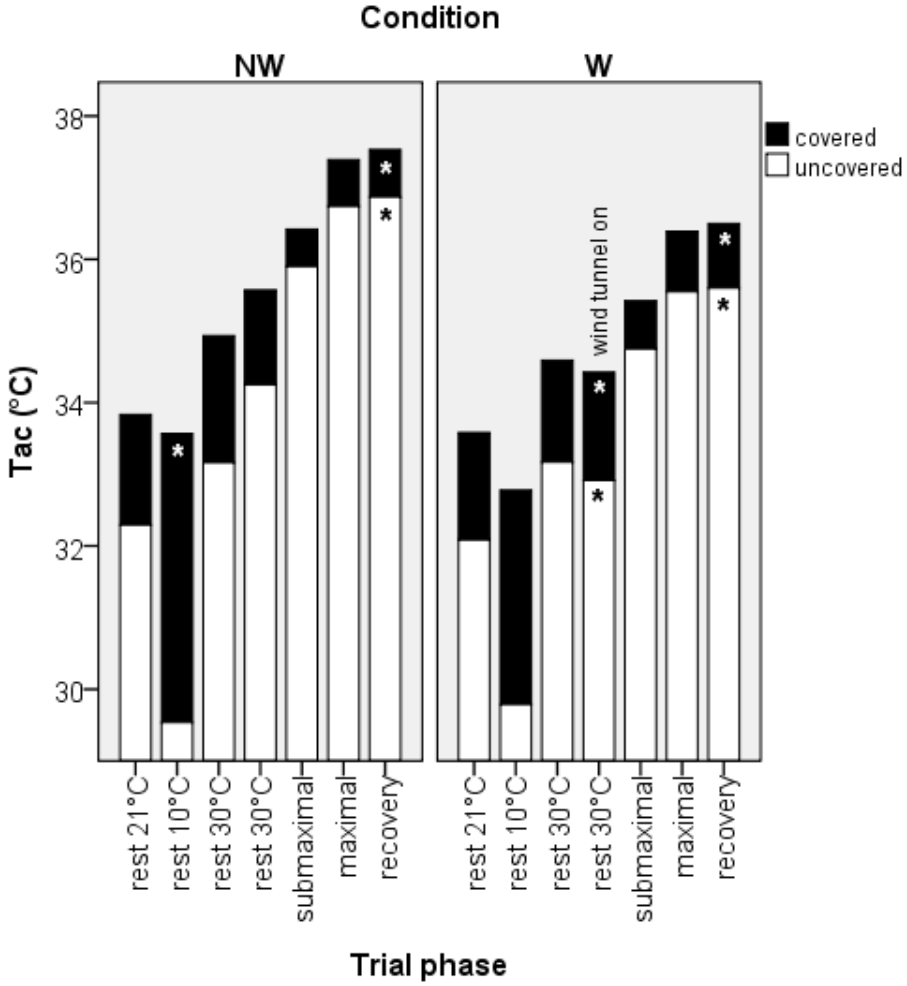

Figure 4.4. *Average covered and uncovered aural canal temperatures (T_{ac}) during all trial phases for the condition without any wind (NW) and with wind (W). In the W-condition, wind started at the second 'rest 30°C' phase. *Not significantly different (p>0.05) from previous phase.*

T_{ac} compared to reference core temperatures during exercise in the heat

During the exercise and recovery periods under consistent ambient conditions, group averages of T_{ac} show a reasonable tracking of T_{re} over time. This is reflected in the acceptable standard deviation (SD) of the group averaged ΔT_{re}-T_{ac_c} and ΔT_{re}-T_{ac_unc} with and without wind (Table 4.2). Bias ± SD of T_{ac} compared to T_{es} was larger, but note that these results are influenced by the delay of T_{ac} compared to T_{es}. Cross correlation revealed that a maximal R value (0.88) was attained for a delay of 3.5 min. Correcting this delay by shifting T_{ac} data 3.5 min backwards, resulted in substantially smaller SD's (ΔT_{es}-T_{ac_c} 0.83 ± 0.18°C and ΔT_{es}-T_{ac_unc} 1.43 ± 0.18°C without wind; 1.78 ± 0.19°C and 2.56 ± 0.19°C respectively with wind).

Further, it is clear that wind strongly increased the absolute difference of T_{ac} with its references, but variability was not severely affected (Table 4.2, row one compared to row two). Finally, individual instead of group averaged calculation reveals a higher variability over time for individual values, especially in de wind condition (Table 4.2, row one and two compared to row three and four respectively).

Table 4.2. *Average differences ± standard deviation of the two aural canal temperatures (covered and uncovered: T_{ac_c} and T_{ac_unc} respectively) with esophageal temperature (T_{es}) and rectal temperature (T_{re}) during the exercise and recovery period in the no wind and wind conditions. Differences are given for 30-s group averaged values (N=60) and 30-s individual values (N=420).*

	ΔT_{es}-T_{ac_c} (°C)	ΔT_{es}-T_{ac_unc} (°C)	ΔT_{re}-T_{ac_c} (°C)	ΔT_{re}-T_{ac_unc} (°C)
No wind (group)	0.89 ± 0.35	1.49 ± 0.33	0.66 ± 0.21	1.20 ± 0.15
Wind (group)	1.87 ± 0.46	2.63 ± 0.41	1.73 ± 0.11	2.49 ± 0.04
No wind (individual)	0.89 ± 0.47	1.49 ± 0.51	0.66 ± 0.32	1.20 ± 0.29
Wind (individual)	1.87 ± 0.71	2.63 ± 0.73	1.73 ± 0.58	2.49 ± 0.47

Ear cover and wind

Figure 4.5 shows the average T_{ac} for the covered and the uncovered ear per 5-min interval (4-min interval for maximal exercise), both in the NW and the W condition. Till the second 'Rest 30°C' phase, the protocol of the two conditions (NW and W) was identical and there was neither for the uncovered nor for the covered ear a significant difference between conditions. However, from the moment the wind tunnel was turned on, both the uncovered and the covered side showed a significant difference between the NW and W conditions at each interval. Remarkably, there was no interaction between wind and ear coverage on T_{ac}; the wind effect was not significantly different for the uncovered and covered ear in any phase. So although T_{ac_unc} was structurally lower than T_{ac_c}, wind had a similar significant temperature effect on both ears.

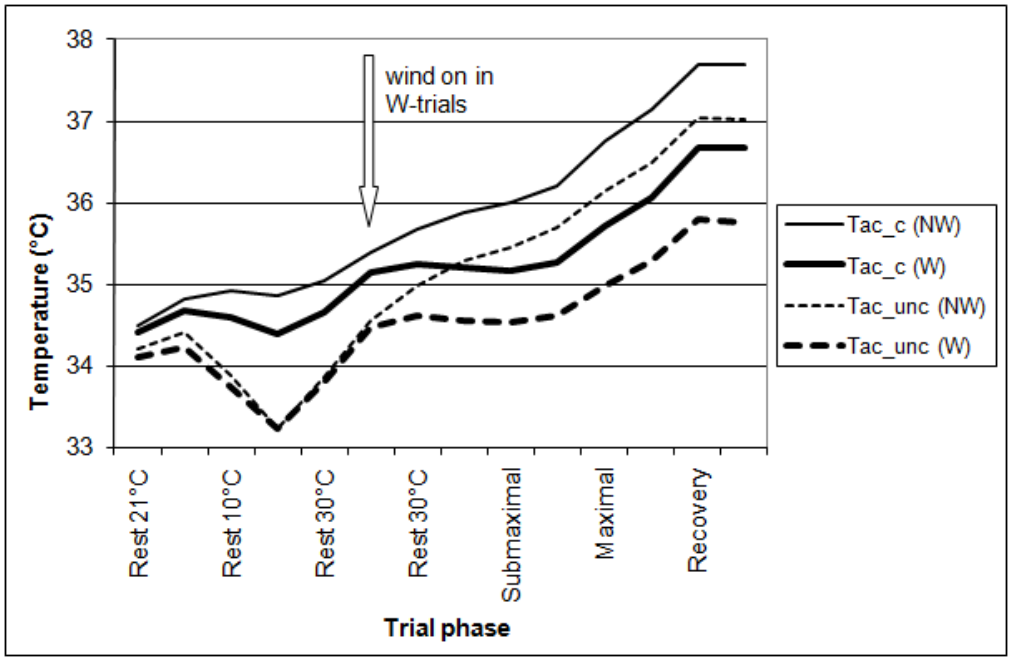

Figure 4.5. *Average covered and uncovered aural canal temperatures (T_{ac_c} and T_{ac_unc}) per 5-min trial interval (4-min interval for max exercise), both in the no wind (NW) and the wind (W) condition. In the W-condition, wind started at the arrow. To the right of this line, data points of the W-condition are significantly different from the NW-condition for both the covered and the uncovered ear.*

DISCUSSION

This study addressed some potential limitations of T_{ac} measurement with a thermistor at the tip of an ear mould as an indicator of core temperature. Results showed that varying ambient temperature in the range of 10-30°C clearly affected T_{ac} and led to a poor estimate of core temperature. Further, it appeared that wind had an immediate significant effect on T_{ac}, which was independent of extra insulation of the auricle. This suggests that wind provides fast local cooling of T_{ac} without the need for direct input on the auricle or aural canal. Finally, during exercise and recovery in stable ambient conditions, T_{ac} gave acceptable group predictions of T_{re} and, when its faster response was taken into account, T_{es}. However, increased SD's of the mean differences (Table 4.2) indicate that individual predictions were less reliable, especially when wind was applied.

Ambient temperature

T_{ac} measured by the EMS in the air chamber between ear mould, tympanum and aural canal wall is a weighted average of its surrounding structures. Ambient temperature

appeared to influence this temperature substantially independent of core temperature changes. This ambient temperature dependence of EMS-measured T_{ac} agrees with previous reports for diverse in-ear measurement methods (2; 36; 42-44).

The influence of ambient temperature on T_{ac} may have been caused by several mechanisms. First, the ear mould probably conducted some of the external cold or heat, which affected the measured temperature at the proximal tip of the ear mould. In that perspective it must be noted that the silicon ear mould had a large time constant causing a transient effect in the temperature pattern (Figure 4.3). Secondly, it has to be noted that the inside of the tympanic membrane is in contact with air of the cavities in the human head and thus, the tympanic temperature may be affected by ambient temperature from the inside as well. Thirdly, ambient conditions may have influenced the temperature of the tympanum and aural canal wall indirectly by conduction via the auricle and surrounding tissue. An accompanying effect of this mechanism would be vasoconstriction of the vessels of the aural canal which leads to less heat emission from the aural canal wall to the air pocket. Finally, ambient temperature may have affected the temperature of the local blood circulation. This mechanism may be induced by superficial cooling of the external carotid artery, which is a main supplier of arterial blood to this area, or passage of cool venous blood from the scalp and face (1; 2; 45).

As expected, covering the entire auricle led to a significantly higher T_{ac} which was closer to core temperature than T_{ac} uncovered. Apparently, the insulation of the ear mould itself was not sufficient to accomplish this. It suggests that the auricle plays a major role in conducting ambient temperature to the aural canal. Admittedly, the ear mould in the uncovered ear also contained an air channel. However, unpublished results without wearing the ear cover suggest that having an air channel in the ear mould does not make a substantial difference; the ear cover seemed fully responsible for the differences by stabilizing the temperature of the outer ear. The merits of stabilizing the temperature of the outer ear during T_{ac} measurements were already appreciated by Keatinge and Sloan (42), who kept the outer ear at the same temperature level as the aural canal by servo-controlled heating. They found that T_{ac} stabilized within 0.35°C of T_{es} in an ambient temperature of 18-45°C and moderate wind; this often held good for cooler temperatures as well, albeit with slower stabilization, and thus prevented serious T_{ac} depression in cold air.

Wind application

Next to ambient temperature, facial cooling by wind also had a significant effect on T_{ac}. As soon as the wind tunnel was turned on, T_{ac} started to differ significantly from the values during the trial without wind. This agrees with Thomas et al. (2) who measured infrared T_{ty} and concluded that facial cooling by fanning altered the relationship between T_{ty} and T_{es}. Remarkable in the current results was the fact that, in contrast to ambient temperature, the wind effect appeared to be independent of the ear cover. Apparently the wind-induced decrease in T_{ac} has not been caused by a direct decrease of the air temperature in the aural canal or around the auricle. This suggests a cooling mechanism by convection via the blood and/or by conduction via surrounding tissue. As mentioned before, convective cooling via the blood can be accomplished by cooled venous blood from the scalp and face or by superficially cooled external carotid blood. As there was a fast distinct response of T_{ac} to wind (within 30 s) and conduction is a slower process than convection, convection might be the primary mechanism.

Prediction of core temperature

Considering the small SD of the difference, group averages of T_{ac} provided a quite reliable prediction of T_{re} during exercise and recovery in stable conditions. This held good for the wind condition as well, although a larger bias had to be taken into account. T_{re} is an important and generally accepted practical measure for core temperature, although it does not indicate rapid changes in central blood temperature, as reflected by T_{es}. Nagano et al. (38) found a ΔT_{re}-T_{ac} of 0.36 ± 0.11°C with a thermocouple insulated by an ear plug under comparable ambient conditions, but during longer and lower intensity exercise. So despite the higher exercise intensity in our protocol, the SD was similar. The mean difference in this study was substantially higher than in Nagano et al. (38), possibly because our T_{ac} was still affected by the cold interval earlier in the protocol. T_{es}-T_{ac} differences seemed more variable, but after correction for T_{ac}'s delayed response, variability was reduced and predictive reliability of T_{es} was close to T_{re}.

Individual predictions of T_{re} during exercise and recovery in conditions without wind have to be judged critically because of the substantial variability of the difference between T_{re} and T_{ac} (SD's of 0.29 and 0.32°C for the uncovered and covered ear). This is in line with the study of Muir (43) who compared T_{ac} and T_{re} during exercise in a hot environment

without wind to evaluate worker safety guidelines. Their group mean predictions were satisfactory, but individual variability was rather large for setting effective guidelines (SD's of 0.28°C for an ear thermistor insulated by an ear plug and 0.36°C for an operationally used personal heat stress monitor). Individual predictions of T_{re} in windy conditions cannot be considered reliable, as variability of the difference was at an unacceptable level (SD's of ~0.5°C). As individual predictions are most relevant and could considerably extend the field of application, improvements on this issue are necessary. Variability might be reduced by bringing the sensor still closer to the tympanum and gluing the thermistors solidly into the ear mould. Applying some artificial heating to the outer ear is also likely to decrease variability in prediction, mainly by reducing external influences.

Predictions during unstable ambient conditions (e.g. changing ambient temperature and/or wind conditions) might be improved when a compensatory calculation would be available, taking into account the environmental situation. Future studies should reveal whether it is possible to predict core temperature reliably from T_{ac} under changing ambient conditions when multipoint measures are used to account for these conditions. A prediction model will have to include the transient effect of the specific ear mould.

Selective brain cooling

One could argue that the results with wind support the concept of selective brain cooling (SBC). SBC may be defined as cooling of the brain temperature (often assumed to be reflected in the tympanic temperature) below arterial blood temperature. For SBC to take place, first venous blood has to be cooled superficially at the upper respiratory tract and at the surface of the head (11; 46-49). Secondly, this cooled venous blood would have to cool the inner brain by 1)countercurrent heat exchange with the internal carotid (50), 2)heat exchange with the cortical cerebral arteries mediated by the cerebrospinal fluid (51) and/or 3)direct contact with brain tissue (13). It is probable that superficial venous blood cooling is stimulated by face fanning. However, it seems improbable that within half a minute from starting fanning, the brain is cooled by one of these mechanisms and causes T_{ac} to stop its increase. Therefore, the cause of the T_{ac} cooling does not seem to originate in whole brain cooling but in more local phenomena.

Numerous studies applied face fanning during rest, active heating or passive heating, while measuring T_{ty}. Nearly all of them found a similar fast and distinct cooling response of T_{ty}, which exceeded the response of T_{es} significantly (4-8; 10; 52-54). Although T_{ty} is not equal to T_{ac}, it is plausible that face fanning affects T_{ty} in a similar way as T_{ac} was affected in this study. So, in agreement with several of the referred studies (4-8; 10; 52-54), it seems not appropriate to use T_{ty} results during face fanning as evidence for the existence of selective brain cooling.

Conclusion

In conclusion, this study showed that changing ambient temperature severely affected the relationship of T_{ac} with T_{es} and T_{re}. Covering the auricle attenuated this effect, but not sufficiently to allow for reliable predictions. Wind also altered the relationship of T_{ac} and its reference core temperatures. As this effect was fast and independent of covering the auricle, local vascular cooling mechanisms seem to be involved. During exercise and recovery in warm and stable ambient conditions, T_{ac} allowed for acceptable group predictions of core temperature. However, for reliable individual predictions, methodological improvements are required.

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Chapter 5

Telemetry pill versus rectal and esophageal temperature during extreme rates of exercise-induced core temperature change

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Physiol Meas 2012; 33(6): 915-924

ABSTRACT

Purpose and methods

Core temperature measurement with an ingestible telemetry pill has been scarcely investigated during extreme rates of temperature change, induced by short high-intensity exercise in the heat. Therefore, nine participants performed a protocol of rest, (sub)maximal cycling and recovery in 30°C during which pill temperature (T_{pill}) was compared to rectal temperature (T_{re}) and esophageal temperature (T_{es}).

Results

T_{pill} corresponded well to T_{re} during the entire trial, but deviated considerably from T_{es} during the exercise and recovery periods. During maximal exercise the average ΔT_{pill}-T_{re} and ΔT_{pill}-T_{es} were 0.13 ± 0.26°C and -0.57 ± 0.53°C respectively. Response time from the start of exercise, rate of change during exercise and peak temperature were similar for T_{pill} and $T_{re.}$ T_{es} responded 5 min earlier, increased more than twice as fast and its peak value was 0.42 ± 0.46°C higher than T_{pill}.

Conclusion

Also during considerable temperature changes at very high rate, T_{pill} is still representative of T_{re}. The extent of the deviation in pattern and peak values between T_{pill} and T_{es} (up to >1°C) strengthens the assumption that T_{pill} is unsuited to evaluate central blood temperature when body temperatures change rapidly.

INTRODUCTION

The last two decades, radio telemetry has become an increasingly popular method for core temperature determination in operational settings and field studies. Radio telemetry uses a 'sensor pill' which is swallowed and transmits FM signals reflecting gastrointestinal temperature. Because of the wireless and comfortable nature of this measurement method, it is regularly used during exercise, for subjects wearing protective clothing and for prolonged monitoring.

It has been recognized for ages that different body sites may be subject to different temperatures (1). The measurement method may even increase variation (2). For monitoring purposes, it is important to determine whether T_{pill} can be used to estimate accepted core temperatures as T_{re} and T_{es} when direct measurement is not feasible. T_{re} is thought to give an indication of the temperature in the vulnerable abdominal cavity and is an adequate index of whole body temperature in rest or steady state exercise (3). T_{es} reflects central blood temperature and responds fast when the body is gaining or losing heat. Both measures are regularly used for clinical monitoring. In addition, during severe hyperthermia, T_{re} and T_{es} may indicate the temperature of the body structures that are most at risk: the gut and the brain respectively (4; 5). In that respect, it would be useful if T_{pill} could provide a reliable estimation of either of these measures.

Most previous studies comparing pill temperature (T_{pill}) to either esophageal (T_{es}) or rectal temperature (T_{re}) showed acceptable levels of agreement (6). As a result, Byrne and Lim (6) concluded in their review that T_{pill} is a valid index of core temperature. However, most of the reviewed studies only looked at slowly and slightly changing core temperatures, due to circadian rhythm, immersion or low intensity exercise (7-14).

Regarding the few studies that applied high intensity exercise, Easton et al. (15) showed very good agreement with T_{re} during 16 km maximal cycling in 30°C ambient temperature, as well as Gant et al. (16) during 4x12 min intermittent shuttle running in 15°C. However, these studies did not include T_{es} in their measurements and exercise duration limited the maximal rate of change in core temperature. Kolka et al. (17) compared T_{pill} to both T_{re} and T_{es} during 3x5 min cycling at 80% VO_{2peak} (30°C ambient temperature), inducing a high rate of temperature change. They concluded that the rate

of change in T_{es} was twice as high as T_{pill} and five times as high as T_{re}. There was also a significant difference in response time, T_{pill} being slower than T_{es}, but faster than T_{re}. This difference between T_{pill} and T_{re} is not in line with Gant et al. (16) and Easton et al. (15), who found similar responses. Although all three studies suggest that T_{pill} is at least not slower than T_{re}, clear evidence about the relationship between T_{pill} and T_{re} during large high-rate temperature changes is warranted to properly judge its value in those conditions. Further, because of the short intermittent protocol in the study of Kolka et al. (1993), temperature changes were small and differences did not reach the hyperthermic range (>38°C). So it could not be established to which extent T_{pill} deviates from T_{es} during larger high-rate temperature fluctuations.

Because of these limitations and inconsistencies in previous studies, the main purpose of this study is to directly compare T_{pill} to both T_{es} and T_{re} during short high intensity exercise in the heat inducing substantial temperature changes at a very high rate. To get more insight in any differences between high intensity exercise at submaximal and maximal level, the protocol consisted of both a submaximal and a maximal cycling exercise bout. In addition, stabilization and recovery periods were monitored. Following Easton et al. (15) and Kolka et al. (17), ambient temperature was set at 30°C to induce a quick and substantial rise in core temperature. We hypothesized that T_{pill} would track T_{re} and give a delayed and attenuated image of T_{es}.

METHODS

The study was approved by the Research and Ethics Committee of TNO, The Netherlands.

Participants

Nine healthy and fit participants (six males and three females, exercising at least two times a week at recreational level) with a mean age of 26 ± 4 years, a mean weight of 72.9 ± 4.6 kg and tolerant of the esophageal probe, participated in this study. Participants were requested to follow their usual diets and lessen physical activities the last day before each trial. Each participant was fully informed of the purposes, protocol,

experimental procedures and any associated risks and benefits before giving their written consent to participate.

Protocol

Four hours before their experimental session, participants swallowed a temperature pill with water. As food, drinks and saliva might affect temperature measurements as long as the pill is located in the stomach, the pill has to be swallowed several hours before the start of measurement in order to reach the intestinal tract (6). Just before the measurement, participants redressed, attached a heart rate sensor and inserted a rectal and esophageal probe themselves. After about 5 min, when the esophageal temperature had stabilized, the measurement protocol in the climatic chamber started (Table 5.1). The submaximal exercise test was performed on a bicycle ergometer and started with an intensity of 130 W. Intensity was, if necessary, increased till participants reached a heart rate of about 150 beats per minute (bpm) in the last three minutes. During the subsequent 8-min maximal exercise trial, participants were instructed to cover as much distance as possible and received distance feedback from a display.

Table 5.1. *Experimental protocol.*

Time (min)	Activity	Intensity
0-20	Habituation	
20-30	Submaximal exercise	HR ~150 bpm
30-32	Break	
32-40	Maximal exercise	self-paced
40-50	Recovery	

Measurement methods and materials

Experiments were carried out in a custom made climatic room (Weiss Enet, Tiel, The Netherlands). Temperature was set at 30°C with 50% relative humidity and still air, to quickly induce hyperthermia (T_{es}>38°C), while having sufficient possibility for evaporative cooling. Exercise was performed on a Lode Excalibur bicycle ergometer (Lode, Groningen, The Netherlands).

Gastrointestinal temperature was measured using Jonah ingestible core body temperature capsules (Philips Respironics, Mini Mitter, Bend, Oregon), which were

logged by the Equivital Life Monitor (Equivital Hidalgo Ltd, Cambridge, UK). The Equivital Life Monitor (ELM) is a wireless chest-mounted system that uses an array of sensors to assess someone's physiological status. Heart rate data were collected by the ELM as well. Data were collected each 15 s interval and displayed and stored instantly on a notebook via Bluetooth®.

T_{es} and T_{re} were measured using thermistors (Yellow Springs Instruments 400 and 700 series respectively, Yellow Springs, OH, USA). Thermistors were calibrated before data acquisition in a thermal water bath (Tamson TLC-15, Tamson instruments, Bleiswijk, The Netherlands) using a certified Pt100 calibration thermometer (P650, Dostmann electronic, Germany) with resistance temperature sensor (PD-13/S, Tempcontrol, Voorburg, The Netherlands). The insertion depth of the esophageal probe was based on sitting height (18), assuring that it was located at the T8/T9 level, close to the left ventricle. The rectal probe was inserted to a depth of 10 cm beyond the anal sphincter and fixed with tape. The esophageal and rectal sensors were attached to a custom-made data acquisition system (VU University, Amsterdam, The Netherlands), consisting of a datalogger with a medical power supply and Labview software (National Instrument, Austin TX, USA). Sample frequency was set at 1 Hz. The mass of the participants was determined on a weighing scale prior to exercise (Sartorius F300S, Göttingen, Germany).

Data analysis

T_{es} data were processed with a gating routine to remove the negative peaks due to swallowing relatively cool saliva. Then individual and group averages per 30 s were calculated for all temperature parameters, as well as individual averages per 5 min. These values have been used for statistical analysis in SPSS statistical software (SPSS 17.0, SPSS Inc, Chicago IL, USA).

ANOVA for repeated measures was used to determine significant temperature changes of all sensors in response to a phase transition. For that purpose the final 30 s of a trial phase was compared to the final 30 s of the next phase. T-tests for paired comparison, with Bonferroni adjustment for multiple comparisons, were performed to check for significant differences between T_{pill} and T_{es}/T_{re} at different intervals. Differences between T_{re} and T_{es} were additionally calculated as well.

As an indication of response time of T_{pill}, T_{es} and T_{re}, time for 0.1°C change from the start and end of exercise have been calculated (17). The average rate of temperature change (the average temperature change per minute for a specific interval) has been calculated for both the submaximal and maximal exercise bouts, as well as for the recovery phase. Further, peak values of the different measurement methods and maximal differences at a discrete time point have been compared by paired t-tests. Values are expressed as means ± standard deviation (SD). Calculated averages are arithmetic averages. Significance level for all tests was set at $p<0.05$.

RESULTS

For one participant, the rectal sensor failed and for another one heart rate was not recorded, so analyses involving T_{re} and HR are based on eight participants. Further, all trials had a complete dataset. No temperature drops in T_{pill} were observed when participants drank cold water prior to the experiment, confirming the 4-hour ingestion time was sufficient.

Exercise intensity

Average power output over the complete submaximal exercise interval was 153 ± 13 W with an average HR of 134±15 bpm and an average maximal HR of 156 ± 16 bpm. During the maximal exercise test, participants cycled on average at 247±61 W with an average HR during the complete interval of 168 ± 14 bpm and an average maximum of 181 ± 9 bpm.

Temperature patterns during the trials

Figure 5.1 shows the averaged temperature patterns for T_{es}, T_{re} and T_{pill}. Table 5.2 shows the exact temperatures at the end of each phase, as well as the total temperature change during exercise (exercise strain). Nearly all phase transitions resulted in significant temperature changes. The increase in T_{pill} during exercise was significantly smaller than T_{es}, but similar to T_{re}.

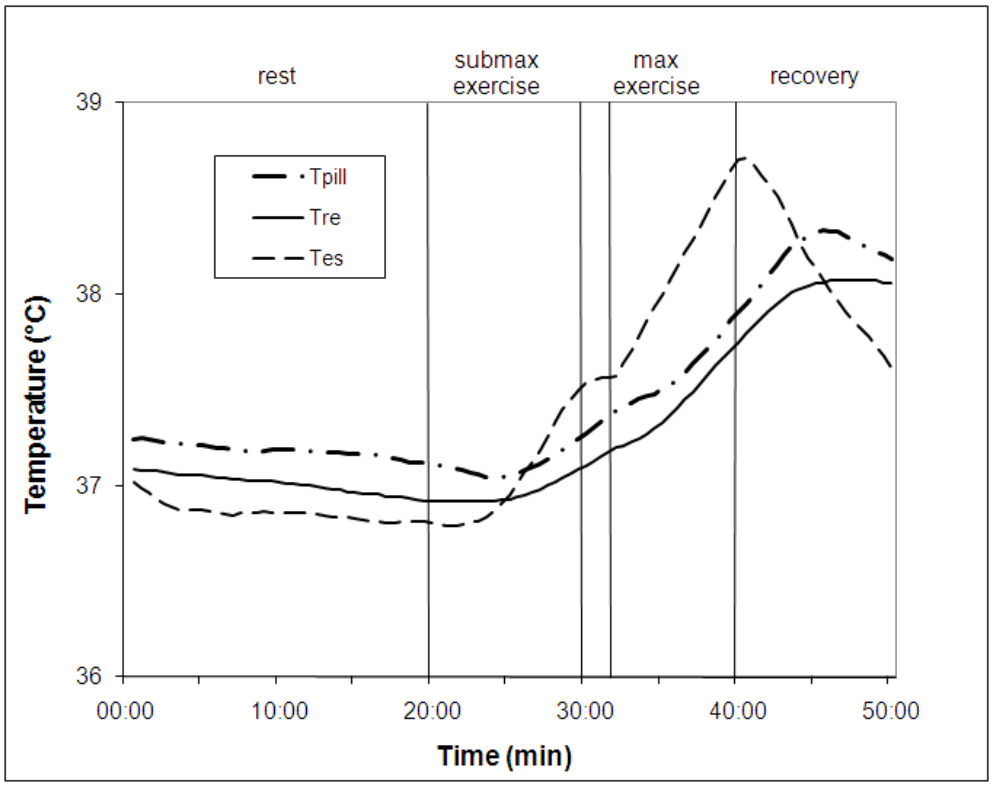

Figure 5.1. *Average esophageal temperature (T_{es}), pill temperature (T_{pill}) and rectal temperature (T_{re}) patterns during the experimental trial. Submax = submaximal; max = maximal.*

Table 5.2. *Pill temperature (T_{pill}), rectal temperature (T_{re}) and esophageal temperature (T_{es}) at the end of each phase. Values are averaged over the last 30 s of rest, submaximal exercise (submax), maximal exercise (max) and recovery. In addition, the last row reports exercise strain, indicating the total temperature increase during the exercise phases.*

	T_{pill} (°C)	T_{es} (°C)	T_{re} (°C)
End rest	37.11 ± 0.28	36.81 ± 0.32*	36.92 ± 0.41
End submax	37.27 ± 0.33†	37.54 ± 0.39†*	37.10 ± 0.39†*
End max	37.91 ± 0.39†	38.72 ± 0.60†*	37.76 ± 0.46†
End recovery	38.19 ± 0.45	37.62 ± 0.39†*	38.06 ± 0.54†
Exercise strain (∆rest-max)	0.80 ± 0.20	1.91 ± 0.63*	0.75 ± 0.54

†Significantly different from previous phase ($p<0.05$)

**Significantly different from T_{pill} ($p<0.05$)*

Differences between measurement methods

Figure 5.2 shows the temperature differences ± SD between measurement methods, averaged over each 5-min interval (for maximal exercise 4-min intervals) and over subjects. T_{pill} and T_{es} were significantly different at all intervals, except for the 'sub2' and 'rec1' period, when the difference was changing from positive to negative and vice versa. At the 'max2' period, ΔT_{pill}-T_{es} amounted 0.72 ± 0.63°C. T_{pill} and T_{re} did not show any significant difference except at the 'max1' interval (0.15 ± 0.15°C). T_{re} and T_{es} differed significantly during the last four phases of the trial (maximal exercise and recovery).

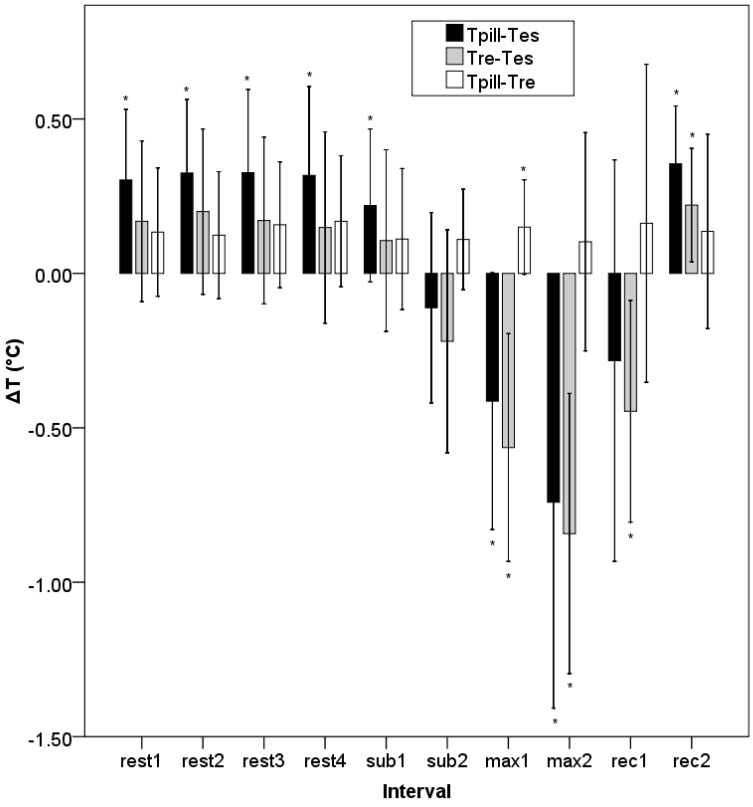

Figure 5.2. *Averaged temperature differences between the different measurement methods - pill (T_{pill}), esophageal (T_{es}) and rectal (T_{re}) - during each 5-min interval of the experimental trial (for maximal exercise 4 min intervals). Sub = submaximal exercise; max = maximal exercise; rec = recovery period. *Significantly different from 0.*

Over the entire trial, T_{pill}-T_{es} and T_{pill}-T_{re} show a mean difference of 0.04 ± 0.52°C and 0.14 ± 0.26°C respectively for all individual 5-min average values of the experimental trials. The 95% limits of agreement thus ranged from -0.97 to 1.05°C for T_{pill}-T_{es} and from -0.38 to 0.65°C for T_{pill}-T_{re}.

Response time and rate of change

Table 5.3 displays response time and rate of change of T_{pill}, T_{es} and T_{re}. T_{es} responded significantly faster to the start of exercise than T_{pill}, increasing 0.1°C about 5 min earlier. T_{pill} did not respond significantly different from T_{re}. After stopping exercise, it took about three minutes before T_{es} had decreased 0.1°C. T_{pill} and T_{re} had not yet returned to end exercise temperatures after 10 min recovery in all except one participant. During submaximal exercise, as well as maximal exercise and recovery, the rate of T_{pill} change did not differ from T_{re}, but was significantly lower than the rate of T_{es} change (Table 5.3).

Table 5.3. *Response time and rate of change of pill (T_{pill}), esophageal (T_{es}) and rectal (T_{re}) temperatures. Response time is expressed as time for 0.1°C increase and decrease from start and end of exercise respectively. Rate of change is expressed as average temperature change per minute during the submaximal exercise (sub), maximal exercise (max) and recovery (rec) phase.*

	T_{pill}	T_{es}	T_{re}
Response time 0.1°C increase (min)	8.8 ± 1.7	3.9 ± 2.1*	9.4 ± 2.6
Response time 0.1°C decrease (min)	>10	3.0 ± 2.8	>10
Rate of change sub (°C/min)	0.016 ± 0.013	0.072 ± 0.017*	0.018 ± 0.010
Rate of change max (°C/min)	0.065 ± 0.022	0.143 ± 0.073*	0.070 ± 0.045
Rate of change rec (°C/min)	0.028 ± 0.046	-0.110 ± 0.041*	0.029 ± 0.028

**Significantly different from T_{pill} ($p<0.05$)*

Peak values and delay

T_{pill}-T_{es} peak temperature difference was -0.42 ± 0.46°C, with individual extremes to -1.21°C. Due to the delay of T_{pill}, the average maximal T_{pill}-T_{es} difference at a discrete time point around the end of maximal exercise was -1.01 ± 0.66°C, with individual extremes to over -2°C. Differences between T_{re} and T_{es} showed a similar pattern. Peak values of T_{pill} and T_{re} did not show a significant difference (0.16 ± 0.31). Maximal temperature differences between T_{pill} and T_{re} did differ (0.47 ± 0.29), but substantially less than compared to T_{es}.

DISCUSSION

This study compared the response of gastrointestinal temperature measured by a temperature pill (T_{pill}) to the responses of T_{es} and T_{re} during rapid core temperature changes due to short high intensity exercise in the heat. Results indicate that even in these extreme conditions, T_{pill} provides a reasonable estimation of T_{re} and subsequently gives an indication of the temperature of vulnerable abdominal organs with a similar thermal delay (3; 19). T_{pill} increasingly deviates from T_{es} when body heat content changes rapidly. Responsiveness, rate of change and peak values all differ to such an extent from T_{es}, that any inference to T_{es} is out of place.

Rest measurements

In rest, T_{pill} was consistently higher than T_{es}, which agrees with some previous studies investigating T_{pill} in rest and low intensity exercise (12; 14). This is in line with the fact that T_{re} has generally been found to be slightly (0.2°C) higher than T_{es} in rest as well (20; 21). The positive bias between T_{pill} and T_{re} in this study has also been reported before (9; 16; 22), but this finding is not consistent in literature (6). The decreasing trend in rest of all temperature profiles is probably caused by cold peripheral blood returning to the body core, as perfusion of the periphery increases on entering the warm climatic chamber due to vasodilation. After a longer rest period, temperatures would be expected to stabilize or slightly increase again.

Exercise and recovery

In agreement with previous studies applying longer exercise protocols with moderately high rates of temperature change (15; 16), T_{pill} and T_{re} followed the same pattern during exercise and recovery. Except for the small and practically meaningless difference at the 'max1' interval, there was no significant bias, although T_{pill} tended to be somewhat higher than T_{re}. At the end of maximal exercise and during the recovery phase, individual variation in ΔT_{pill}-T_{re} increased. This is probably due to an individually different thermal delay of the intestinal tract. T_{es} showed an increasing difference with T_{pill} during exercise, up to an average bias of >0.7°C. In the course of the recovery phase, the difference increased in the opposite direction to significant and meaningful proportions. Apparently, the previously reported deviation of T_{es} from T_{pill} during exercise induced

core temperature changes (17; 22), is enlarged with the magnitude of the temperature change.

Response time, rate of change and peak values

Response time was similar for T_{pill} and T_{re} (~9 min), increasing 0.1°C after the start of exercise about 5 min later than T_{es}. Response times of T_{es} and T_{pill} (3.9 and 9.4 min respectively) were larger than reported by Kolka (17), who found 1.8 and 3.8 min at 80% VO_{2max} in a similar ambient temperature. However, their participants had already performed a low intensity cycling protocol before. T_{pill} and T_{re} reached their peak value/plateau about 5-6 min after the end of exercise. In line with Kolka (17), the rate of change in T_{es} during (sub)maximal exercise was more than two times higher than T_{pill} and T_{re}. On the contrary, the current study did not find Kolka et al.'s (17) significant difference in rate of change between T_{pill} and T_{re}. Possibly this is due to the longer ingestion time and thus different pill location in this study, although several human studies found a similar ΔT_{pill}-T_{re} at different time points after ingestion (7; 23). Alternatively, the different exercise protocol may have affected the results.

The slower response of T_{pill} compared to T_{es} can first be explained physically, as it requires a great amount of energy to change the temperature of the entire intestinal tract (15; 19; 24-26). In addition, blood supply plays a role during moderate to heavy exercise. Sympathetic activity is increased and parasympathetic activity reduced, leading to vasoconstriction of the vessels in the gastrointestinal tract. There is a linear reduction in splanchnic blood flow with increasing exercise intensity from 2.8 l/min at rest to 0.5 l/min during heavy exercise (27; 28). It has been reported that maximal exercise even leads to gastric ischemia (23; 29). As the local temperature of the gastrointestinal tract depends on its blood supply, this reduction in blood flow results in a substantial delay in temperature response.

Peak values of T_{pill} and T_{re} did not differ, but were substantially lower than T_{es}, sometimes more than 1°C. On a discrete time point, measurement differences of over 2°C were even possible. So it has to be recognized that there are substantial temperature differences across the body when a high rate of heat storage or heat loss is present. Viewing the temperature patterns (Figure 5.1), T_{pill} and T_{re} can actually be considered as

a low pass filtered version of T_{es}. As exercise duration increases and/or exercise intensity decreases, temperature patterns are expected to become gradually more similar.

In view of their similar response, T_{re} might be preferable to T_{pill} in situations where practical and comfort motives are less important. Temperature pills require considerable ingestion time and are possibly influenced by gastrointestinal motility (17). Besides pills are more expensive than rectal probes, are for some subjects difficult to swallow and can suffer from electromagnetic interference.

Conclusion

Radio telemetry is a useful tool for continuous core temperature determination in an operational setting. T_{pill} has been shown to reflect both T_{re} and T_{es} reliably when changes in core temperature are small and/or gradual and has been suggested to track T_{re} better than T_{es} at higher rates of change (6). This study proves that also during extreme rates of temperature change, induced by short maximal exercise in the heat, T_{pill} is representative of T_{re}. So in those conditions, T_{pill} provides a valuable indication of the thermal stress imposed on the vulnerable abdominal organs (3). Further, having quantified the extent of the deviation between T_{pill} and T_{es} (up to >1°C), this study confirms and strengthens the assumption that T_{pill} is of no use for evaluating central blood temperature when body temperatures change rapidly. As central blood temperature is thought to approximate the temperature perfusing the brain (30), brain temperature should not be monitored by T_{pill} in these conditions.

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Chapter 6

Effect of warm-up and precooling on pacing during a 15-km cycling time trial in the heat

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ABSTRACT

Purpose

It is still unclear whether precooling or warm-up should be preferred for endurance exercise in the heat. Therefore, we analyzed the effect of different preparation regimes on pacing during a 15-km cycling time trial in the heat.

Methods

Ten male subjects completed four 15-km time trials (30°C), preceded by different preparation regimes: 10 min cycling (WARM-UP), 30 min scalp cooling of which 10 min cycling (SC+WARM-UP), ice slurry ingestion (ICE) and ice slurry ingestion + 30 min scalp cooling (SC+ICE).

Results

No differences were observed in finish time and mean power output, although power output was lower for WARM-UP than for SC+ICE during km 13-14 (17 ± 16 and 19 ± 14 W, respectively) and than for ICE during km 13 (16 ± 16 W). Rectal temperature at the start of the time trial was lower for both ICE (~36.7°C) than both WARM-UP (~37.1°C) conditions and remained lower during the first part of the trial. Skin temperature and thermal sensation were lower at the start for SC+ICE.

Conclusion

In conclusion, the preparation regime providing the lowest body heat content and sensation of coolness at the start (SC+ICE) was most beneficial for pacing during the latter stages of the time trial, although overall performance did not differ.

INTRODUCTION

Generally, athletes will perform an active warm-up consisting of muscular exercise similar to the competitive performance to prepare for the upcoming exercise. Most beneficial physiological responses of a warm-up are associated with increased core and muscle temperature and include: accelerated $\dot{V}O_2$ kinetics (1), increased nerve conduction rate (2) and decreased muscle stiffness (3). Warming-up has proved to be beneficial for performance during exercises up to 5 min (4), but for longer durations the effects remain equivocal (5).

Although warming-up before exercise can have beneficial physiological effects, performing a warm-up will also elevate core body temperature. This is a major factor causing fatigue and reduced performance during endurance exercise in the heat (6; 7). One method to attenuate the detrimental effect of an elevated core temperature is precooling (8; 9). Precooling increases the heat storage capacity of the body and as a result, it reduces thermal strain and increases performance in endurance and intermittent sprint exercise (10; 11). Therefore, precooling can possibly prevent or delay the reduction in power output that is generally observed during prolonged aerobic exercise in the heat (9) and is suggested to be more beneficial for performance than a warm-up (7).

Several methods have been shown to be successful in cooling the body core and improving endurance exercise performance (10; 12), but few of these are suited for practical use. One method that does appear to be both effective and practically usable is ice slurry ingestion (11; 13; 14). It is effective in reducing core temperature, as the phase change of ice to water retracts extra heat from the body (15). Compared to liquid water ingestion, this leads to a more pronounced decrease in body core temperature, and therefore a greater increase in heat storage capacity (16). The lower core temperature associated with ice slurry ingestion can prevent or delay the reduction in central neural drive that is a major factor causing performance decrements in the heat (17).

Not only the lowering of the core temperature, but also a lower skin temperature and the perception of coolness could increase performance (13; 18). Recently, Schlader et al. (18) stated that thermal perception appears to be an important signal for the selection

and modulation of exercise intensity, possibly by affecting the motivation to continue exercise in the heat (19) and reducing the rating of perceived exertion (RPE). This RPE is generally accepted as an integrator of several physiological, psychological, and environmental signals and is important for the selection and modulation of work rate during self-paced exercise (20). A part of the body that is potentially suited for precooling the skin and increasing the sensation of coolness is the scalp. Although it has a limited surface area (combined with the neck ~8% of total body surface area), it is close to the thermosensitive region of the face and is easily accessible for cooling (21). Moreover, previous studies have showed that cooling of the head improves endurance cycling performance in the heat, which may be explained by a reduction of cardiovascular and thermoregulatory demands and an increased central motor drive (22). Recently, a new convective cooling method for reducing chemotherapy-induced hair loss has become available for clinical use. This method uses glycol-perfused caps to cool the skin of the scalp. By lowering the scalp skin temperature, these caps create a strong sensation of coolness. Also, cooling of the scalp might provide selective brain cooling (23) leading to maintenance of central neural drive during exercise in the heat (22). Both the sensation of coolness and possible selective brain cooling might translate into an RPE-mediated improvement in self-paced exercise performance, even when core temperatures are well below critical values associated with fatigue (24).

Although both a warm-up and precooling have proved to be beneficial for endurance exercise performance, it remains unclear which preparation regime should be preferred for relatively short self-paced endurance exercise in the heat. Furthermore, the additive effect of scalp cooling when the core body temperature is already increased by a warm-up remains unclear. Therefore, the main goal of this study is to investigate the effect of different preparation regimes (involving warm-up, ice slurry ingestion and scalp cooling) on pacing and performance during a 15-km cycling time trial in the heat. In view of the anticipatory regulation of exercise intensity, we expect 15 km to be sufficient to observe changes in pacing pattern as a result of the different preparation regimes (25). We hypothesize that a lower body heat content and sensation of coolness at the start will result in a more beneficial time trial pacing and performance.

MATERIALS AND METHODS

Subjects

Ten healthy and physically active male subjects with an age of 24 ± 5 years, height of 187 ± 7 cm and a weight of 77 ± 6 kg participated in this study. The subjects were recreational cyclists, familiar with cycle ergometer testing and trained 7 ± 3 hrs per week at the time of the study. Each subject was fully informed of the purposes, protocol, experimental procedures and any associated risks and benefits before giving their written consent to participate in all testing procedures. Subjects were requested to follow their usual diet and physical activities the last day before each trial. The study was approved by the Research and Ethics Committee of TNO, The Netherlands.

Overview

Subjects visited the lab five times. In the first meeting they were familiarized with the experimental set-up and distance (15 km) of the cycling time trial. During the familiarization session, in which the same protocol was used as in the experimental trials, no physiological parameters were measured. The four following sessions involved the 15-km cycling time trial in the heat (30°C, 50% RH) preceded by one of the different preparation regimes in a moderate climate (22°C): active warm-up by 10-min cycling (WARM-UP), scalp cooling + active warm-up by 10-min cycling (SC+WARM-UP), ice slurry ingestion (ICE), or scalp cooling + ice slurry ingestion (SC+ICE).

Interventions

In the precooling trials (ICE and SC+ICE), a decrease in body core temperature was created by ingestion of ice slurry with added syrup (containing approximately 6 g carbohydrates) for flavour. Subjects were instructed to ingest a total amount of 2 g ice slurry per kg body mass (BM) in 5 min to ensure a standardized ingestion rate. Pilot testing revealed that ingestion of this amount of ice slurry resulted in a T_{re} decrease of ~0.5°C and was well tolerated by the subjects. The ice slurry ingestion period was followed by 15 min of rest, allowing the ice slurry to adequately cool the body. Within the pre-warming trials (WARM-UP and SC+WARM-UP), the subjects cycled at a moderate power of 2 W/kg BM for 10 min. This intensity and duration was chosen to induce beneficial physiological responses associated with a common warm-up without creating

substantial fatigue that could limit subsequent time trial performance. Scalp cooling (SC) was accomplished by wearing a neoprene-covered silicone cooling cap (Paxman, Huddersfield, UK) for 30 min. After this period, stable scalp skin temperatures can be expected (26). When the ears of the subject were inside the cap or when a subject was bald, direct contact with the cooling cap was avoided using gauze swabs. The cap was connected to a cooling machine (Paxman cooler PScalpC-1, Paxman, Huddersfield, UK), which was turned on at least half an hour prior to the experiment to achieve a temperature of the coolant between -9°C and -10°C. All the interventions were carried out in a climatic chamber set at 22°C, after which subjects were transferred to the warm climatic chamber.

Protocol

Each session consisted of a 20-min habituation period in a 22°C climatic chamber (Weiss Enet, Tiel, The Netherlands) after which baseline body temperatures were determined. Then the intervention period started, which lasted 10, 20, or 30 min depending on the experimental condition (Figure 6.1). Subsequently, during a 5-min break, subjects were transferred to an adjacent 30°C, 50% relative humidity (RH) climatic chamber (Weiss Enet, Tiel, The Netherlands). This was followed by a short final preparation period of 3-min cycling at 120 W.

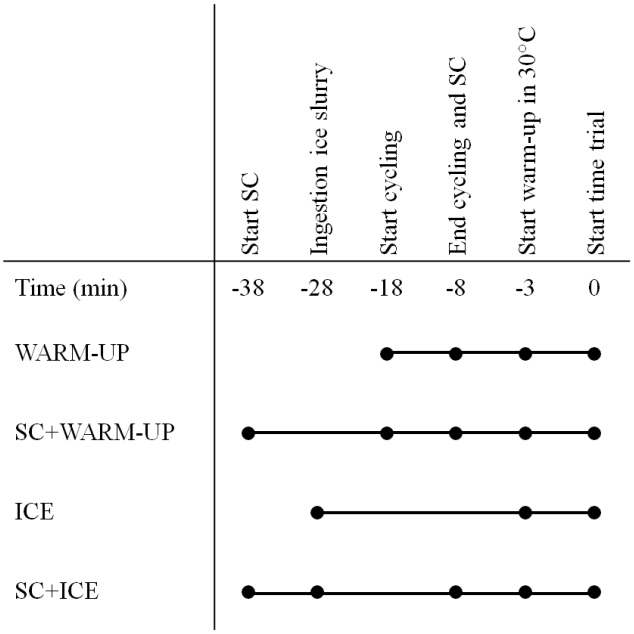

Figure 6.1. *Timescale for the four interventions. Black dots indicate the applied interventions.*

After the final preparation, subjects performed a 15-km self-paced time trial on a cycle ergometer (Lode, Groningen, The Netherlands). During the trial the subjects where blind to performance measures (power, cadence and heart rate), but were informed of completed distance each kilometre. The four time trials were allocated in a balanced order and all experimental sessions of one subject were performed on the same time of the day, separated by at least two days of recovery.

Measurements

During the time trials, power output was recorded (Lode Ergometry Manager, Lode, Groningen, The Netherlands) and averages per second were calculated. Knowing the amount of work per second and the total amount of work for the trial, the percentage of trial completion was determined for each second. As percentage of completion reflects distance, mean power output per kilometre could be determined.

Rectal temperature (T_{re}) was measured using a rectal thermistor (Yellow Springs Instruments 700 series, Yellow Springs, OH, USA). The rectal thermistor was calibrated before data acquisition in a thermal water bath (TLC 15, Tamson Instruments, Bleiswijk, The Netherlands) using a Pt100 digital temperature indicator (P650, Dostmann Electronic, Wertheim-Reicholzheim, Germany) with resistance temperature probe (PD-13/S, Tempcontrol, Voorburg, The Netherlands). This certified combination of calibration instruments had an accuracy of ±0.03°C. The rectal probe was inserted to a depth of 10 cm beyond the anal sphincter and was fixed to the lower back with tape. The sensor was attached to a custom-made data acquisition system (VU University, Amsterdam, The Netherlands), consisting of a data logger with a medical power supply and Labview software (National Instrument, Austin TX, USA). Sample frequency was set at 1 Hz.

Skin temperature was measured at eight locations (forehead, right scapula, left upper chest, right arm in upper location, left arm in lower location, left hand, right anterior thigh, left calf) with a sample frequency of 0.1 Hz using iButtons (DS1922L, Maxim Integrated Products Inc, Sunnyvale, CA, USA). A weighted average of the eight iButtons resulted in the mean skin temperature, as described by ISO 9886 (27). Mean body temperature (T_{body}) was calculated using the following equation: $T_{body} = \alpha * T_{re} + (1 - \alpha) * T_{sk}$ (Eq. 1), where α was set at 0.6 ($T_{sk} < 31.5$°C), 0.7 (31.5°C < $T_{sk} < 33$°C) or 0.8 ($T_{sk} > 33$°C) (28). Forehead temperature (T_{fh}), one of the eight measured skin temperatures, was also

analyzed separately to get more insight into the effect of scalp cooling on the skin temperature of the forehead.

Thermal perception and comfort were measured on a 9-point and 5-point scale, respectively (29), every 5 km during the 15-km time trial. Rating of perceived exertion (RPE) was measured every kilometre on a 20-point scale (30). Heart rate was measured using a Polar sport tester (Polar Electro, Finland) at 5-s intervals. Nude body mass of the subjects was determined on a weighing scale (Sartorius F300S, Göttingen, Germany) with resolution of one gram, directly before and after exercise.

Statistics

Statistical analysis was performed in SPSS statistical software (SPSS 17.0, SPSS Inc., Chicago, IL, USA). Experimental condition (WARM-UP, WARM+SC, ICE, SC+ICE) was the independent variable, whereas PO, T_{re}, T_{sk}, T_{body}, HR, RPE, TS, and TC were the dependent variables. Significance of effects over time was determined using two-way ANOVAs for repeated measurements, with two within-subject factors (experimental condition and distance completed). Post-hoc analyses used Bonferroni correction to adjust for multiple comparisons. One-way ANOVAs were used to determine the significance of effects of the experimental conditions at separate kilometres as well as on finish times, average PO, TS and TC. Statistical significance was set at the 5% level for each analysis. For differences in finish time, we additionally drew magnitude-based inferences using a 3-level scale of magnitude (positive difference, trivial, negative difference) (31). A trivial difference was defined as the 90% confidence interval of common day to day variation in cycling time trial performance, which amounts ± 30 s (32). Values are reported as mean ± SD.

RESULTS

Effect of preparation regimes

In Figure 6.2, temperature patterns before and during the time trial are shown. In this figure, the first two data points per condition represent the temperature before the intervention (pre-intervention: PI) and at the start of the time trial (0 km). Before the start of the intervention, no significant differences in T_{re}, T_{sk}, T_{body}, and T_{fh} were observed between the experimental conditions (p<0.05).

Precooling by ice slurry ingestion resulted in a cooler core at the start of the time trial than performing an active warm-up: T_{re} was significantly lower for SC+ICE (36.67 ± 0.18°C; p<0.01) and ICE (36.84 ± 0.31°C; p<0.05) than for SC+WARM-UP (37.12 ± 0.34°C) and WARM-UP (37.24 ± 0.27°C). There was a trend that T_{re} was more reduced in SC+ICE than in ICE (p=0.06).

The combination of ice slurry ingestion and scalp cooling (SC+ICE) led to a lower T_{sk} at the start of the time trial (32.58 ± 0.37°C) than the other conditions (ICE: 33.10 ± 0.83°C, SC+WARM-UP: 33.17 ± 0.66°C and WARM-UP: 33.57 ± 0.38°C; p<0.05 for all comparisons). Similarly, T_{body} at the start of the time trial was significantly lower in the SC+ICE condition compared to all other conditions (p<0.05). In addition, T_{body} was lower for ICE compared to WARM-UP (p=0.01).

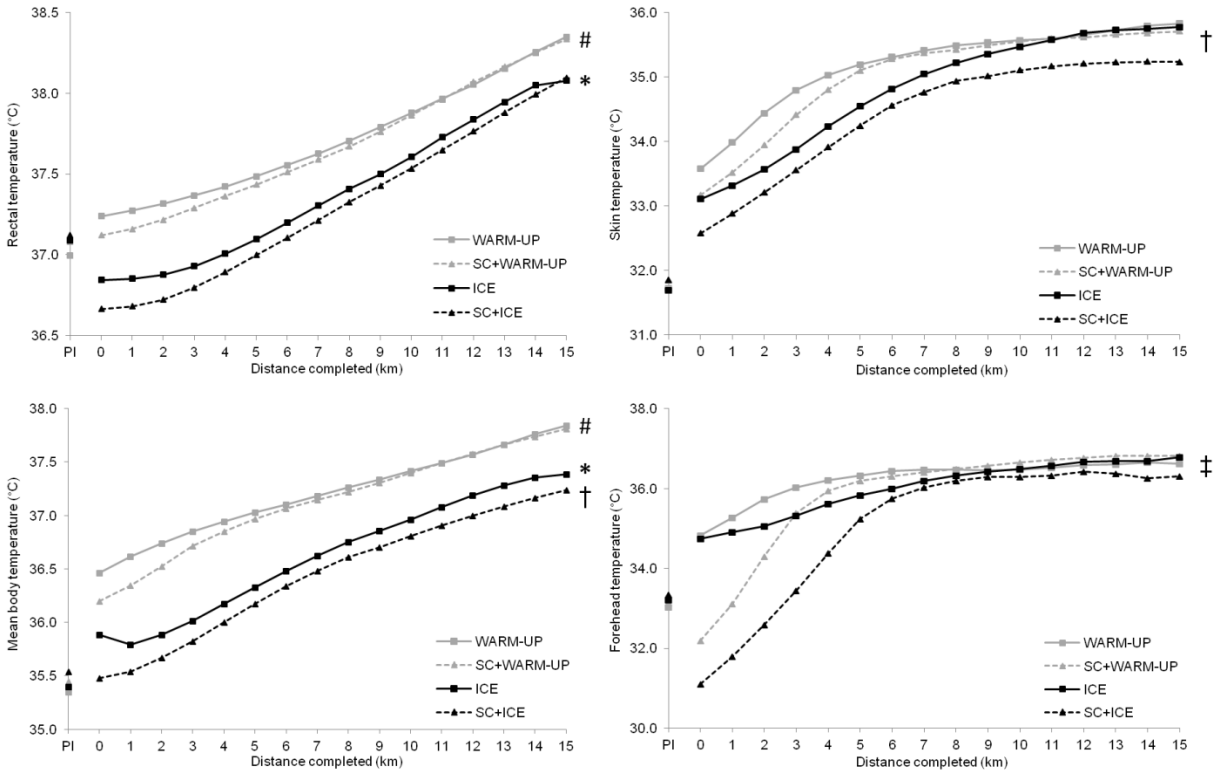

Figure 6.2. *Temperature patterns (T_{re}, T_{sk}, T_{body} and T_{fh}) pre-intervention (PI), at the start of the time trial (km 0) and averaged per km of the time trial. *Significant difference between SC+WARM-UP and SC+ICE (p<0.05). #Significant difference between SC+WARM-UP and ICE (p<0.05). †Significant difference between WARM-UP and SC+ICE (p<0.05). ‡Significant difference between SC+ICE and all the other conditions. For clarity of the figure, no error bars are displayed.*

Looking at forehead temperature separately, both SC+ICE and SC+WARM-UP decreased T_{fh} substantially (p<0.05) to 31.10 ± 1.79°C and 32.20 ± 1.79°C at the start of the time trial. This was significantly lower (~3.7°C and ~2.6°C, respectively; p<0.001) than the conditions without scalp cooling. For SC+WARM-UP, the lower T_{fh} did not result in a lower average T_{sk} as the active warm-up rescinded its effect on T_{sk}.

In line with the T_{sk} results, the TS score at the start of the time trial was lower for SC+ICE (0.0 ± 0.8) than for ICE (0.7 ± 0.7; p<0.05), SC+WARM-UP (0.8 ± 0.6; p<0.05) and WARM-UP (1.4 ± 0.7; p<0.001). However, no significant differences were observed in TC. HR at the start of the time trial in WARM-UP (125 ± 10 bpm) was higher than for the other conditions (SC+ICE: 111 ± 11 bpm, ICE: 114 ± 10 bpm, SC+WARM-UP: 119 ± 7 bpm; p<0.05 for all comparisons).

Time trial performance

In Figure 6.3, the average PO per kilometre of the time trial is shown. There was no overall effect between conditions (p=0.32). However, during km 13 and 14, PO for SC+ICE (231 ± 23 and 239 ± 24 W, respectively) was significantly higher than for WARM-UP (214 ± 28; p=0.01 and 219 ± 27 W; p=0.02, respectively). In addition power output for ICE (230 ± 32 W) was higher than for WARM-UP during km 13 (p=0.03).

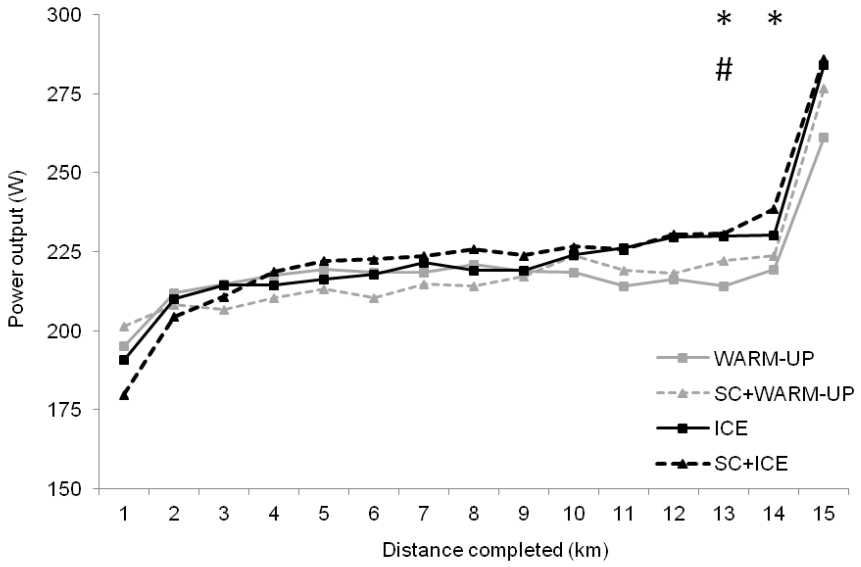

Figure 6.3. *Power output during the time trial. *Significant difference between WARM-UP and SC+ICE (p<0.05). #Significant difference between WARM-UP and ICE (p<0.05). For clarity of the figure, no error bars are displayed.*

This did not result in significant differences in finish time: SC+ICE: 29:07 ± 3:59 ICE: 29:19 ± 04:07 WARM-UP: 29:50 ± 4:07 and SC+WARM-UP: 29:58 ± 4:19 min (p=0.28). Also, when drawing magnitude based inferences (31) on the differences in finish time, the outcomes are unclear. Therefore, from the current data, no meaningful differences in finish time could be detected.

Physiological responses

In Figure 6.2, the temperature patterns during the time trial are shown. Regarding T_{re}, there was a significant overall difference between SC+WARM-UP and ICE (p<0.05) and between SC+WARM-UP and SC+ICE (p<0.05). Analyzed per kilometre, significant differences in T_{re} between the ice slurry and warming-up conditions were observed during the first half of the trial: SC+ICE and WARM-UP were different during km 1-9, SC+ICE and SC+WARM-UP during km 1-7, ICE and WARM-UP during km 1-6 and ICE and SC+WARM-UP during km 1-4.

During the time trial, T_{sk} was significantly lower for SC+ICE (34.25 ± 0.74°C) than for WARM-UP (35.29 ± 0.38°C; p=0.02). Per kilometre, differences were found between the ice slurry and active warm-up conditions during the first part of the trial. T_{sk} in SC+ICE was lower than WARM-UP and SC+WARM-UP during km 1-6. T_{sk} in ICE was lower than WARM-UP and SC+WARM-UP during km 1-4.

For T_{body}, differences in T_{re} and T_{sk} add up to overall differences of SC+ICE (36.50 ± 0.35°C) vs. both WARM-UP (37.25 ± 0.36°C; p=0.001) and SC+WARM-UP (37.19 ± 0.38°C; p=0.004) and of ICE (36.68 ± 0.43°C) vs. WARM-UP (37.25 ± 0.36°C; p<0.001). The differences with SC+ICE could be observed during each separate kilometre, differences of ICE vs. WARM-UP and SC+WARM-UP during km 1-11.

HR patterns deviated most at the initial stages of the trial. Overall, HR was significantly higher for WARM-UP (170 ± 9) than for SC+WARM-UP (165 ± 10; p=0.04). HR for WARM-UP was higher than for SC+ICE during the first 3 km of the time trial and higher than for ICE during the first 2 km.

Perceptual responses

No overall effect for RPE was observed, but at separate kilometres in the final stages of the time trial, some RPE scores deviated (Figure 6.4). During km 12, SC+ICE (15.8 ± 1.8) scores were significantly lower than WARM-UP (17.3 ± 1.6; p=0.03), while in km 14, both SC+ICE (17.3 ± 2.0) and SC+WARM-UP (17.2 ± 2.0) scores were lower than WARM-UP (18.7 ± 1.2; p=0.02 and p=0.04, respectively). No significant main effects for TS and TC were observed during the time trial (p=0.09 and p=0.23, respectively), nor were there any differences in these scores at separate measurement moments.

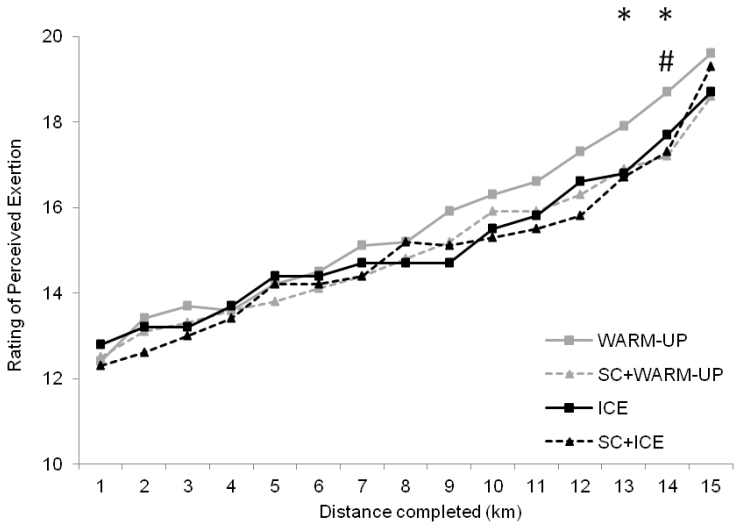

Figure 6.4. *Rating of perceived exertion during the time trial. *Significant difference between WARM-UP and SC+ICE (p<0.05). #Significant difference between WARM-UP and SC+WARM-UP (p<0.05). For clarity of the figure, no error bars are displayed.*

DISCUSSION

The aim of this study was to determine the effect of different preparation regimes on pacing and performance during a 15-km cycling time trial in the heat. The main outcome was that the lower the mean body temperature and sensation of coolness at the start of the time trial, the more beneficial it was for the pacing profile (higher power output) at the final stages. However, this did not result in a higher mean power and a faster finish time. Therefore, we largely have to reject our hypothesis.

Our results are only partly in accordance with Ihsan et al. (13) and Duffield et al. (9), who studied performance during a 40-km cycling time trial after precooling by ice slurry ingestion and cold water immersion, respectively. In line with the current data, both studies showed physiological differences in the first part of the trial and pacing adjustments at the final stages when physiological differences had largely disappeared. However, they also found an improvement in performance while we only observed a difference in power output during km 13 and 14, and no overall effect on performance. Improved performance in endurance exercise performance of >40 min after ice slurry ingestion has also been found in a study on running to exhaustion (14). The mentioned studies are difficult to compare directly with the current study due to methodological differences, but it becomes clear that exercise time is an important issue for obtaining performance benefits from precooling. Nevertheless, although we did not find performance benefits for this 15 km time trial, a higher work rate near the finish as a result of precooling may still be beneficial during tactical races.

Forehead temperature after scalp cooling was, not surprisingly, strongly reduced. This reduction decreased substantially from removal of the cooling cap and the influence on average skin temperature was small from the start of the time trial. The limited physiological effects of scalp cooling may be due to the insulative capacity of the skull. Mathematical modelling suggests that conductive heat loss through the skull surface or the upper airways is minimal (33). Furthermore, Pretorius et al. (34) showed that the head does not contribute more than the rest of the body to heat loss when surface area is taken into account. Although the physiological effects of scalp cooling are limited, this method may have beneficial effects by creating a sensation of coolness. At the start of the time trial, thermal sensation (TS) was lower for SC+ICE than for all the other conditions. Most likely, this was a result of the lower skin temperature caused by the scalp precooling and the ice slurry ingestion. This result is in line with Kato et al. (35) who showed that skin temperature is the most important signal for TS. Although TS was lower at the start of the time trial, the initial power output did not differ between conditions. The relationship between thermal perception and exercise regulation is still debated. Barwood et al. (36) found that inducing a feeling of coolness and increasing thermal comfort by putting on a menthol-sprayed jersey before the start of a 40-km cycling time trial in the heat did not influence the anticipatory selection of power output. On the contrary, Schlader et al. (18), observed that a more favourable thermal sensation and

thermal comfort due to menthol gel application on the face, did increase the total work completed during a fixed-RPE cycling protocol in a moderate ambient conditions. Our data confirm the results of Barwood et al. Possible explanations for the discrepancy in conclusions regarding the importance of these psychophysiological parameters could be the location of the intervention that elicited changes in thermal perception, the period that the psychophysiological parameters were affected and the differences in experimental protocol. In summary, it can be concluded that scalp precooling leads to a marginal decrease in thermal strain and a sensation of coolness at the start of the time trial. However, pacing and performance benefits during the time trial seem to be limited.

Another interesting observation in this study was the significant difference in RPE between WARM-UP and both SC+WARM-UP and SC+ICE during final stages of the time trial (Figure 6.4). The higher RPE for WARM-UP was accompanied by a significantly lower power output compared to SC+ICE. This finding is not in line with the concept that athletes adjust their work rate to prevent an excessive rise in RPE during exercise to maintain (thermal) homeostasis and to successfully complete the exercise bout (37). According to this theory, the increase in RPE should be similar across conditions since power output is adjusted to prevent differences in RPE between trials of the same length. The higher RPE towards the end of the trial in WARM-UP can possibly be explained by the fact that that subjects experience such an amount of strain in the beginning of the race that the hazard score (38) becomes too high. Down-regulating power output at this point of the time trial is not sufficient to get an RPE similar to the other conditions. However, it remains questionable whether the observed difference in RPE towards the end of exercise is caused by actual (psycho)physiological effects of the warm-up, especially since no effects on the end-spurt phenomenon were observed.

In addition to the performance enhancing effect of precooling, also the carbohydrate content of the ice slurry might have affected performance. The ~18 g syrup that was added to the ice slurry to facilitate ingestion contained approximately 6 g of carbohydrates, providing 100 kJ of (extra) energy to the exercising muscles. It is unlikely that this ingestion of carbohydrates before medium-duration aerobic exercise (<45 min) improves performance by extending body glycogen content, since depletion of already available energy stores is not expected to be a performance-limiting factor (39).

However, it has been reported that ingestion of carbohydrates can also improve performance by a non-metabolic pathways, like the activation of reward centres in the brain and increasing the excitability of the motor cortex (40). Since in our study the higher power output only became apparent in the final kilometres of the trial, it is not to be expected that the carbohydrates that were ingested more than 20 min before the start of exercise caused this increase in work rate.

PERSPECTIVES

In this study, we compared the effect of four preparation regimes with different combinations of active warm-up, ice slurry ingestion and scalp cooling on 15-km cycling time trial pacing in the heat. The preparation regime providing the lowest body heat content and sensation of coolness at the start of the time trial (ice slurry ingestion + scalp cooling) appeared to be most beneficial for pacing in the latter stages. Moreover, precooling the core with ice slurry ingestion seems to be more effective in accomplishing this benefit than increasing the sensation of coolness with scalp cooling. The observation that precooling provides benefits in the final stages of self-paced exercise in the heat is in accordance with previous studies (9; 13; 14). However, in contrast to these studies, overall performance in the current experiment was not significantly improved after precooling. Possible explanation for this could be the limited length of the time trial.

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Chapter 7

Effects of wind application on thermal perception and self-paced performance

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ABSTRACT

Purpose

Physiological and perceptual effects of wind cooling are often intertwined and have scarcely been studied in self-paced exercise. Therefore, we aimed to investigate 1)the independent perceptual effect of wind cooling and its impact on performance and 2)the responses to temporary wind cooling during self-paced exercise.

Methods

Ten male subjects completed four trials involving 15 min standardized incremental intensity cycling, followed by a 15 km self-paced cycling time trial. Three trials were performed in different climates inducing equivalent thermal strain: hot humid with wind (WIND) and warm humid (HUMID) and hot dry (DRY) without wind. The fourth trial (W3-12) was equal to HUMID, except that wind cooling was unexpectedly provided during km 3-12. Physiological, perceptual and performance parameters were measured.

Results

Subjects felt generally cooler during the WIND than the HUMID and DRY trials, despite similar heart rate, rectal and skin temperatures and a WBGT of ~4°C higher. The cooler thermal sensation was not reflected in differences in thermal comfort or performance. Comparing W3-12 to HUMID, skin temperature was 1.47 ± 0.43°C lower during the wind interval, leading to more favourable ratings of perceived exertion, thermal sensation and thermal comfort. Overall, power output was higher in the W3-12 than the HUMID-trial (256 ± 29 vs. 246 ± 22 W), leading to a 67 ± 48 s faster finish time.

Conclusion

In conclusion, during self-paced exercise in the heat, wind provides immediate and constant benefits in physiological strain, thermal perception and performance. Independent of physiological changes, wind still provides a greater sensation of coolness, but does not impact thermal comfort or performance anymore.

INTRODUCTION

For optimal performance in hot conditions, athletes need to determine their pacing strategy in such a way that exercise intensity is regulated to maximal level without collapsing prematurely due to heat exhaustion. However, the mechanisms underlying the regulation of exercise in the heat are still largely unknown. Current theories focus on the rating of perceived exertion (RPE) as the controlled parameter during pacing in the heat. It is proposed that numerous afferent signals are integrated into the RPE, mediating exercise pacing by an anticipatory adjustment in work load (1-6). Skin temperature is thought to be one of the main inputs for this regulatory mechanism (7-9).

Whole body wind application cools the skin by increasing evaporative and convective power (10; 11). As a result wind effectively lowers thermal strain and improves thermal perception (11-16). *Thermal strain* refers to the rise in body temperature and activation of thermoregulatory mechanisms in response to thermal stress (17), the heat load on the body. *Thermal perception* is the way in which a subject perceives his thermal status, here considered to cover both *thermal sensation* (TS; how warm/cold do you feel) and *thermal comfort* (TC; how comfortable do you experience these thermal conditions). As a result of its beneficial thermal effects, wind cooling has been shown to improve exercise endurance time. Head and whole body ventilation have been reported to improve cycling time to fatigue by >50% (11; 12).

It is unclear whether only thermal perception is relevant to obtain such beneficial effects, or that an actual change in skin temperature (and thus thermal strain) is required. Recently, two studies used menthol application to induce a sensation of coolness while keeping a similar thermal state, trying to separate thermal perception and thermal strain. Schlader et al. (18) concluded that thermal perception is capable of controlling thermoregulatory behaviour during exercise. On the contrary, Barwood et al. (19) reported that thermal perception did not drive exercise pacing during a 40 km cycling time trial. These opposing results do not allow any inference regarding the independent perceptual effect of wind on pacing and performance.

Further, the beneficial thermal effects of wind cooling (irrespective of its physiological or perceptual origin) and its consequences for performance, have largely been studied during fixed load exercise protocols (11; 12; 14). Few studies investigated how the effects of wind cooling on thermal perception, pacing and performance translate to self-paced exercise. Yet, self-paced exercise is most common in sports and operational settings. More insight into the relationships between wind, thermal perception and self-paced exercise responses could improve prediction of behaviour and optimize performance, well-being and safety guidelines.

Because of the deficient knowledge on the independent perceptual impact and the self-paced exercise responses of wind cooling, this study has two main purposes: 1) to separate physiological and perceptual climatic effects and investigate whether a windy climate with similar thermal strain but different thermal perception than climates without wind, leads to variations in pacing and performance and 2) to investigate which physiological, perceptual, pacing and performance benefits are provided by sudden whole body wind application during a self-paced cycling time trial.

To address the first purpose, we compared submaximal fixed-paced and maximal self-paced cycling in a hot-humid climate with wind (WIND), a warm-humid climate without wind (HUMID) and a hot-dry climate without wind (DRY) inducing equivalent thermal strain. Equivalent thermal strain could theoretically be accomplished by creating conditions with a similar wet bulb globe temperature (WBGT). The WBGT gives a single measure for thermal stress, including ambient temperature, relative humidity, radiation and wind and may determine whether exercise restrictions are warranted (20). However, there are indications that in practice the relationship between WBGT and thermal strain may not always be consistent, underestimating conditions in which evaporation is limited (20-23). Therefore, pilots using a standardized submaximal exercise protocol were accomplished to find conditions inducing a similar heart rate (HR) response. Because of the similar thermal strain, our first hypothesis was that all conditions would result in a similar thermal perception, pacing pattern and performance.

To address the second purpose, subjects cycled a fourth trial (W3-12) in which wind was unexpectedly turned on from km 3 to 12. The ambient temperature, humidity and protocol were equal to the HUMID condition, which functioned as control condition for this part of the study. We expected an instantaneous decrease in T_{sk} in the W3-12 condition compared to HUMID when turning on the wind. Based on previous research (11; 12; 24), our second hypothesis was that the lowered T_{sk} would decrease thermal strain and improve thermal perception, leading to an attenuation in RPE. Subsequently, work load was expected to be increased in order to maintain the planned RPE template.

METHODS

Subjects

Ten healthy male recreational cyclers volunteered to participate in this study. Subjects had an age of 24 ± 5 years, height of 186 ± 6 cm, body weight of 81 ± 5 kg and were active in sports for 10 ± 8 hours per week. Each subject was fully informed of the purposes, protocol, experimental procedures and any associated risks and benefits before giving their written consent to participate in all testing procedures. Subjects were requested to follow their usual diet and physical activities the last day before each trial. The study was approved by the Research and Ethics Committee of TNO (Soesterberg, The Netherlands).

Design

Subjects participated in one familiarization and four experimental sessions in different climatic conditions. All trials involved 15 min submaximal cycling at a standardized incremental intensity, followed by a maximal 15 km self-paced cycling time trial.

The familiarization session took place in moderate conditions of 18°C ambient temperature (T_{amb}) and 50% relative humidity (RH). This trial aimed to determine the right bicycle settings, get used to the entire experimental protocol and practice the 15 km time trial in order to get a feeling for the right pacing.

The four experimental sessions took place in strenuous conditions with different combinations of T_{amb}, RH and wind (Table 7.1). The climatic characteristics of condition 1-3 were established in various pilot sessions, which indicated that these microclimates induced a comparable physiological strain during standardized submaximal exercise, operationalized by HR response. The W3-12 condition was equal to the HUMID condition, except for the wind intervention. The wind tunnel was turned on unexpectedly at the 3 km mark and turned off unexpectedly at the 12 km mark. Subjects did not have any prior knowledge on this intervention. Wind speed was set at 4 m/s, as Saunders et al. (11) showed that most of the reduction in heat storage is realized in the 0-3 m/s range.

The submaximal part of the sessions aimed to determine thermal strain and thermal perception during standardized exercise, the maximal time trial dealt with self-paced performance. The experimental sessions were allocated in a balanced order and subjects were ignorant of the exact test conditions. Each subject performed his sessions on the same time of the day, separated by at least two days of recovery.

Table 7.1. *Climatic conditions of the experimental sessions.*

Condition	T_{amb}	RH	Wind
WIND	33°C	80%	4 m/s (entire session)
DRY	33°C	40%	-
HUMID	28°C	80%	-
W3-12	28°C	80%	4 m/s (time trial km 3-12)

Protocol

Just before a measurement session, participants redressed, attached a heart rate (HR) sensor and inserted a rectal probe themselves. Each session started with a 15-min habituation period in the climatic chamber (Weiss Enet, Tiel, The Netherlands), which comprised seated rest. During the habituation period, skin temperature (T_{sk}) sensors were attached and after taking place on the bicycle, the oxygen analysis apparatus was connected. This was followed by a 3-min rest measurement. Then the submaximal exercise was executed, consisting of 5x3 min cycling at 80-100-120-140-160 W. During a

5-min break the oxygen analysis equipment was removed and subjects prepared for the time trial. Subjects performed a 15 km self-paced time trial with the instruction to finish in the fastest possible time. During the trial subjects were informed of completed distance each kilometre. Finally subjects got 10 min of (active) recovery before ending the measurement. The entire experimental protocol in the climatic chamber, which is summarized in Table 7.2, took on average ~80 min. Subjects were allowed to drink water at libitum. Nude body mass and water bottle mass were measured just before and after the experimental protocol.

Table 7.2. *Experimental protocol.*

Time (min)	Activity	Intensity
15	Habituation	
3	Rest measurement	
15 (5x3)	Submaximal test	80-160 W
5	Break	
Variable	15 km time trial	Maximal
10	Recovery	

Measurements

Exercise was performed on a Lode Excalibur bicycle ergometer, using Lode Ergometry Manager (Lode, Groningen, The Netherlands) to record power output (PO) during the time trial. The bicycle ergometer was placed in a wind tunnel (DCTLL 850-8, Ziehl-Abegg, Künzelsau, Germany). Wind speed was measured with a flow meter (LV110, Kimo Instruments, France). The WBGT was measured with a heat stress monitor (QUESTEMP°36, Quest Technologies, WI, USA) just before the exercise session, during the break and just after the time trial, after which a single average session value was calculated. Heart rate (HR) was measured using a Polar sport tester (Polar Electro, Finland) at 5 s intervals.

Rectal temperature (T_{re}) was measured using a rectal thermistor (Yellow Springs Instruments 400 series, Yellow Springs, OH, USA). The rectal thermistor was calibrated before data acquisition in a thermal water bath (TLC 15, Tamson Instruments, Bleiswijk,

The Netherlands) using a Pt100 digital temperature indicator (P650, Dostmann Electronic, Wertheim-Reicholzheim, Germany) with resistance temperature probe (PD-13/S, Tempcontrol, Voorburg, The Netherlands). This certified combination of calibration instruments had an accuracy of ± 0.03°C. The rectal probe was inserted to a depth of 10 cm beyond the anal sphincter and the end was fixed to the lower back with tape. The sensor was attached to a custom-made data acquisition system (VU University Amsterdam, The Netherlands), consisting of a data logger with a medical power supply and Labview software (National Instrument, Austin TX, USA). Sample frequency was set at 1 Hz.

T_{sk} was measured at eight locations with a sample frequency of 0.1 Hz using iButtons (DS1922L, Maxim Integrated Products Inc, Sunnyvale, CA, USA). A weighted average of the eight iButtons resulted in the mean T_{sk}, as described by ISO 9886 (25).

TS and TC were measured on a 9-point and 5-point scale respectively (26), just before the submaximal and maximal exercise tests, at the end of each submaximal exercise step and at every 5 km mark during the 15-km time trial. RPE was measured at the end of each submaximal exercise step and at every kilometre of the time trial on a 20-point scale (27). Nude body mass (BM) and water bottle mass was determined on a weighing scale (Sartorius F300S, Göttingen, Germany) with resolution of one gram, directly before and after exercise. From these weightings, sweat rate and fluid ingestion could be determined.

Data analysis

Average HR and body temperature values were calculated across the final minute of the rest measurement (rest) and each fixed-paced exercise step, as well as across the final 30 s before the start of the time trial (start) and the final 30 s of the recovery period (rec). Regarding the time trial, the percentage of trial completion was determined for each sample dividing the amount of work performed at that moment by the total amount of work for the trial. As percentage of completion reflects distance, mean PO, HR, respiratory values and body temperatures per kilometre could be determined.

Statistical analysis was performed using SPSS (SPSS 17.0, SPSS Inc., Chicago, IL, USA) and Statistica (version 10, StatSoft Inc., Tulsa, OK, USA) statistical software. In a first analysis, the experimental conditions WIND, DRY AND HUMID were compared to cover our first research question. A second analysis compared the conditions HUMID and W3-12 to cover our second research question.

One-way ANOVAs were used to evaluate effects of experimental condition at separate data points (rest, each fixed-paced exercise step, start, each time trial kilometre and/or rec), as well as to determine significance of overall effects for fluid parameters and finish time. Further, overall differences over time were determined for HR, T_{re}, T_{sk}, RPE and PO during both the fixed interval (rest and fixed-paced exercise) and the self-paced interval (time trial), using two-way ANOVAs for repeated measurements with two within-subject factors (experimental condition and trial phase). For PO, interaction with time was evaluated to detect any pacing differences.

For the analyses including three conditions, post-hoc calculations were applied using Bonferroni correction to adjust for multiple comparisons. Statistical significance was set at the 5% level for each analysis. Values are reported as mean ± standard deviation (SD).

RESULTS

In each substudy (climate comparison and wind cooling), two subject had to be excluded due to physical issues, preventing a valid comparison of the trials. As a result, all analyses have been done on eight subjects, seven of which are included in both substudies.

The temperature and relative humidity settings of the climatic chamber were very close to the measured values. During all experimental conditions, T_{amb} was on average 0.13 ± 0.13°C and RH 2.28 ± 1.28% higher than the set value. This resulted in the following WBGT values: WIND 30.7 ± 0.16°C; DRY 26.4 ± 0.15°C; HUMID 26.5 ± 0.08°C; W3-12 26.0 ± 0.04°C and 26.4 ± 0.07°C with and without wind respectively.

Climate comparison (WIND vs. DRY vs. HUMID)

Heart rate and thermal responses (Figure 7.1)

In accordance with our purpose to compare 3 climates inducing similar physiological responses, there were no differences in HR and T_{re} between WIND, DRY and HUMID during the fixed interval of the protocol. However, across this entire interval T_{sk} in WIND and DRY was higher than in HUMID (ΔT_{sk}: 0.70 ± 0.35°C and 0.91 ± 0.36°C respectively; $p<0.01$). During the time trial, HR, T_{re} and T_{sk} did not show any overall effects, but there were slight HR and T_{sk} differences during some separate kilometres.

Perceptual responses (Figure 7.2)

WIND resulted in a more favourable TS score than DRY and HUMID at the higher intensities of the fixed-exercise protocol, as well as just before the start of the time trial ($p<0.01$). TS for WIND remained more favourable than HUMID the entire time trial (ΔTS 0.9 ± 0.5; $p<0.01$), whereas WIND felt only cooler than DRY at 10 km (ΔTS 0.9 ± 0.8; $p<0.01$). TC did not differ during the fixed-exercise test or time trial, although HUMID tended to be less comfortable than DRY at 160 W (ΔTC 0.7 ± 0.7; $p=0.05$). RPE did not show any differences between conditions over time nor at separate measurement points during the entire trial.

Performance responses (Figure 7.3, Table 7.3)

In Figure 7.3 the pacing profile of the 15 km time trial is shown. There were no differences in PO between conditions across the entire time trial ($p=0.24$), although PO was higher in the DRY condition during a few separate kilometres ($p<0.05$). Logically, finish times did not differ either.

Fluid balance (Table 7.3)

Sweat rate during the HUMID condition was lower than during DRY (Δsweat rate: 0.12 ± 0.08 L/h; $p<0.05$) but was just not significantly different from WIND ($p=0.052$). As fluid ingestion did not show any differences between conditions, percentage BM loss was also lower for HUMID than for DRY (ΔBM loss: 0.19 ± 0.23%; $p=0.04$), but not different between HUMID and WIND ($p=0.20$).

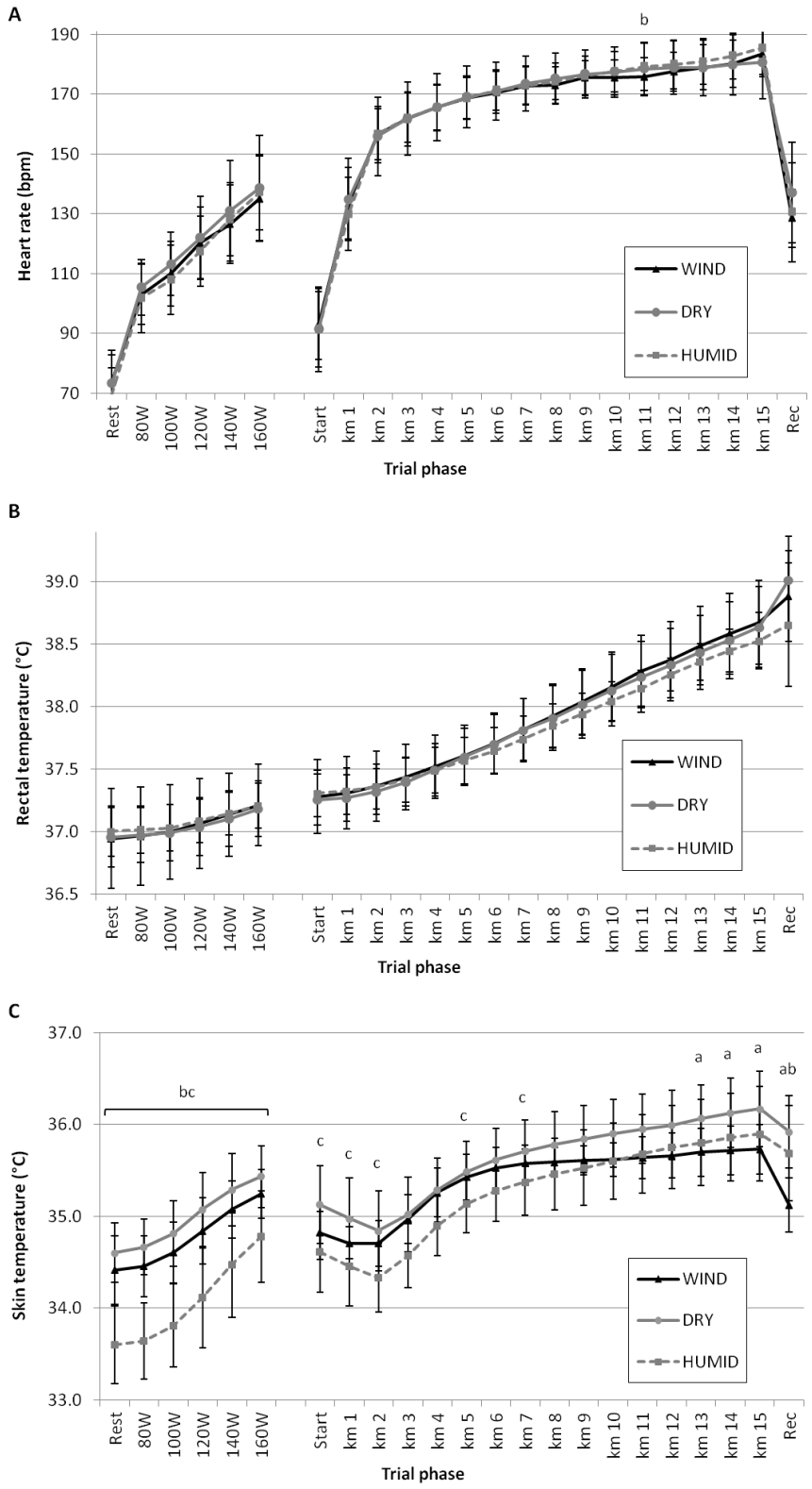

Figure 7.1. *Average patterns of heart rate* ***(A)****, rectal temperature* ***(B)*** *and skin temperature (****C****) during the experimental protocol of rest, fixed paced submaximal exercise, 15 km time trial and recovery (rec). Error bars indicate SD. The depicted conditions include WIND (33°C, 80% RH, 4 m/s wind), DRY (33°C, 40% RH, no wind) and HUMID (28°C, 80% RH, no wind). a: WIND significantly different from DRY; b: WIND significantly different from HUMID; c: DRY significantly different from HUMID.*

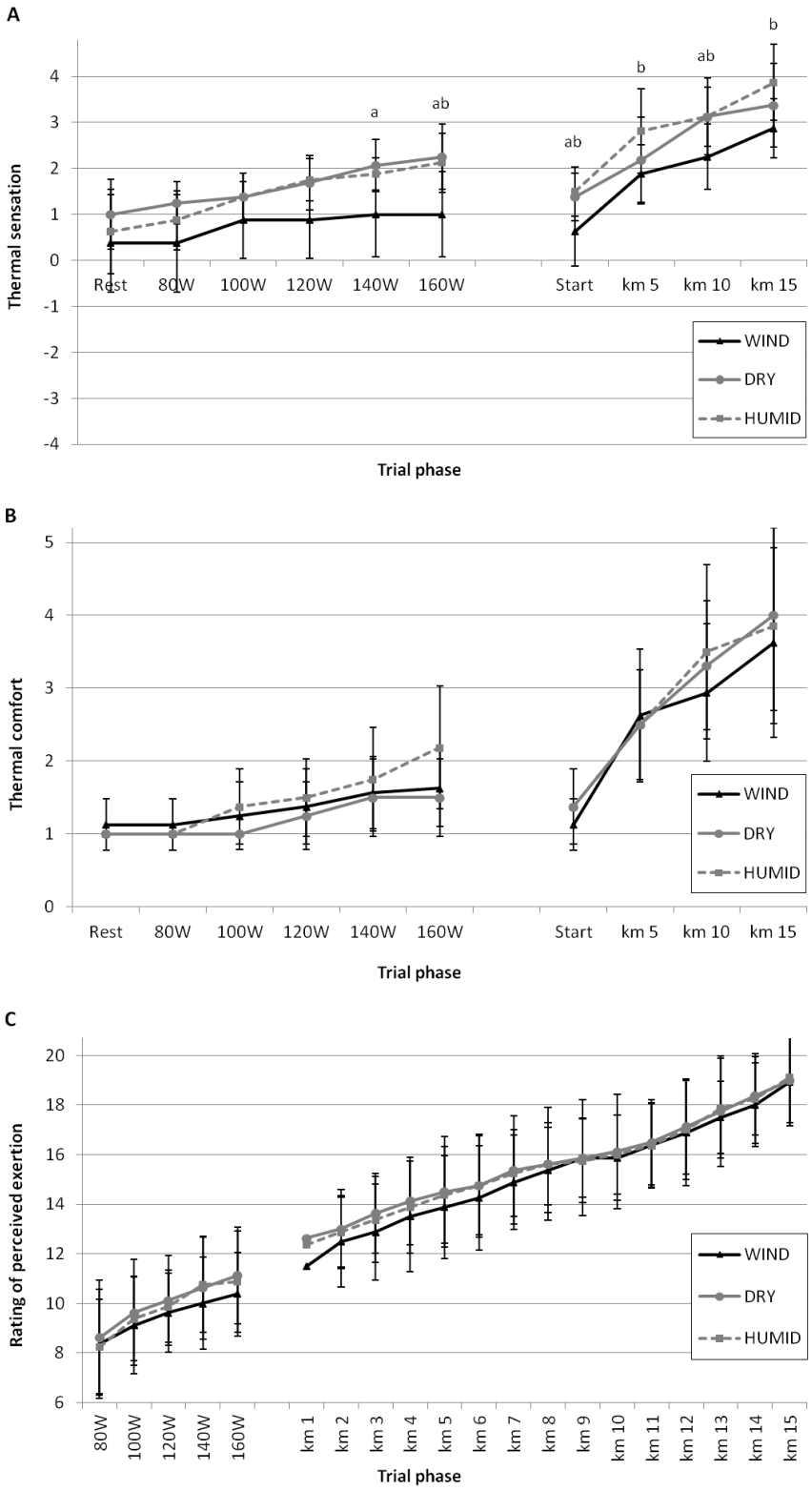

Figure 7.2. *Average patterns of thermal sensation* ***(A)****, thermal comfort* ***(B)*** *and rating of perceived exertion (****C)*** *during the experimental protocol of rest, fixed paced submaximal exercise, 15 km time trial and recovery (rec). Error bars indicate SD. The depicted conditions include WIND (33°C, 80% RH, 4 m/s wind), DRY (33°C, 40% RH, no wind) and HUMID (28°C, 80% RH, no wind). a: WIND significantly different from DRY; b: WIND significantly different from HUMID.*

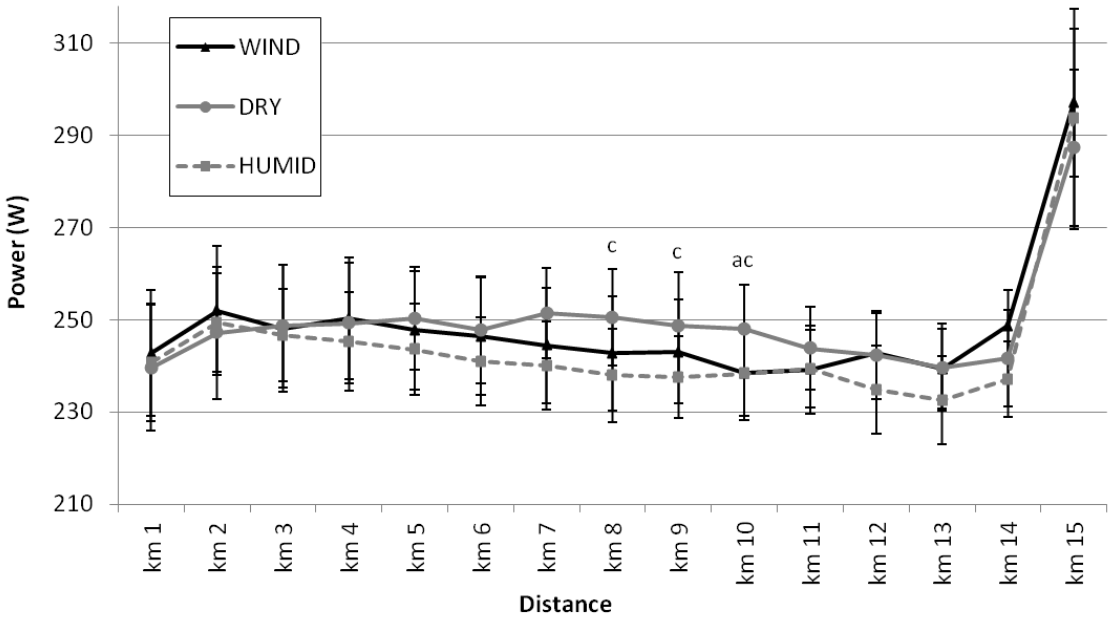

Figure 7.3. *Average patterns of power output during the 15 km time trial. Error bars indicate SEM. The depicted conditions include WIND (33°C, 80% RH, 4 m/s wind), DRY (33°C, 40% RH, no wind) and HUMID (28°C, 80% RH, no wind). a: WIND significantly different from DRY; c: DRY significantly different from HUMID.*

Table 7.3. *Mean power output (PO), finish time, sweat rate and BM loss ± SD.*

Condition	Mean PO (W)	Finish time (min:s)	Sweat rate (L/h)	BM loss (%)
WIND	249 ± 31	26:09 ± 3:26	0.87 ± 0.19	0.50 ± 0.36
DRY	248 ± 30	26:05 ± 3:37	0.90 ± 0.17	0.53 ± 0.41
HUMID	244 ± 26	26:37 ± 3:10	0.79 ± 0.25*	0.29 ± 0.44*

**Significantly different from DRY*

Wind cooling (HUMID vs. W3-12)

Heart rate and thermal responses (Figure 7.4)

As expected in equal conditions, no significant differences were observed before the start and during the first 3 km of the time trial. Regarding the wind interval, HR did not show an effect over time (p=0.08), but was lower for W3-12 during km 9, 10 and 11 (mean ΔHR: 4.6 ± 4.4 bpm, p<0.05). T_{re} was similar for both conditions across the wind interval and during each separate kilometre. However, wind application induced a clear difference in T_{sk}, with a main effect across the wind interval (ΔT_{sk}: 1.47 ± 0.43°C; p<0.01). T_{sk} also differed at each separate kilometre from km 4 to 15, being maximally 2.00 ± 0.57°C lower for W3-12 during km 12 (p<0.01).

Perceptual responses (Figure 7.5)

Also for TS, TC and RPE, no differences were observed before the start of the time trial. But during the time trial, the W3-12 condition resulted in a more favourable TS and TC at both measurement points (mean ΔTS: 1.8 ± 1.3; p<0.01 and mean ΔTC: 0.8 ± 0.7; p<0.01), with TS still being rated slightly better at 15 km. RPE showed a main effect across the wind interval, W3-12 being 0.7 ± 0.6 lower (p<0.05). At separate kilometres, RPE was lower in km 8 to 11, with the largest difference (1.0) at km 10.

Performance responses (Figure 7.6, Table 7.4)

Across the entire trial, subjects had a higher PO in the W3-12 than the HUMID trial (256 ± 29 vs. 246 ± 22 W; p<0.01), leading to a 67 ± 48 s faster finish time. There was no effect across the first three km interval (ΔPO: 4 ± 7 W, p=0.10), but there was during the wind interval (ΔPO: 13 ± 9 W, p<0.01). Per kilometre, PO differences between conditions were detected in km 4 to 14. These differences were largest in km 12 and 13 (20 W).

Fluid balance (Table 7.4)

There were no differences between conditions regarding sweat rate, fluid ingestion or BM loss.

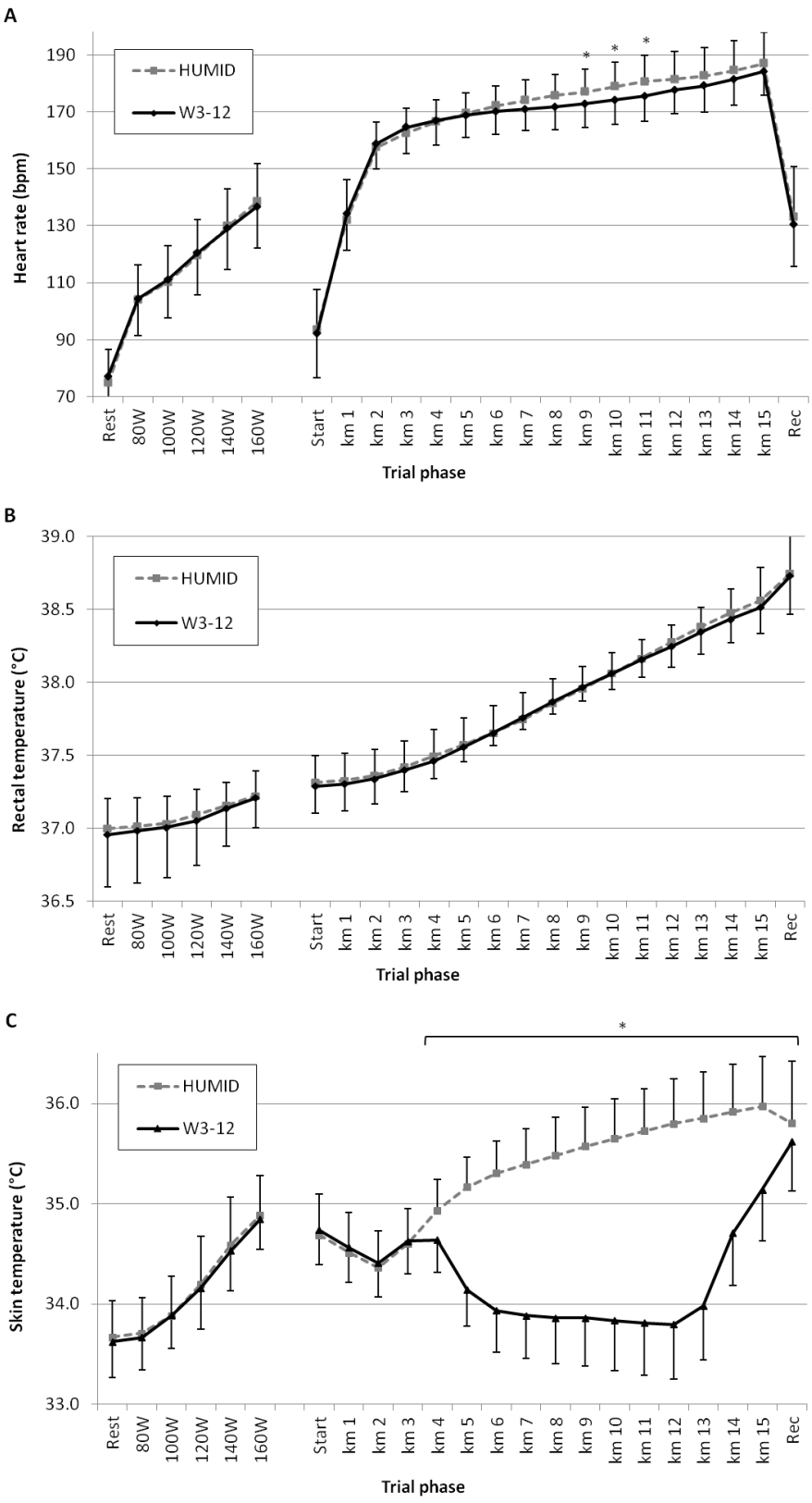

Figure 7.4. *Average patterns of heart rate* ***(A)****, rectal temperature* ***(B)*** *and skin temperature (****C****) during the experimental protocol of rest, fixed paced submaximal exercise, 15 km time trial and recovery (rec). Error bars indicate SD. The depicted conditions include HUMID (28°C, 80% RH, no wind) and W3-12 (28°C, 80% RH, 4 m/s wind from 3-12 km). * denotes a significant difference at separate measurement points.*

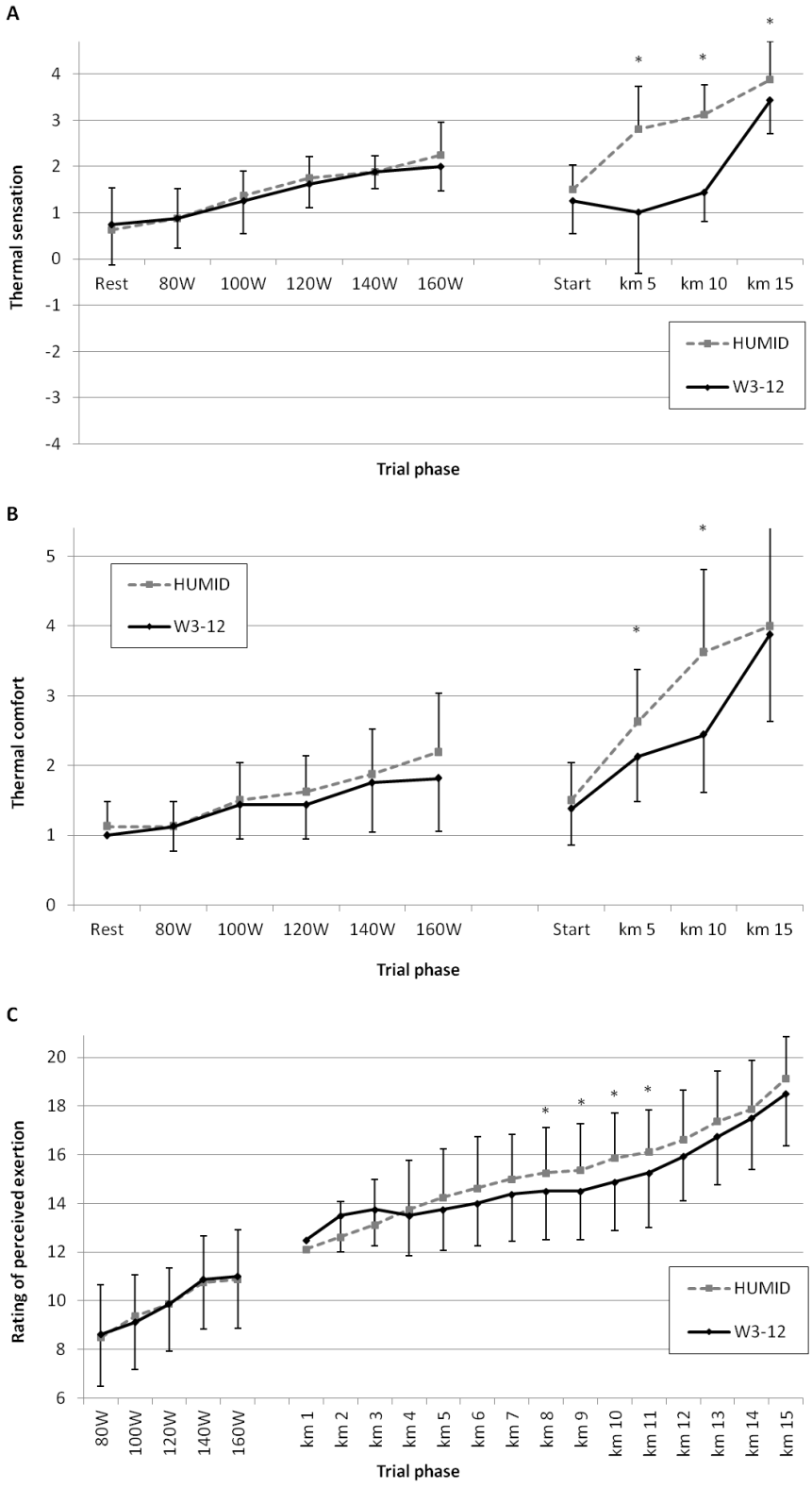

Figure 7.5. *Average patterns of thermal sensation* ***(A)****, thermal comfort* ***(B)*** *and rating of perceived exertion (****C****) during the experimental protocol of rest, fixed paced submaximal exercise, 15 km time trial and recovery (rec). The depicted conditions include HUMID (28°C, 80% RH, no wind) and W3-12 (28°C, 80% RH, 4 m/s wind from 3-12 km). * denotes a significant difference.*

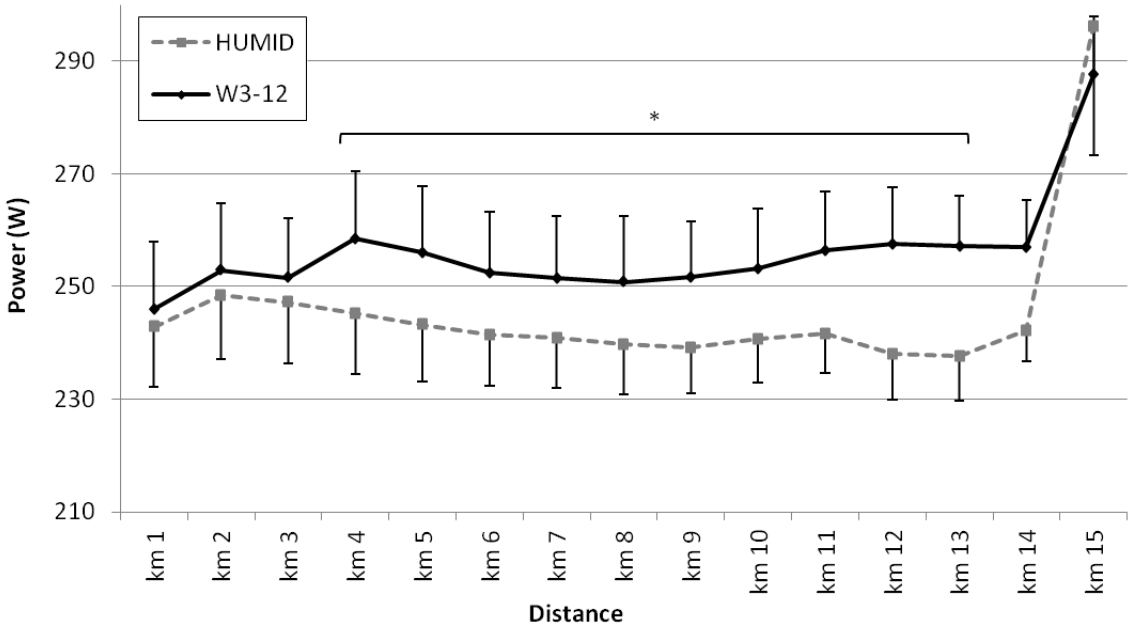

Figure 7.6. *Average patterns of power output during the 15 km time trial. Error bars indicate SEM. The depicted conditions include HUMID (28°C, 80% RH, no wind) and W3-12 (28°C, 80% RH, 4 m/s wind from 3-12 km). * denotes a significant difference at separate kilometres.*

Table 7.4. *Mean power output (PO), finish time, sweat rate and BM loss ± SD.*

Condition	Mean PO (W)	Finish time (min:s)	Sweat rate (L/h)	BM loss (%)
HUMID	246 ± 22	26:22 ± 2:40	0.77 ± 0.27	0.26 ± 0.44
W3-12	256 ± 29*	25:15 ± 3:11*	0.75 ± 0.20	0.27 ± 0.30

**Significantly different from HUMID*

DISCUSSION

The main purpose of this study was to investigate the effects of wind application on thermal perception, pacing and performance during exercise in the heat. We can largely accept our first hypothesis: although we found that a climate with wind felt cooler, it was not more comfortable than windless climates that induced a comparable thermal strain nor did it change perceived exertion, pacing and performance. This suggests that thermal sensation itself does not affect exercise performance. Our second hypothesis was confirmed: when wind temporarily reduced thermal stress during a time trial interval, it provided immediate benefits in T_{sk}, thermal perception and RPE, leading to an increased PO. These benefits were maintained throughout the race without imposing a higher

thermal strain. It is proposed that deviations in the RPE pattern were followed by adjustments in PO.

Climate comparison

All climates resulted in similar HR and T_{re} responses during rest and standardized submaximal exercise. Therefore, the intention to impose climates with a comparable thermal stress was successful. Nevertheless, T_{sk} was significantly lower (~0.5-0.9°C) in the HUMID than the other conditions. As the lower T_{sk} is not reflected in HR and T_{re}, it is presumed to have limited meaning regarding thermal strain. Increased skin wettedness in combination with lower T_{amb} may explain the lower T_{sk} measurements. Similar HR and T_{re}, but lower T_{sk} responses in humid vs. dry conditions at equivalent WBGT (29°C) have been observed before (28).

Previous research showed that thermal perception and exercise performance are related to microclimatic conditions, including T_{amb}, wind speed and RH (12; 16; 29; 30). However, climatic factors have scarcely been balanced at equivalent thermal stress to enable the separation of physiological and psychological effects. Even though physiological responses are similar, the perception of strain may differ. In this study, it appears that wind has a beneficial effect on TS, independent of differences in body temperatures and HR. In contrast to previous reports using wind cooling (24), this finding indicates that TS is not necessarily dependent on T_{sk}. Apparently the air movement itself is sufficient to trigger cold receptors in the skin.

TC displayed another pattern than TS, with no differences between conditions up to 140 W. So the more favourable TS of the WIND condition did not translate into a more favourable TC. Possibly, the 5-point scale was not sufficiently sensitive, with only one score on the 'positive' side (i.e. comfortable). On the other hand, a similar disagreement between TS and TC was visible during the time trial when ratings were spread over the entire scale. Further, TC is reported to depend on both core and skin temperature (31). The similar core temperatures and lack of large T_{sk} differences, apparently led to similar TC ratings. Yet, note that HUMID tended to be judged less comfortable at 160 W. As TC is determined by skin wettedness above a certain threshold (15), this likely explains the higher TC rating at 160 W. Summarizing, wind and humidity are able to induce perceptual effects independent of absolute T_{sk}.

During the time trial, TS in the WIND condition continued to be lower, but all other physiological and perceptual measures were comparable. Pacing and performance did not show substantial differences either, so self-paced performance appeared not to be driven by TS. This agrees with the conclusion of Barwood et al. (19) that TS, manipulated by menthol spray, is not a driver of early pacing during a 40 km time trial. However, the similar conclusion they drew on TC cannot be confirmed, as TC was not affected in our time trial.

With a high water vapor pressure and a lack of wind, HUMID was the most difficult condition to evaporate sweat. The resulting increase in skin wettedness apparently attenuated the drive to sweat during the trial, leading to a more than 10% lower sweat rate. It has been reported that sweat loss can even be one-third less than in humid than in dry climates with similar WBGT (32). As drinking behaviour did not differ between conditions, this indicates that thermally comparable conditions that facilitate evaporation by low humidity and/or wind, seem to bear more risk for dehydration than humid low-wind conditions.

Wind cooling

Unexpected wind application during a time trial in warm humid conditions substantially reduced thermal strain, despite a nearly stable WBGT value. Wind instantly induced a decrease in T_{sk} and an improvement in thermal perception and RPE. This resulted in a direct increase in PO, although it cannot be excluded that a psychological reflex, increasing PO to maintain speed when facing head wind, also plays a role. Wind cooling fully compensated for the rise in T_{sk} during the HUMID condition, leading to a 2°C lower T_{sk} in the wind trial. It confirms the capacity of wind as a cooling strategy, increasing evaporative power (10; 13).

The higher PO was maintained throughout the wind interval at similar T_{re} and at similar or lower HR values than during the HUMID-trial, reflecting the lower thermal stress imposed on subjects during the wind trial. The consistency in T_{re} response despite a climate induced performance difference, is in agreement with Tatterson et al. (30) who studied 30 km self-paced cycling in 23°C and 32°C. It suggests an important role for core temperature in regulating PO. Tucker et al. (4) postulated that not absolute temperature, but rate of heat storage mediates an anticipatory adjustment in exercise intensity. As

absolute T_{re} was relatively low, but rate of heat storage substantial, the current data support this notion. It is generally accepted that hyperthermic fatigue has a central origin (33; 34), so it could be speculated that the brain senses the rate of heat storage and consequently adjusts the drive to exercise by neurophysiological mechanisms (30).

Obviously, wind improves the rating of TS and TC during fixed paced exercise (12; 14; 16). This study showed that also during a self-paced time trial, subjects felt cooler, more comfortable and slightly less exerted when wind was present, despite a higher PO and similar T_{re}. The wind intervention shows that a change in T_{sk} is clearly related to a similar change in TS. So although the first part of this study showed that TS is not necessarily dependent on T_{sk}, a change in T_{sk} does affect TS. This is in line with multiple studies indicating that TS is predominantly determined by T_{sk} (24). Again, the TC pattern seems to agree with the notion that TC depends on both skin and core temperature (24; 31). However, the observation that TC habituates to a decrease in T_{sk}, following the dynamic behaviour of the cutaneous cold receptors (24), could not be confirmed.

The RPE pattern of the wind trial is partly in accordance with the theory stating that RPE mediates exercise pacing (3). The initial change in RPE pattern at the fourth kilometre was counterbalanced by an instant rise in PO. However, the slight RPE deviation in the following kilometres was not reflected in PO until the 10^{th} km. It suggests that subjects are restrained to prematurely deviate from their original pacing template. They seem to 'save' some energy until a certain threshold in RPE deviation and/or distance is passed. This threshold might be represented by the hazard score, which is the product of RPE and fraction of the trial remaining (35). In addition, the conservative RPE pattern in the wind trial may also be explained by the core temperature, which increased at a similar rate as in the control condition and may have inhibited the central drive to accelerate early in the trial. Further, subjects may have feared for more unexpected interventions, and may have limited their PO likewise.

Notably, turning off the wind at 12 km did not result in substantial pacing adjustments, although all wind-induced benefits on physiological and perceptual measures were nearly or completely abolished during these last 3 km. Probably, time to finish was sufficiently short at that moment to ignore these adverse signals. Further, both conditions showed the well-known end spurt phenomenon to a similar extent. At last,

moderate wind cooling during the middle 60% of the race resulted in a significant 67 s time benefit, emphasizing the potential of wind cooling for performance improvement.

The improved performance results of the W3-12 condition are in line with previous studies precooling the skin independently by whole body immersion (36). It suggests that a lower T_{sk} and the accompanying benefits for thermal strain and perception improve self-paced performance in the heat. However, it cannot be concluded from our study whether T_{sk} or TC is most influential in the regulation of pacing. Schlader et al. (9; 18) concluded that thermal (wind) and non-thermal (menthol application) face cooling had a similar performance enhancing effect in a clamped RPE protocol, suggesting TC regulates pacing independent of T_{sk}. It should be investigated whether improving TC without changing T_{sk} during a self-paced time trial will result in similar performance improvements.

WBGT

The WBGT value required to induce comparable physiological responses was >4°C higher in the WIND condition than in the DRY and HUMID condition. In addition, the W3-12 condition was only 0.5°C WBGT lower than HUMID, while inducing more favourable responses. The observation that a single WBGT value may lead to different physiological responses dependent on the actual temperature, wind speed and humidity, is in line with the statement of Budd (20) that “conditions with similar levels of WBGT may be far more stressful when the evaporation of sweat is restricted (by high humidity or low air movement) than when evaporation is free”.

The issue that thermal strain increases disproportionately at low wind speeds has already been observed a long time ago. Clothed men exercising and resting for several hours increased time to exhaustion significantly when some wind (0.8 m/s) was applied, apparently because the lack of wind reduced evaporative capacity to one-third of the former value (37). Occupational experience resulted in recommendations to separate WBGT limits for air velocities above 1.6 m/s , differing about 3°C (23). ISO 7243 (38) partly followed these recommendations, in establishing separate limits at moderately high and high intensity work (differing 1°C and 2°C, respectively). In view of our results, these differences in limits are still quite conservative for high intensity self-paced

performance. In any way, WBGT values should be treated with caution when wind is present and adjusted limits are warranted.

Literature regarding the extra stress of humid conditions at equivalent WBGT is unclear. During a 2 h fixed paced walking test, a higher strain has been observed for high vs. low humidity at WBGT 31.7°C, but differences were much smaller at WBGT 29.4°C (21). Wright et al. (28) did not observe physiological or perceptual differences between 10% and 60% RH at WBGT 29°C. The current study does not show a clear difference between HUMID and DRY conditions at similar WBGT either. Possibly, humid conditions only impose more thermal stress than dry conditions at very high equivalent WBGT values (>30°C). In that case, separate limits might be required.

Conclusions

In conclusion, this study shows that wind is an effective tool to provide immediate and constant benefits in thermal strain, thermal perception and performance during self-paced exercise in the heat. When physiological strain is kept equivalent, wind application still improves thermal sensation, but not thermal comfort. The difference in thermal sensation alone does not lead to improvements in pacing strategy or performance. Apparently, decrements in T_{sk} and/or improvements in TC are required for that purpose. Finally, the considerable impact of wind cooling should be acknowledged in judging WBGT values.

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Chapter 8

Heat strain and performance in ice hockey goalies

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ABSTRACT

Purpose

High metabolic activity combined with reduced heat loss in protective equipment predisposes ice hockey goalies to heat strain. This could have a negative impact on their performance. Therefore, we explored the level of heat strain experienced by ice hockey goalies during practice and its association with performance.

Methods

Six ice hockey goalies were tested on gastrointestinal (T_{gi}) and skin (T_{sk}) temperature, heart rate and fluid loss during a regular practice (~60 min, 11.9°C, 62% relative humidity). A vigilance and shoot-out task pre- and post-practice aimed to reveal any association with cognitive function and performance.

Results

Heart rate averaged 141 ± 14 bpm (maximum 173 ± 12 bpm) during practice. T_{gi} averaged 38.1 ± 0.3°C and T_{sk} was 32.8 ± 0.6°C, attaining average maximum values of 38.4 ± 0.4°C and 34.2 ± 0.6°C respectively. Local T_{sk} values on the scapula rose up to >36°C. Sweat rate over the practice and performance tests was 1.1 ± 0.5 L/h. With 58% fluid replacement, this resulted in a body mass loss of 1.1 ± 0.7%. Despite the moderate heat strain and decrement in thermal comfort, no decrements in vigilance and shoot-out performance were observed, rather slight improvements.

Conclusions

Ice hockey goalies experience moderate heat strain, body mass losses and thermal discomfort during practice in cool conditions. Associated impairments in cognitive function and performance were not found. In the studied conditions, extra measures for heat strain reduction do not seem necessary from a health and performance perspective.

INTRODUCTION

In contrast to common belief, heat strain may occur even at temperatures as low as -20°C during heavy exercise when wearing protective garments (1). The sport of ice hockey is performed in a moderate to cool climate with a reported ice rink ambient temperature for practices at 10.7 to 12.7°C and professional games at 14.0 to 17.7°C (2). Ice hockey players are required to wear protective equipment which covers their entire body allowing only areas of the face and neck to be exposed. The equipment worn interferes with the subject's ability to evaporate sweat and causes an increase in core temperature and sweat rate during their exercise. Depending on exercise intensity and permeability of the equipment worn, this can result in measurable heat strain (3). Early signs of heat strain may be experienced with a core temperature of 38-40°C, a skin temperature above 35°C and/or a fluid loss of 2% body mass (BM) (4). Elevated core temperature seems to impair repeated explosive exercise performance (5). Further, research in several team sports (soccer, football, basketball) indicated that 2% BM loss can be detrimental to skill performance (6-9).

Previous research performed on collegiate ice hockey forwards and defenders reported an average gastrointestinal temperature of 38.4°C (10). Average sweat rates ranged from 0.8-1.8 L/h, leading to BM losses of 0.8-1.3% (2; 10-13) with individual losses exceeding 2%. Goalies have been reported to have a higher sweat rate during practice than players, although BM losses seemed quite comparable (12; 13). The higher sweat rate may be caused by the fact that they are the ones wearing the most bulky protective clothing, are continuously involved during practice drills and get less cooling from air movement than players. However, only fluid balance data on a small number of subjects were reported. Further research on ice hockey goalies is sparse, so clear insight in the level of experienced heat strain is lacking.

Possible heat strain and dehydration may affect cognitive function, like gazing behaviour, vigilance and reaction time. Gazing behaviour research shows that a goalie's focus is intense, with 96.2% fixation on the puck, stick and area of the ice just in front of the puck (14). Their peripheral vision is also used to read the play around them. Further, it has been shown that heat load and dehydration negatively affects vigilance and cognitive task performance (15; 16). It has even been suggested that a fluid loss as little as 1% BM

may have an adverse effect on cognitive function (17) and poses a higher risk of exertional heat-illness(18). Additionally, research in field hockey goalies shows that in hot conditions, reaction times in post-game tests were 0.08 s slower than pre-game tests. In cool conditions no reaction time difference was observed (19).

In summary, ice hockey goalies may experience heat strain due to their protective clothing, possibly deteriorating their cognitive functioning and performance. Therefore, the first aim of this study was to explore the level of heat strain experienced by ice hockey goalies in moderate practice conditions. In additions relations between heat strain, fluid balance and drinking behaviour were investigated. For that purpose, six ice hockey goalies were tested on gastrointestinal temperature (T_{gi}), skin temperature (T_{sk}), heart rate (HR) and fluid loss during a regular practice. The second aim of this study was to reveal any association of heat strain with cognitive function and performance, tested by a vigilance and shoot-out task. Knowledge on these issues could indicate whether preventive measures should be applied to reduce health risks and/or improve performance.

METHODS

Subjects

Six goalies averaging 20.0 ± 5.9 years of age and 73.9 ± 13.6 kg body mass, volunteered to participate in this study. Four goalies were part of the Dutch junior talent selection and two goalies played at national senior teams. All subjects and parents were fully informed of the purposes, protocol, experimental procedures and any associated risks and benefits before giving their written consent to participate. The study was approved by the VU University Amsterdam ethics committee.

Design

In this observational research, subjects completed a protocol of pre-practice performance tests, usual practice and post-practice performance tests, while physiological parameters were measured. Each subject went through the experimental protocol once; two subjects on day 1 and four subjects on day 2, starting the protocol from weigh-in about 10 min after each other.

Methodology

Experiments were carried out in a standard ice hockey practice centre. Ambient temperature was measured on both days with a digital thermocouple thermometer (Vaisala HM 34, Finland) at chest level in the goal crease. T_{gi} and HR (Equivital Life Monitor, Hidalgo Ltd, Cambridge, UK) as well as T_{sk} (iButton, Maxim Integrated Products Inc., Sunnyvale, USA) were continuously recorded to give an indication of heat strain and exercise intensity. T_{gi} was measured with Jonah ingestible telemetry pills (Philips Respironics, Mini Mitter, Bend, Oregon). iButtons were applied at the right scapula, left hand, right shin and back of the neck. A weighted average of the four iButtons was used as an estimate of the mean skin temperature (20), giving an overall indication of the micro-environment under the goalies' protective equipment. An extra iButton (not factored into the mean T_{sk} calculation) was placed behind the ear as an exploratory measurement of the thermal environment under the helmet. Just before and after the complete testing session, nude body mass (BM) and water bottle mass were measured.

Performance tests included the visual vigilance and tracking task (VigTrack) and a shoot-out. The VigTrack is a computer based 5 min dual-task vigilance test that has frequently been used to assess cognitive performance (e.g. 21; 22). It is applied to test the goalies' ability to maintain their attention, measuring reaction time (RT) and control. In the RT task, subjects had to fire when stimuli that appeared in the screen changed shape. Reactions >1 s, missed stimuli and false responses were reported as errors. At the control task, subjects were required to control a ball with a joystick while the computer randomly pulled the ball in various directions. Output measure was the number of pixels displacement from the centre of the screen. In order to remove the learning effect, all subjects played the VigTrack three times before the start of the project. Just before the VigTrack test, subjects reported their thermal comfort (TC). TC was measured on a 5-point likert scale (21); 1 equals comfortable and 5 extremely uncomfortable. The shoot-out consisted of 100 tennis balls from a tennis ball cannon placed 7 m away from the goal line. Tennis balls were shot at the goalie at a speed of approximately 100 km/h in random directions. Through the use of a high speed digital camera (Canon EOS 550D, 60 FPS) and a mirror to see the moment of ball release, RT and save percentages could be determined (Figure 8.1).

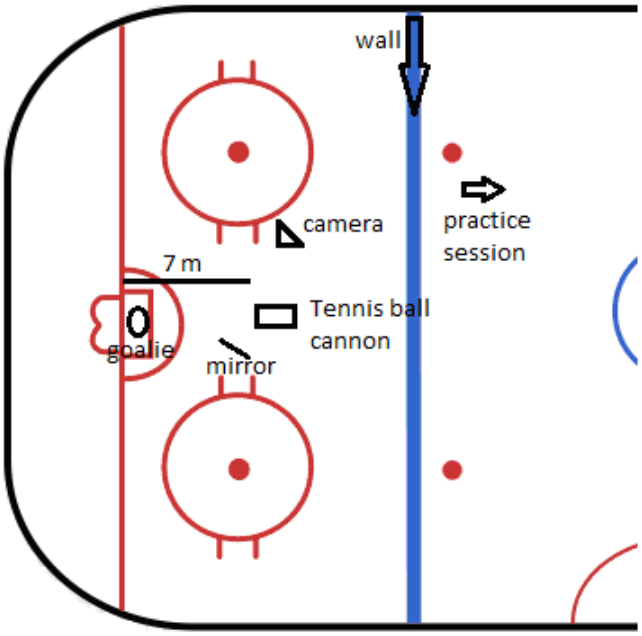

Figure 8.1. *Lay-out of the shoot-out.*

The test protocol (Figure 8.2) used on both testing days began with the goalies swallowing the temperature pill six hours before the start of their on-ice session, as recommended to avoid temperature fluctuations in the upper gastrointestinal tract (24). To ensure euhydration, each subject drank 750 ml of water 1-2 h before arriving at the ice rink, and were asked to empty their bladders before nude body mass was recorded and water bottles were weighed. After the weigh-in, the Hidalgo system and iButtons were applied and the goalies were asked to get dressed before continuing on to the VigTrack (each goalie staggered by 10 min). After VigTrack was completed the subjects gave their thermal comfort rating before entering the ice for a shoot-out, ~60 min usual practice and a second shoot-out. The VigTrack test was repeated when the player left the ice, directly followed by a thermal comfort rating, removal of equipment and weigh-in. The protocol from start pre-VigTrack to end post-VigTrack lasted 1.5-2 h. During this period, it was allowed to drink water ad libitum.

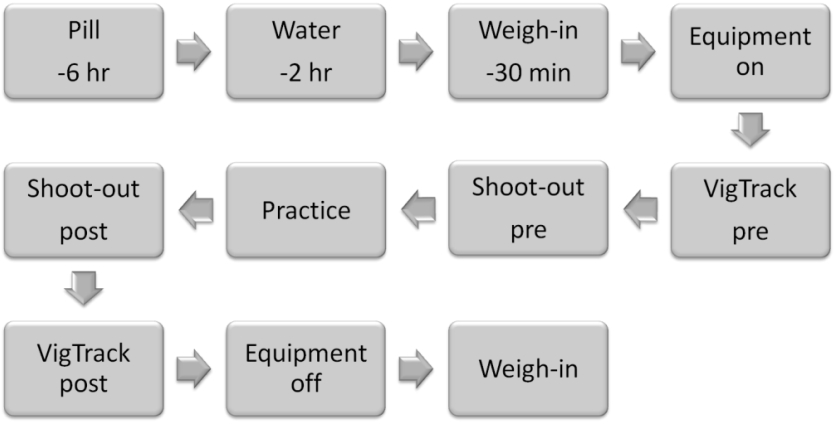

Figure 8.2. *A timeline of the test protocol used on both testing days.*

Statistical analysis

For T_{gi}, T_{sk} and HR, individual and group averages were calculated over the on-ice period from the start of the pre shoot-out to the end of the post shoot-out. In addition separate averages of these measures were determined for the VigTrack and shoot-out sessions. Ingested fluid was determined from pre/post water bottle mass. Sweat loss was calculated by summing BM loss and ingested fluid, subtracted by any urine output. Sweat loss divided by the time interval of the practice and performance tests resulted in the sweat rate. Loss of respiratory water and substrate mass are known to have negligible effects on this calculation and have been ignored (22). Replacement was calculated as the percentage sweat loss that was replaced by ingested water. Finally absolute and relative BM loss were determined, the latter being a percentage of pre-practice BM. Correlations between body temperature, sweat, drink and BM parameters were calculated using Pearson's r.

VigTrack data were analyzed with a custom made Matlab routine, providing RT (s), error (%) and control (average number of pixels deviation from the target). Regarding the shoot-out, RT was measured beginning with first sight of the ball leaving the machine and ending with the first identifiable movement from the goalie to stop the ball. To remove the learning effect and to give the goalies time to adjust to seeing tennis balls instead of pucks, 80 of the 100 shots fired were used to calculate reaction time and save percentages. The 80 shots were selected by removing the first 20 shots. However, shots that were considered not clean (too wide, not ready or moving before shot was fired)

were removed and replaced by shots from the first 20. Paired T-tests were used to reveal pre-post differences of the performance tests, with statistical significance set at the 5% level. Values are reported as mean ± SD.

RESULTS

Ambient conditions on the first day were 11.6°C and 67% RH, on the second day 12.0°C and 59% RH. All subjects completed the protocol, but one temperature pill did not provide any data due to technical failure, so T_{gi} values are based on five subjects.

Physiological responses

Table 8.1 shows the group average, group averaged maximum and maximal individual values for HR, T_{gi}, T_{sk} and $T_{scapula}$ (warmest skin location) over the on-ice session from start shoot-out 1 to end shoot-out 2. Further, group average and highest individual value for fluid balance parameters are displayed. Absolute BM loss was significantly correlated to absolute sweat loss (r^2: 0.84, p=0.036), correlation of the relative BM and sweat losses was borderline significant (r^2: 0.81, p=0.053). Further, BM was correlated to sweat rate (r^2: 0.90, p=0.015) and HR to T_{gi} (r^2: 0.95, p=0.013). Fluid ingestion was not correlated to any other parameter.

Table 8.1. *Session average, average maximum value (average max) and maximal individual value (individual max) for the main physiological parameters. T_{gi}: gastrointestinal temperature; T_{sk}: mean skin temperature; $T_{scapula}$: skin temperature at the scapula; BM: body mass.*

	Session average	Average max	Individual max
HR (bpm)	141 ± 14	173 ± 12	187
T_{gi} (°C)	38.09 ± 0.31	38.41 ± 0.36	38.82
T_{sk} (°C)	32.77 ± 0.62	34.24 ± 0.63	35.18
$T_{scapula}$ (°C)	34.87 ± 0.32	36.01 ± 0.66	36.74
Sweat loss (L)	1.8 ± 0.7		3.0
Sweat rate (L/h)	1.1 ± 0.5		1.9
Ingested fluid (L)	1.0 ± 0.4		1.7
Replacement (%)	58 ± 22		85
BM loss (kg)	0.8 ± 0.7		1.8
BM loss (%)	1.1 ± 0.7		1.9

Regarding T_{gi}, the main temperature increase took place in the first 40% of the on-ice session, remaining relatively stable thereafter. The pattern of average T_{sk}, its local determinants (right scapula, left hand, right shin and neck) and the extra measurement behind the ear (head) are displayed for a typical (junior) subject in Figure 8.3. It expresses the skin temperature in various areas under the equipment. The intermittent nature of the practice session and occasional removal of equipment is reflected in the fluctuation of the lines. Especially notable is the large decrease in T_{sk} from about half of the practice time due to a 15 min break. The iButton behind the ear, measuring skin temperature under the helmet, showed a pattern similar to the neck.

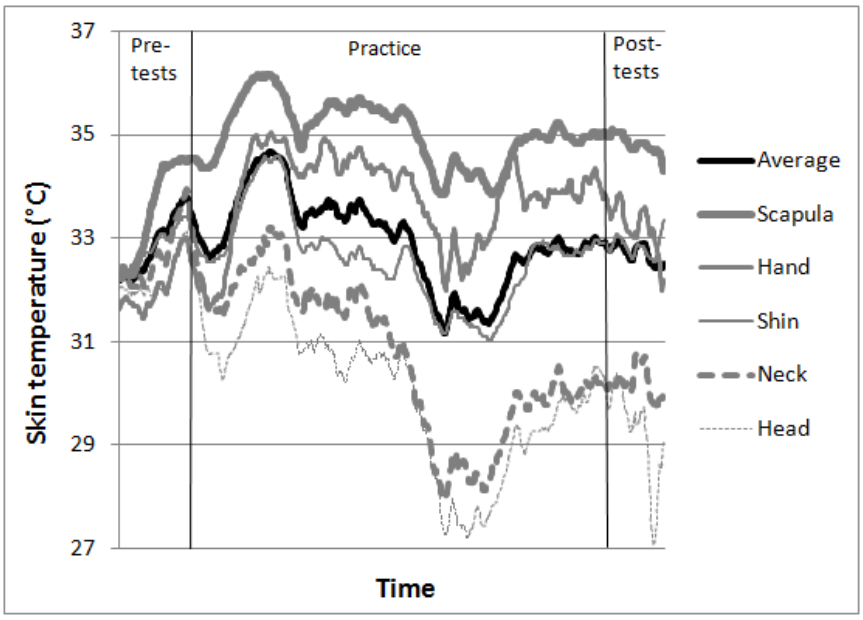

Figure 8.3. *Separate and averaged skin temperatures for a typical subject.*

Performance measures

The results from the shoot-out test are shown in Table 8.2. T_{gi} (p=0.019) and HR (p=0.001) were higher during the post shoot-out, while T_{sk} tended to be lower (p=0.084). Reaction time (RT) (p<0.001) and percentage of saves both improved in the post shoot-out (p=0.001). During the post VigTrack test, T_{re} (p=0.041) and HR (p=0.002) were still higher than the pre-test, but T_{sk} was lower (p=0.027). Subjects felt less comfortable (p=0.025). RT and error percentage did not differ between pre and post, but the number of pixels displacement decreased (p=0.019), indicating better control after the ice session.

Table 8.2. *Physiological and performance measures of the pre- and post-practice shoot-out and VigTrack session. T_{gi}: gastrointestinal temperature; T_{sk}: mean skin temperature; HR: heart rate; RT: reaction time; TC: thermal comfort; pix: pixels.*

	Pre-practice	Post-practice
Shoot-out		
T_{gi} (°C)	37.53 ± 0.28	38.18 ± 0.39*
T_{sk} (°C)	33.09 ± 0.60	32.19 ± 1.31
HR (bpm)	132 ± 8	156 ± 15*
RT (s)	0.18 ± 0.01	0.16 ± 0.01*
Saves (%)	76.9 ± 9.3	87.3 ± 4.5*
VigTrack		
T_{gi} (°C)	37.45 ± 0.41	38.23 ± 0.40*
T_{sk} (°C)	33.29 ± 0.40	32.09 ± 1.08*
HR (bpm)	85 ± 9	125 ± 19*
TC	1.3 ± 0.5	2.7 ± 1.2*
RT (s)	0.63 ± 0.07	0.60 ± 0.09
Control (pix)	84.3 ± 30.3	66.9 ± 29.1*
Error (%)	13.8 ± 10.7	14.3 ± 11.3

**Significantly different from pre-practice ($p<0.05$)*

DISCUSSION

The purpose of this study was to explore the amount of heat strain ice hockey goalies experience during practice and whether or not this heat strain affects their cognitive function and performance. It appears that ice hockey goalies develop moderate hyperthermia and lose a considerable amount of fluid, but a decrement in cognition and performance could not be observed.

Despite the cool practice environment of around 12°C and the rather static and intermittent nature of their exercise, ice hockey goalies experience a moderate level of heat strain. The thermal insulation of the protective equipment, in combination with the high water vapor barrier, makes it difficult to lose body heat and evaporate sweat. Core temperature increased to about 38.4°C with an individual maximum of 38.8°C, which is similar to values found in ice hockey players during practice (10). The core temperatures observed in this study are not alarmingly high and did not pose the goalies at risk for uncompensable heat stress and heat exhaustion. After the initial increase during the pre shoot-out and start of practice, core temperatures generally reached a plateau for the

rest of the on-ice session. Average skin temperatures reached 34-35°C, while local skin temperatures increased up to >36°C. Skin temperatures fluctuated by the intermittent nature of the exercise and the possibility to remove some equipment (helmet and gloves) during breaks. The hottest spot appeared to be the scapula, which is well protected and hard to ventilate, while the neck and head remained cooler.

The average sweat rate of 1.1 L/h during practice and tests led to a total sweat loss of 1.8 L, with individual losses up to 3.0 L. So despite the cool ambient temperature of 11.9°C, substantial evaporative cooling was required to restore the heat balance. The four goalies in the study of Palmer et al. (13) showed a higher sweat rate of 2.9 L/h during a 1-h practice in ambient conditions of 13.9°C and 66% RH, while the goalies of Logan-Sprenger et al. (11) sweated at a lower rate of ~0.8 L/h during a 2.5-h junior game in 10.8°C, 30% RH. The different sweat rates may be explained by differences in exercise intensity. For example, goalies are presumed to be more constantly involved in the play during practice drills than during a game situation, possibly affecting their sweat rate (11; 13). Unfortunately, HR data have not been reported in these or other previous studies on ice hockey goalies, so the extent of the differences in exercise intensity cannot be established. In addition, the ambient conditions and possibly body size are likely explanations for the observed differences in sweat rate as well.

As reported by previous studies on ice hockey as well as numerous other sports (26), goalies did not ingest sufficient fluid to replace their sweat losses. Fluid was replaced by 58%, leading to 1.1% BM loss with an individual maximum of 1.9%. BM loss was comparable to previous data of goalies (13) and players (2; 10-13). The similar level of BM loss across studies despite different amounts of sweat loss, suggests a relationship between sweat rate and fluid intake. However, within this study fluid intake appeared independent of both sweat loss and BM loss, while the latter two were correlated. So higher sweat loss was not compensated by higher fluid intake and directly affected the hydration status. This in line with most previous studies (27; 28). A relationship between BM loss and T_{gi} increase that has been reported previously (29) was not observed in the current study. This relationship could not be shown in ice hockey players at a comparable level of heat strain either (10).

The post-practice shoot-out and VigTrack tests did not reveal any impact of heat strain on cognitive function and/or performance. The level of heat strain attained in this study does not seem to have exceeded the threshold for performance decrement. Although Lieberman (17) suggests that BM losses of 1% may already have adverse effects on cognitive performance, previous research in team sports indicates decreased skill performance at BM losses of ~2% (6-9), which none of the goalies in the current study reached. Further, T_{gi} was in general only moderately elevated during the post-test, while T_{sk} even tended to be lower. Therefore it is likely that the shoot-out performance was not compromised by heat-related central fatigue. Post-practice thermal state may even have been beneficial for the shoot-out, as elevated muscle temperature is known to enhance sprint performance (30; 31). In summary, the additional heat strain during the post-test was limited and if it was associated with any detrimental heat-related effect, this test set-up was not sensitive enough to detect it. The test set-up may be improved by testing multiple days after comparable exercise at different levels of thermal stress. In addition, attention should be paid to extensive habituation. Although subjects in this study got 20 'habituation-shots' from the tennis ball cannon and practiced the VigTrack three times before the test day, a learning effect cannot be ruled out. A more specific test device like a puck cannon and establishing normal variation in test performance would also be helpful in that respect.

Practical applications and conclusions

At a rather cool practice temperature, the ice hockey goalies in this study became somewhat hyperthermic and experienced substantial sweat loss. Sweat loss was partly replaced, limiting average BM loss to a moderate level around 1.1%. These physiological effects did not lead to performance impairment on a shoot-out and visual vigilance and tracking task. So in the studied conditions, there does not seem to be reason for extra measures to reduce heat strain.

Nevertheless, as the rather cool conditions of this study were sufficient to induce some heat strain, a professional game in temperatures of 14-18°C may have a more serious physiological and performance impact. As mentioned, ambient conditions seem to have considerable impact on at least sweat rate. So far, it seems that most goalies ingest sufficient fluid to prevent detrimental BM losses, but the effect of more strenuous conditions on fluid ingestion and BM loss remains unclear. Further, any larger increases

in core temperature could induce a performance deterioration in repeated explosive exercise performance (5). More research is needed to explore whether or not the level of heat strain experienced by ice hockey goalies interferes with performance at game temperatures. A comparison of exercise intensity, heat strain and performance between strenuous game conditions and cooler practice conditions, using more sensitive performance measures, would be useful.

Currently, dehydration seems to be the primary thermal concern for ice hockey goalies. The individuals at the upper end of the BM loss range in this study came close to the 2% limit. Although the impact of moderate dehydration on health and performance has lately been challenged (32), facilities for hydration ad libitum seem useful. BM was correlated to sweat rate, so heavier subjects should be aware to be at greater risk for dehydration. Further, the decrement in TC observed during the practice session could possibly be limited by equipment improvements, including better ventilation and sweat management. Especially the heavily equipped torso area deserves attention, as the scapula skin appeared to attain the highest skin temperature. More extensive skin temperature and breathability research could provide more information on this issue. Simpler recommendations for improving TC might be the removal of equipment whenever possible, improving evaporation and convection, and storing equipment in a cool and dry environment to ensure an optimal pre-use thermal state.

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Chapter 9

Summarizing discussion

Humans are proficient in maintaining a stable heat balance due to effective physiological and behavioural mechanisms. However, pathology, clinical treatment, exercise or extreme environments can induce severe heat or cold stress, causing core temperature to exceed its normothermic limits. This may lead to serious consequences for health and performance. As a result, reliable monitoring of core temperature is of major importance in medical, occupational and sports settings. It can detect illness at an early stage, guide appropriate action and prevent heat or cold injury in rest and exercise.

Although one single core temperature does not exist, temperature measurement in the pulmonary artery or brain are considered as the gold standard (1). However, such invasive measurements are not feasible in practice, raising the need for a non-invasive method that is reliable, fast, convenient and easy to handle. But despite the comprehensive list of alternative methods at numerous body locations, each of them has drawbacks and confounding factors (Table 1.2). Especially continuous monitoring of core temperature (changes) in an operational setting remains a challenge. So determining the benefits and limitations of promising measurement methods is warranted. The first section of this thesis tried to contribute to this methodological matter.

The second section of this thesis focused on heat stress during exercise and its effects on performance. Exercise in combination with a high climatic load and/or wearing protective clothing imposes a substantial thermal and cardiovascular strain on the body. This heat strain impairs work capacity and performance (2-5). During self-paced exercise, there might be a central role for the rating of perceived exertion (RPE), linking changes in heat strain to the adjustment of power output (6). Further, if heat loss mechanisms are insufficient to restore the heat balance, uncompensable heat stress arises, ultimately ending up in hyperthermic fatigue, exhaustion and/or heat-related illness. Especially in occupational or sports settings, this is a regularly occurring phenomenon (7; 8).

Current evidence indicates that a high core temperature itself is the main factor causing hyperthermic fatigue and exhaustion, independent of cardiovascular strain. Central mechanisms seem predominantly involved, impairing the voluntary contraction of skeletal muscles, arousal and RPE (9; 10). When subjects are allowed to determine their own pace, anticipatory regulation generally prevents premature hyperthermic fatigue (6). Only when a subject continues unrestrained, as may happen during special

competitive events like the Olympics, exhaustion terminates exercise at a critical core temperature to prevent collapse (11). Heat-stressed performance may be improved by maximally avoiding heat stressors, but also by reducing their impact. The latter can be accomplished by cooling the skin and/or body core before or during exercise. Practical and effective cooling methods are required, which reduce thermal strain and improve thermal perception.

More knowledge on the mechanisms that relate heat stress to performance and optimal ways to manipulate this relation, could optimize performance, well-being and safety for subjects experiencing exertional heat stress. The second section of this thesis aimed to extent the current knowledge in this field.

CORE TEMPERATURE DETERMINATION

The first section of this thesis discussed four studies to different practically applicable measurement methods for core temperature determination during rest and exercise in the heat, exploring some of their specific benefits and limitations.

In **Chapter 2**, we investigated the reliability and response time of a newly developed non-invasive measurement device, that applied the zero heat flux (ZHF) technique at the forehead. The experiment involved rest, exercise and recovery in hot conditions, inducing a sequence of stable, increasing and decreasing body temperatures. ZHF temperature was compared to esophageal temperature (T_{es}) as gold standard and rectal temperature (T_{re}) as commonly used reference. During all phases of the experiment, the ZHF device closely corresponded to T_{es} (95% limits of agreement within ±0.50°C) with negligible delay. In contrast, delay and deviation from T_{re} was substantial during exercise and recovery. The results indicate that the studied ZHF sensor is a reliable tool for non-invasive continuous determination of T_{es} in hot and stable ambient conditions. However, improvements in usability are required before widespread application is possible. Further, because of the long start-up time, its application is limited to prolonged monitoring (12).

Chapter 3 examined whether infrared thermal imaging, as recently applied for mass screening of fever during pandemics, was able to track core temperature changes during exercise, recovery and passive heating. Temperature determined by a thermal image of the inner canthus of the eye (T_{ca}) was compared to T_{es}. It appeared that T_{ca} and T_{es} showed large and inconsistent differences, T_{ca} hardly responding to core temperature changes. As a result, the use of T_{ca} as a technique for core temperature estimation is discouraged, although generalization of these results to fever detection should be verified experimentally using febrile patients (13).

Chapter 4 dealt with aural canal temperature measurements using an ear mould integrated sensor (T_{ac}), which seems a practical but error prone method for continuous non-invasive core temperature estimation in operational settings. Therefore, we studied the effect of ambient temperature, wind and high intensity exercise on T_{ac} and its ability to predict T_{es} and T_{re}. Changes in ambient temperature and wind speed severely affected T_{ac} measurements, which could not or only partly be attenuated by auricle insulation. In steady ambient conditions, T_{ac} provided acceptable group predictions of core temperature, while individual predictions were more varied. Consequently, the use of T_{ac} is currently limited to core temperature assessment of groups in warm and stable conditions (14).

Chapter 5 focused on ingestible temperature pills, which are often used to establish core temperature in field research. Pill temperature (T_{pill}) reflects both T_{re} and T_{es} reliably at small and/or gradual changes in core temperature, while it seems to correspond best towards T_{re} at higher rates of change (15). However, it had been scarcely investigated how T_{pill} relates to these references during extreme rates of temperature change, induced by short high-intensity exercise in the heat. Our experimental data confirmed that also during considerable core temperature changes at a very high rate, T_{pill} is still representative of $T_{re.}$ The extent of the deviation in pattern and peak values between T_{pill} and T_{es} (up to >1°C) strengthens the assumption that T_{pill} is unsuited to evaluate central blood temperature when body temperatures change rapidly (16).

Chapter 2 to 5 confirm the notion that there is not a single core temperature and there is no universal ideal measurement method yet. Knowledge on the benefits and limitations of measurement devices and measurement sites, appreciation of natural thermal

differences across the body, as well as awareness of the purposes and conditions of a measurement, should be decisive in choosing which method rises best to the occasion. Generally, a trade-off will have to be made between measurement time, accuracy, ease of use and subject convenience, mediated by the requirement for continuous measurement and the appropriate level of invasiveness. The discussed studies focused on practically applicable non-invasive measurement methods, in which such a trade-off indeed appeared to be unavoidable.

For continuous monitoring in hospital, ZHF is potentially an improvement on currently used methods. It appears accurate, has little response time and is convenient for the patient (12; 17). Also in lab research, ZHF application is more convenient for subjects than the usual esophageal or rectal probes. In addition, unlike esophageal measurement, drinking and swallowing does not disrupt the temperature profile (18). However, for field applications, the studied ZHF device suffers from a lack of mobility and wireless communication, has a long start-up time and is less reliable in wind and cold conditions. For that purpose a heat flux sensor measuring the thermal gradient of a thermal bridge at the skin, mathematically predicting core temperature, may be better suited (19; 20). The ear-mould integrated sensor also has a better practical usability in that respect, but appeared to be error prone during changing ambient conditions (14). This limits its practical application considerably and additionally reconfirms the hazardous nature of in-ear measurements. As a result, the temperature pill currently still seems the designated choice for field measurements. Despite some drawbacks on the cost, ingestion time, gastrointestinal motility and electromagnetic interference, it conveniently provides an acceptable indication of rectal temperature in both stable and dynamic environments (15; 16).

The future of temperature measurement probably lies in high tech solutions and development of brain temperature measurement methods. Initial steps have been taken with MRI and NIRS. These methods seem useful for thermal therapy applications, but quite some issues have to be resolved before it is suited for reliable core temperature determination in practice. Therefore, new technologies, providing the opportunity to end the quest to an optimal core temperature measurement method, are still required.

HEAT STRESS AND PERFORMANCE

In the second section of this thesis, three studies on heat-stressed exercise were discussed. Experiments investigated the physiological, perceptual and performance effects of (pre)cooling, climatic variations and protective clothing.

Chapter 6 dealt with the opposing interests of warming-up and precooling the body prior to endurance exercise in the heat. We analysed the effect of different preparation regimes on pacing strategy during a 15 km cycling time trial in the heat, including warm-up, ice slurry ingestion and/or scalp cooling. The preparation regime that provided the lowest body heat content and sensation of coolness at the start of the time trial (ice slurry + scalp cooling) appeared to be most beneficial for pacing in the latter stages. Precooling the core with ice slurry ingestion was more effective in accomplishing this benefit than precooling the scalp. However, in contrast to previous studies (21-23), overall performance was not significantly improved in any condition. This might be due to the limited length of the time trial. To demonstrate significant performance benefits in average populations, an exercise time of >30 min seems to be required. Minor benefits at shorter intervals may only be demonstrable using highly trained populations that are fully habituated to test and intervention protocols.

Chapter 7 reported a twofold experiment to the effects of wind cooling during exercise in the heat. The first substudy focused on the perceptual effect of wind cooling, independent of physiological strain. For that purpose, we compared cycling exercise in different windy and windless climates inducing equivalent physiological strain. Results showed that, in the absence of substantial physiological differences, wind application provides a cooler thermal sensation, but does not change thermal comfort, pacing or performance. The second substudy focused on the physiological, perceptual and performance effects of wind cooling when unexpectedly applied from km 3 to 12 during a 15 km cycling time trial. When wind temporarily reduced thermal stress, it provided immediate benefits in skin temperature, thermal perception and rating of perceived exertion, leading to an increased power output. These benefits were maintained throughout the race without imposing a higher thermal strain, resulting in a significantly faster finish time. Notably, in both sub-studies, wet bulb globe temperature (WBGT) was

not proportional to thermal strain when wind was involved, allowing a 4°C higher WBGT for similar thermal strain and performance.

Chapter 8 described a study on ice hockey goalies, who are predisposed to heat strain by their high metabolic activity combined with reduced heat loss in protective equipment. It was explored to what extent goalies experience heat strain during practice in cool conditions and whether this is associated with effects on cognitive function and performance. We found that body temperatures were only moderately increased, with core temperatures up to 38-39°C and some local hot spots on the skin. Body mass was significantly reduced by fluid losses, but this did not exceed the generally accepted limit of 2%. Impairment in cognitive function and/or performance could not be detected, but methodological issues may have obscured an effect.

Chapter 6 to 8 considered different aspects of the relation between heat stress and performance. It has been known for decades that heat stress incurs several physiological and perceptual responses that are detrimental for prolonged performance (24; 25). As pointed out in the introduction, this seems to be based on a complex process with a major central component. Performance would benefit from optimally manipulating the determinants of this process. In that respect, chapter 7 suggested that not the type of climate and subsequent thermal sensation, but rather thermal strain and comfort affect performance. This may explain why scalp cooling in chapter 6 provided little effect: although it slightly improved thermal sensation and slightly reduced core temperature increase during warm-up, its effect was not strong and durable enough to substantially lower thermal strain and comfort.

Whole body skin precooling may be an effective alternative in that respect. Chapter 7 showed that whole body skin cooling by wind is a very effective tool to reduce thermal strain and perception during exercise. This mechanism may be applied to limit the increase in body heat content prior to exercise during a preparation period. This holds especially good in hot conditions, when most athletes still tend to stick to a (too) long warm-up prior to exercise. To attain an extra reduction in body heat content, ice slurry ingestion seems a useful addition. Although we did not find significant performance benefits, chapter 6 suggests that precooling is at least as beneficial as a preparation regime for endurance exercise in the heat as a common warm-up. Further, literature

shows significant performance benefits, especially at prolonged exercise of >30 min (21-23; 26). Nevertheless, performance enhancement by precooling should also be established in practice, as lab experiments may overestimate the beneficial effect due to the lack of air flow during a stationary time trial. Chapter 7 showed that this factor cannot be neglected.

In addition, the results in chapter 7 incite to make better use of wind cooling applications. Next to cooling during a warming-up, it might also provide easy cooling in indoor sport/event facilities or occupational settings. It would provide an enhancement of performance and comfort as well as a reduction in strain and health risks for athletes, spectators and labourers. Further, a wind dependent use of WBGT is recommended, ensuring that WBGT and thermal strain are still proportional at changing wind conditions. Finally, a slight modification of Tucker's (6) RPE based pacing model may be considered. Although RPE changes generally seem to be followed by an adjustment in power output in order to restore the original RPE template, chapter 7 showed that subjects are restrained to do this prematurely as long as the deviation in RPE is limited. This pleads for the addition of a time to finish component, as has been tried in the hazard score (26).

Apart from endurance performance in the heat, chapter 8 focused attention on heat strain and cognitive performance in cool conditions. Our study on ice hockey goalies confirmed that heat stress also occurs during exercise in cool environments when heat loss is restricted by protective clothing. Although thermal strain appeared to be limited in this study, results indicate that heat stress effects in cool environments cannot be neglected. Dehydration with possible consequences for thermoregulation and performance may be a risk, although the extent of this risk has recently been challenged (27). Decrements in agility and cognitive performance could not be detected. However, research involving better tests and more demanding (game) conditions would give more insight. More in general, research to the effect of heat stress on cognitive function remains ambiguous (28) and would be a relevant topic for future research.

CONCLUDING REMARKS

The fields of core temperature determination, heat stress and performance are closely intertwined. Better core temperature measurement during heat stress and performance could be of considerable scientific and practical value, better controlling occupational safety limits, providing sportsmen and coaches with thermal information, giving more insight in the acclimatization process, improving thermoregulatory research in the field, etc.

Especially interesting in this respect would be the evaluation of brain temperature and its relation with other core temperatures. Scientifically, it would provide more insight in thermoregulatory mechanisms, like the hyperthermia induced decrease in central neuromuscular activation, the effect of cooling manipulations and the existence of human selective brain cooling. In practice, monitoring brain temperature in emergency situations or during therapeutic thermal treatment could guide appropriate action, as brain temperatures >40.5°C can be life threatening and at >42°C proteins denaturize. For sportsmen, it would be relevant to determine a brain temperature threshold at which muscular activation starts to decline. Unfortunately, technical developments are not sufficiently advanced yet to attain all these goals in a short term.

Another point of interest for future research is the individual variability in response to thermal stress. For example, the mechanisms relating fitness level to hyperthermic exercise tolerance are still unclear. In addition, the generalization of adult male research results to women, children and elderly has been underexposed; most studies (also in this thesis) investigated well-trained adult males. A final important issue is the transfer of laboratory research to practice. Differences in environmental conditions, specific activity (type, duration, intensity) and involvement of psychological factors may lead to different behavioural responses. Therefore, research closing the gap between physiological and psychological responses in laboratory and actual behaviour in an occupational or sports setting would provide valuable insights.

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Appendix

Overview of core temperature measurement methods

A.1 ELECTRICAL RESISTANCE

The electrical resistance of a metal or semi-conductor changes with temperature. With the right calibration, both can be used to measure temperature. Most digital thermometers make use of a semi-conductor resistance, like a thermistor, which is a temperature sensor made of a heavy metal oxide. In general it is accurate, reliable and can be made very small. A disadvantage may be that the direct contact with body tissue poses the risk of inconvenience, injury and infection. Further, reliability can become lower when metal resistance increases over time, which makes frequent calibration necessary (1). An extensive report on these and other biosensors can be found in Wise (2). This chapter will list the locations at which this type of core temperature measurement has been applied.

Pulmonary artery temperature (T_{pa})

As discussed previously, T_{pa} is considered as a gold standard for core temperature (3-6), but only usable during specific clinical interventions.

Comparative analysis. When properly measured, pulmonary arterial temperature is per definition a reliable value for the core temperature of the trunk. Whether it is also a reliable measure for brain temperature is not clear. Camboni et al. (7) found that brain temperature better correlated with T_{bl} and T_{ty} than with T_{pa}. However, these measurements were done in hypothermic circulatory arrest during cardiac surgery.

Contraindications. Tricuspid or pulmonary valve mechanical prosthesis, tricuspid or pulmonary valve endocarditis, right heart mass (thrombus and/or tumour).

Esophageal temperature (T_{es})

T_{es} is a reliable alternative for T_{pa}. Therefore, it is frequently used as a reference temperature in scientific research (8-15). An esophageal probe is introduced through the nose, swallowed with water and placed at the required position in the thermally stable lower third of the esophagus. The optimal location is the region at the level of the 8^{th} and 9^{th} thoracic vertebrae. At this level, the esophagus is close to the lower border of the left atrium and the upper border of the left ventricle (16). This is sufficiently beyond the tracheal bifurcation to exclude ventilatory influence and the cold spots of the corniculate

cartilage. Mekjavic et al. (16) developed a standardized probe length (L) for esophageal measurements. Sitting height is the preferred parameter to calculate the optimal L for a subject: L = (0.479 x sitting height) – 4.44 (r^2=0.86).

T_{es} is a reliable indicator of core temperature, which responds almost instantly to central blood temperature changes. However, insertion of the probe is often experienced as difficult and uncomfortable and can even be dangerous (nasal trauma, esophageal perforation). Some subjects have a strong rejection reflex and do not tolerate the esophageal probe. Therefore, T_{es} is not suitable to use at home and regularly not preferred in clinic or laboratory. Further disadvantages are the fact that ingestion of food and drinks, as well as breathing cold air may confound the measurement and the fact that swallowing saliva causes temporary relapses that have to be filtered out (17).

Comparative analysis. Robinson et al. (5) report that T_{es} is more accurate than T_{ty}, T_{re}, T_{ax} and T_{bl} over a wide range of temperatures in anesthetized patients. Lefrant et al. (4) compared several measurement sites to T_{pa} as gold standard in critically ill patients. The esophagus and bladder appeared the most reliable locations, better than the rectum, axilla and inguinal region. Based on theoretical considerations and empirical results, T_{es} is in the scientific world considered as a reliable gold standard for core temperature.

Contraindications. T_{es} should not be used in case of esophageal disorders, a cold, strong gagging reflexes and when undergoing procedures on the face, airways or esophagus.

Nasopharyngeal temperature (T_{np})

T_{np} is a more superficial surrogate for T_{es}, in which the esophageal probe has to be placed above the palate, in contact with the mucosa. It is suited for subjects that have difficulty swallowing the esophageal probe and its proximity to the brain suggests a reliable reflection of core temperature. However, research results are scarce. Besides, measurements can be disturbed by displacement of the probe and nose bleedings.

Oral temperature (T_{or})

In 1776, John Hunter was the first known clinician to measure body temperature with a mercury-in-glass thermometer under his patients' tongue (1). And still it is the standard method in US hospitals and widely used in other medical settings. A sensor is placed

under the tongue in the posterior sublingual cavity, which is supposed to reflect the temperature of the lingual arteries. The mouth should be held closed for minimal 4 min (18), ISO/CD 9886 (19) even recommends 8 min at ambient temperatures between 18 and 30°C. They also recommend not to use T_{or} under 18°C ambient temperature.

T_{or} is easy to use, convenient for the subject and has a small delay of about 2 min (20; 21). However, it is difficult to measure T_{or} properly. Measurements can be severely affected by probe positioning, (hyper)ventilation, food, drinks and external conditions (22; 23). Face and head temperature, saliva and local infection might also confound results. Therefore it is an error prone method, which cannot be used during exercise above 35% VO_{2max}, eating/drinking and talking (21). Further, it is unsuited for young children and shivering subjects who may bite and break the thermometer.

Comparative analysis. Compared to T_{es}, negative offsets of 0.1°C (24), 0.16°C (25), 0.1-0.4°C (26) have been found, although Erickson and Kirklin (27) report a positive offset of 0.1°C. Giuliano et al. (3) compared T_{or} to T_{pa} and measured a positive offset of 0.15 ± 0.36°C. However, mostly T_{or} is considered to be 0.4°C below central blood temperature (21; 28). Methodological differences might explain the varying offset, but overall these studies show an acceptable agreement. So under strict conditions and when properly measured, T_{or} may be a useful temperature measure in a clinical setting (29).

Contraindications. T_{or} should not be measured in patients following oral surgery, children under five years of age, uncooperative or unconscious children and in patients receiving oxygen therapy.

Exhaled breath temperature (T_x)

Because airway temperature appears to be reflect mucosal and bronchial blood flow (30), exhaled breath was recently explored as a way to estimate core temperature (31). T_x was measured in the one-way valve of a mask and put into a linear regression model to predict T_{re}. During a protocol in which subjects were heated and cooled in a dynamic sequence, T_x significantly correlated with T_{re} and model predictions were within acceptable levels of agreement. However, temperature fluctuations during the trial were limited and the protocol was performed under controlled conditions. Therefore, the

usability of a single T_x based model for individual core temperature prediction across a large temperature range and in various conditions remains to be tested.

Tympanic temperature – direct contact (T_{ty-c})

The tympanum is potentially a good location for temperature measurement. It is protected from the external environment, but still easily accessible. Due to a partly common blood supply, the tympanic membrane is said to have a temperature similar to the hypothalamus, the main human thermoregulatory node (32; 33). As this suggests tympanic temperature (T_{ty}) is a reliable, fast responding and practical measure of core temperature, it is a regularly used parameter. T_{ty} can be measured directly and indirectly. This paragraph will discuss the direct contact method, paragraph A.2.1 describes the indirect (infrared) method.

Direct T_{ty} measurements can be obtained by holding a thermocouple against the tympanic membrane. If contact is maintained at the lower anterior quarter of the membrane and the sensor is insulated from outside conditions by cotton and earmuffs or rubber pads (34), a reliable measurement can be obtained. Repositioning of the sensor might be necessary during multiple measurements (14).

The major disadvantage of this method is the risk of pain or damage. Making contact between sensor and tympanum may damage the membrane. A slight touch of the inner ear canal causes severe pain because of the many pain sensors on that location. So the method is only suitable for use during research and even then not preferable because of the inconveniences. In addition, T_{ty-c} measurement can be confounded easily by insufficient isolation of the probe (14) and slight displacement of the probe from the tympanum. Further, T_{ty} itself might be affected by external conditions, which cause local cooling or warming of superficial blood vessels of the head (35-37).

Comparative analysis. Because of its location close to the hypothalamus, T_{ty} has been thought to reflect brain temperature. However, brain temperature cannot yet be studied in healthy subjects. Some studies compared T_{ty} to brain temperature and T_{es} during surgery (7; 9; 33; 38; 39) but results were inconclusive, possibly due to the extraordinary measurement conditions. In addition, in any attempt to estimate brain temperature, the gradient within the brain is a factor to account for (40-42). Superficial layers may display

more 'tympanic like' behaviour than deeper locations and may not give a good indication about the average or deep brain temperature. So measurement location may affect research results on the agreement of T_{ty} and brain temperature.

More often, studies have investigated the agreement of $T_{ty\text{-}c}$ with T_{es}. If properly measured in stable conditions, $T_{ty\text{-}c}$ is equal or slightly higher than T_{es} at rest (8; 14; 34; 38; 43; 44). However, in studies applying manipulations like heat stress and/or face fanning $T_{ty\text{-}c}$ has been regularly reported to deviate from T_{es}, showing a stronger cooling or suppressed temperature increase (10; 12; 13; 40; 44-46). Again, the occurrence and extent of the deviation is inconclusive. The varying results may be caused by methodological differences in protocol, ambient conditions, measurement technique etc. But even if $T_{ty\text{-}c}$ and T_{es} physiologically differ in certain conditions, it is still debatable whether this is a local tympanic phenomenon or a demonstration of selective brain cooling across (part of) the brain.

Aural canal temperature (T_{ac})

The temperature of the external aural canal (T_{ac}) is a socially acceptable and occasionally used surrogate for T_{ty}. A small temperature sensor has to be placed against the wall of the aural canal, preferably close to the tympanum.

Comparative analysis. The correlation between T_{ac} and core temperature is disputable (47). Daanen and Wammes (48) measured T_{ac} at several locations in the ear. Even at room temperature, they measured a temperature difference of >1°C between two points that were 9 mm apart. Thus thorough insulation by cotton and earmuffs or rubber pads is required to prevent the ear canal wall and sensor from being affected by environmental conditions (49). Some promising results have been achieved with T_{ac} measurement, at least in warm and stable conditions (50; 51), but individual monitoring and application in colder conditions do not seem reliable (18; 52). Chapter 4 elaborates more on this subject.

Forehead temperature (T_{fh})

Skin temperature of the forehead is sometimes used as an estimate of brain temperature. Cutaneous liquid-crystal thermometers, thermistors or thermosensitive materials are available as measurement devices. However, simply touching the forehead

is still used as a quick assessment method as well, especially providing a rough first approximation in fever situations.

Comparative analysis. Research results indicate that T_{fh} is not a very reliable method. Ikeda et al. (53) used LCD thermometers to test core-to-forehead and core-to-neck temperature differences. They concluded that core-to-forehead temperature difference was smaller than the core-to-neck difference, which frequently exceeded 1.0°C. However, the core-to-forehead temperature difference was still >0.5°C during approximately 35% of the measurements. Rasch et al. (13) measured T_{fh} values that deviated 1.5-3.0°C from T_{es} and T_{ty} in rest. During moderate exercise, the difference increased even more, because T_{fh} slightly decreased. Head cooling experiments indicate that during wind or cold, T_{fh} deviates enormously from core temperature (14; 15). For hypothermia T_{fh} is not a suited indicator of core temperature at all. In a study of Singh et al. (54), mothers touched the forehead, abdomen and feet of their babies. Only abdomen and feet gave a good estimation of hypothermia.

Axillary temperature (T_{ax})

A thermometer in the axilla theoretically gives an estimate of the temperature in the subclavian artery and thus indirectly core temperature. It is an easy and convenient method that might give some approximation in vasodilated subjects with the arm held tightly against the body. However, the subclavian artery is not a major vessel and external influences (ambient temperatures, changes in skin perfusion, sweat, hair density) are considerable. So the method is very error prone, especially in cold conditions (27; 55).

Comparative analysis. T_{ax} is known to be about 1-2°C lower than other core temperatures (56) and highly variable (27; 57; 58). Several studies showed a poor sensitivity of 27-33% (59; 60). In a study on nearly 1000 small children, a false negative rate for fever of 75% at home and 27% in hospital was measured (61). Robinson et al. (5) reported that their axillary probe showed a mean difference of 1.3°C ± 1.3°C with T_{pa} in anesthetized children. In comparative studies, T_{es}, $T_{re,}$ T_{ty}, T_{bl} and T_{fh} all appeared more reliable than T_{ax} (4; 5; 62). It can be concluded that T_{ax} is one of the least reliable of all well-known measurement methods and should only be used as a last resort.

Rectal temperature (T_{re})

The rectum is one of the most often used methods for core temperature determination, as well in hospital as in laboratories as at home. Currently, electronic devices have replaced the mercury devices on the home market, laboratories mostly use a flexible catheter. Usually a minimum insertion depth of about 8 cm is accepted. ISO/CD 9886 (19) recommends an insertion depth of >10 cm for scientific studies, as insertion depth may affect the temperature readings by 0.1-0.2°C (63).

The rectum provides a stable temperature measurement, because it consists of a large mass of deep body tissue and is not affected by environmental conditions (64-66). For some people it is an acceptable measurement, but others find it uncomfortable, dislike the concept or consider it unhygienic. For children it may be traumatic. An important issue regarding T_{re} is the considerable delay time of up to 10-20 min in response to changes in central blood temperature, which makes the method unsuited for monitoring rapidly changing body temperatures (7; 65; 67). Rectal temperature has a slow response, because blood flow to the rectum is low and the mass of organs in the body cavity is large, requiring a greater amount of energy to change temperature (64; 65; 68; 69). Further, T_{re} may be confounded by cold blood from vasoconstricted legs, warm blood from exercising legs, insulation by feces or heat-producing bowel organisms (55).

Comparative analysis. In a stable situation, T_{re} has been found to be about 0.2°C higher than T_{es} (25; 32) and provides a reliable indication of the thermal situation of the body. When body heat content changes rapidly, it should be recognized that T_{re} can differ substantially from faster responding measures like T_{pa}, T_{es} and T_{ty} (7; 25). Proulx et al. (69) showed for example marked T_{re}-T_{es} differences during their warming/cooling protocol. They concluded that T_{re} did not provide a timely thermal status of the vital organs. This may have dangerous consequences, for example during treatment of hyper/hypothermia (65; 69). For the same reason, using T_{re} as a reference for other measurement methods (70-73) may be hazardous. Hansen et al. (71) and Roth et al. (73) measured T_{re} and T_{ty} in heat-suffering marathon runners. They found T_{ty} to be significantly lower and therefore discouraged the use of T_{ty}. However, the ?10-20 min time delay of T_{re}, possibly explaining the difference, was ignored.

So in a stable situation with well controlled insertion depth, T_{re} is suited as a general reference for core temperature (25). In rapidly changing thermal conditions, T_{re} does not provide an appropriate indication of central blood temperature, but still reliably indicates the temperature in the thermally vulnerable abdominal cavity. This might still be valuable information.

Contraindications. T_{re} measurement is contraindicated for the following conditions: gastrointestinal/rectal bleeding, following rectal surgery, bleeding tendency (e.g. leukemia, thrombocytopenia), prolapsed rectum, imperforate anus, severe diarrhea, local infections, immuno-compromised state, heart condition (the thermometer probe could stimulate the vagus nerve in the rectum and cause cardiac arrhythmias), severe haemorrhoids (when a thermometer would damage a haemorrhoid this could result in bleeding and pain). For children who are premature, under one year of age or have an oncology diagnosis, T_{re} measurement is also contraindicated.

Bladder temperature (T_{bl})

Urine temperature is representative of body core temperature, as urine is a filtrate of blood plasma (18). One way of measuring urine temperature is directly in the bladder. This is only possible in clinic in patients who require urinary catheters and in that case, it causes little additional discomfort. Although response time is slightly faster than T_{re}, there is a significant delay when body heat content fluctuates (20; 55).

Comparative analysis. Most studies show good agreement between T_{bl} and other core temperature measures. Patient studies found differences with T_{pa} of 0.03 ± 0.23°C and -0.21 ± 0.20°C (4; 27). They concluded that T_{bl} and T_{es} are more reliable for estimating core temperature in critically ill patients than T_{re} and T_{ax}. Nimah et al. (62) also reports good correlation of T_{bl} and T_{pa} in their study with febrile children. Fallis (20) reviewed several studies to T_{bl} measurements and states that these studies support the use of T_{bl} as an index of core temperature during times of thermal stability. So it appears that under steady state conditions, T_{bl} is a reliable method to measure core temperature in patients requiring a urinary catheter. Under thermally unstable conditions, other methods are preferable.

Urine temperature (T_{ur})

Besides measuring inside the bladder, urine temperature can also be measured outside the body, placing a sensor with short response time directly in the flow of urine (67). The ambient temperature is recommended to be between 15 and 25°C (19). The non-contact nature of this method is an advantage, but it is has some practical limitations like the fact that it can only be used during urination. Further, just like T_{re}, the time constant is quite long (67). T_{ur} appears to be systematically lower than T_{re} by 0.2-0.5°C and is not highly reliable (18; 67). It might be used for comparative or supportive purposes, or when other methods are unacceptable (18), but is not a preferable method.

Vaginal temperature (T_{va})

Vaginal temperature is an alternative for rectal temperature in females. However it is not generally acceptable and has no advantage over rectal temperature (18).

A.2 INFRARED (IR)

IR thermometry determines the temperature of an object by measuring the IR radiation from its surface. The wavelength of IR radiation corresponding to body temperatures between 36 and 40°C is 9.38-9.26 µm (15). It is a non-invasive, convenient and safe measurement technique with little delay (73). But it is a disadvantage that measurement results can be affected by the position towards the measurement surface, heating of the detector and use of a probe cover (74). Further Pusnik and Drnovsek (74) showed that many commercially available IR devices do not meet the calibration standard (ASTM, 1998 and CEN12470-5, 2003). An IR thermometer has to be calibrated at regular intervals using a black body radiator and reference thermometer.

Tympanic temperature – IR ($T_{ty\text{-}ir}$)

Next to direct contact, T_{ty} can also be determined indirectly by an IR thermometer. The IR tympanic thermometer measures the IR radiation emitted by the tympanic membrane. Using IR sensors increases safety, speed and comfort of tympanic measurements. Because of the high acceptability for subjects (75) it is a very popular method for clinical and private use.

However, there is a major risk of underestimating the real T_{ty} and thus incorrectly estimating core temperature. The ear canal is shaped irregularly and a measurement is easily taken too superficial or aiming in the wrong direction (25; 36). As a result, the view at the tympanum is compromised and the relative contribution of the temperature of the ear canal wall increases. External conditions affect this temperature increasingly as one gets further from the tympanum (36; 37; 48). Other blockades that affect the visibility of the tympanum, like cerumen and to a minor extent hair, may cause an underestimation as well (25).

Comparative analysis. The methodological issues of $T_{ty\text{-}ir}$ measurement might well explain the fact that studies to commercial IR devices have shown very divers research results in comparison to other temperature measures, with often a high variability. Compared to a standard reference, the 95% limits of agreement (LoA) exceed in many studies ±1.0°C (3; 5; 7; 25; 27; 62; 76; 77), which is an unacceptable level (70). Daanen et al. (25) found that ear canal circumference is the most reliable parameter in explaining differences of T_{es} with T_{ty}. Currently, $T_{ty\text{-}ir}$ does not seem to be a reliable measurement method for core temperature determination (78), although it may be usable for monitoring rough changes in core temperature during exercise (72).

Contraindications: An infected or draining ear, a lesion/incision adjacent to the ear, otitis media or sinusitis, premature infants with a small ear canal.

Temporal radiation temperature (T_{tr})

Measuring the radiant skin temperature at the region of the superficial temporal artery is a quite recent way of determining core temperature. This major artery of the head has a constant blood flow because it lacks arteriovenous anastomoses. Further it is fast responding to temperature changes. The reliable blood flow theoretically allows for an accurate calculation of the arterial temperature, taking into account the heat losses to the environment (79). The thermometer measures the emitted IR heat and ambient temperature at the measurement site and synthesizes these into the body temperature (55).

This contact free IR measurement is simple, convenient and safe. Besides the fast response time, the costs are low and it can be used in sleeping subjects. So the method seems very suitable for measuring patients, babies and children. However, few validation trials have been carried out so far and reliability is questionable.

Comparative analysis. Two studies found that the temporal radiation thermometer performs well in stable periods, but does not agree to T_{re} and T_{es} during periods of increasing body temperature (80; 81). In a study on adults and children with mild fever, T_{tr} differed >0.5°C in more than 89% of the measurements (82). In studies with infants only, sensitivity and specificity for detecting rectal fever <39°C was rather poor as well (83; 84). More recently, Rubbens (85) compared T_{tr} with T_{re} and T_{ty} in 48 child patients at rest and found values that were 0.63 ± 0.43 and 0.94 ± 0.89°C lower respectively. The distance between T_{tr} device and temporal skin may have been a cause for these large offsets. The head-thermometer distance should be 1-2 cm, because T_{tr} decreased when at greater distances. Further research has to prove whether the T_{tr} method with a corrected offset and a short head-thermometer distance is clinically useful for infants and/or adults.

Infrared thermography

IR thermography involves the composition of a thermal image of the body, reflecting emitted radiation. This is largely determined by superficial temperature and is usually applied for diagnostic purposes or neonatal monitoring (86-88). However, the method has also been used for mass screening of fever (88; 89), predicting core temperature from the thermal image of the entire face (90) or more specific the ear (91) or the inner canthus of the eye (92). The latter is supplied by the internal carotid artery, which is thought to provide a better estimation of core temperature than the external carotid which supplies most of the face. However, reliability of IR thermography for core temperature estimation is questionable (93). Chapter 3 is focused on this subject.

Near infrared spectroscopy (NIRS)

The spectral change of near infrared light returned from biological tissue is temperature dependent. Penetrating a few centimetres into the body, it can provide an estimation of core temperature, but in vivo research is scarce.

A.3 RADIO WAVES

Radio waves are a type of electromagnetic radiation with a frequency from about 300 GHz to 300 Hz, containing temperature dependent information. This could allow for convenient non-invasive temperature measurement. However, apart from the temperature pill, most methods are only at the initial stage of development.

Intestinal temperature measured by a temperature pill (T_{pill})

The temperature in the abdominal cavity can be measured by a temperature pill, which is swallowed and passes gradually through the gastro-intestinal tract. These temperature pills contain a quartz crystal, which vibrates at a frequency relative to its surrounding temperature. The low frequency FM signal of the crystal is received outside the body (radio telemetry) and converted into a temperature value. As such, it is a convenient and wireless alternative for the traditional measurement methods, especially suitable for operational settings and/or long-term recordings.

Gastrointestinal temperature is not influenced by environmental conditions and is reported to respond slightly faster than rectal temperature (94). However, food, drinks and saliva might affect temperature measurements as long as the pill is located in the stomach. Therefore, the pill is recommended to be swallowed 6 h before the start of measurement in order to reach the intestinal tract (95). As transit time varies from eight hours to five days, the exact measurement location is unknown and there is a risk that the sensor is expelled before finishing the measurement. Further disadvantages are that the pills are quite expensive, may be difficult to swallow and its measurement might be disturbed by gastrointestinal motility and electromagnetic interference (94; 96; 97).

Comparative analysis. In a recent review, Byrne and Lim (94) showed that there is an acceptable level of agreement between T_{pill} and T_{es} (systematic bias <0.1°C and 95% LoA within ±0.4°C). The 95% LoA of T_{pill} with T_{re} were also acceptable, though there was a systematic bias of >0.1°C. Response time of T_{pill} was slower than T_{es}, but faster than T_{re}. Byrne and Lim (94) conclude in their review that T_{pill} is a valid index for core temperature in ambulatory field-based applications, though they state that care should be taken to

control sensor calibration and ingestion time. Chapter 5 discusses the use of T_{pill} during high intensity exercise.

Contraindications. T_{pill} should not be used in patients who weigh less than 36 kg, have a known or suspected obstructive disease of the GI tract, exhibit or have a history of exhibiting gag reflex impairment, have undergone GI surgery, have felinization of the esophagus, have a hypomotility disorder of the GI tract, have a cardiac pacemaker or other implanted electromedical device or might undergo magnetic resonance imaging while the sensor is still in the body

Magnetic resonance imagery (MRI)

The last decade, MRI is emerging as a tool to measure deep body temperatures non-invasively. Nuclear magnetic resonance measures proton motion, which is dependent on temperature. This magnetic resonance signal can be translated into a picture of the human body by MRI. Several MRI based methods have been studied for this purpose and some of them are already being applied during thermotherapy of tumours. Recent literature indicates that some MRI based methods, particularly proton MR spectroscopy, may also be suited to determine human brain temperature (98).

A great disadvantage is the fact that MRI devices are bulky and expensive. Miniaturisation of the technique might give it potential for success in practice (67). Further, the procedure takes at least 30 min, although new techniques claim to reduce measurement time to about 3 min (99). Finally, the technique is unsuited for people with conductive implants.

Comparative analysis. Comparative temperature studies with MRI are scarce. Comparisons in gel phantoms resulted in acceptable deviations within 0.3°C of reference temperature (100-103). However, some exploratory papers on the measurement of brain temperatures in vivo report more variable data (101; 102; 104; 105). Repeated measurements on individual voxels showed a standard deviation of 1.2°C (102) and an average difference with T_{re} of 1.3 ± 0.4°C was found (104). A complication in these studies is that a reliable reference for brain temperature is unavailable. Currently, measurement precision may be sufficient for pathophysiological studies to brain

disorders (102) or for monitoring long term temperature changes (105), but further improvements are required for usable absolute temperature measurements.

Microwave radiometry

Microwaves are radio waves with lengths of a metre to a millimetre. The microwave spectrum is temperature dependent and has been explored for temperature measurement of subcutaneous tissue and the neonatal brain (106; 107). Although the method is more practical than MRI and penetrates deeper than IR thermography, it suffers from electrical interference and a poor spatial and temporal resolution (108).

Ultrasound

The time and frequency spectrum of ultrasound reflection is temperature dependent and might be used for core temperature estimation. Ultrasound is cheaper and easier to measure than MRI. So far, this method has shown potential for monitoring tissue temperature change during thermotherapy (109; 110).

A.4 HEAT FLOW

In 1973, Fox et al. (111) were the first to develop a zero heat flux (ZHF) sensor in order to conveniently measure core temperature at the skin. ZHF sensors locally insulate the skin, ensuring the particular patch of skin is warmed by the natural heat flow from the body core to the skin. When the core and skin come into thermal equilibrium, a situation of zero heat flux has been reached and core temperature can be measured at the skin.

The probe of a ZHF thermometer consists of two thermistors, of which the lower one is in contact with the skin. The thermistors are separated by a thermal insulator and a heating element is mounted on top of the probe. The heater is set to drive the heat flux between the thermistors to zero in order to eliminate heat loss from the skin. The probe has to function as an ideal insulator, since it has to prevent heat loss from the skin surface beneath the probe (112-114).

ZHF sensors are acceptable for subjects and quickly respond to temperature changes (18). They require a very good insulation of the used skin from external influence. A

disadvantage is the long start-up time and the requirement of power supply. Further, it is not entirely known to what extent a ZHF sensor really reflects the core temperature beneath it and which body site is most suitable for measurements. A suitable body location has low skinfold thickness and few large veins (112). The deeper the sensor has to measure, the larger the required sensor, measurement time and power supply, which is not desirable. Typical body locations for ZHF sensors are the sternum, forehead and occipital region of the head.

Gunga et al. (70) developed an innovative heat flux device. Their 'Double Sensor' does not contain a heating element, which brings the heat flux down to zero. Instead, it predicts core temperature mathematically by analysing skin temperature, heat flux through the sensors and heat losses through the exterior surface. This improves the start-up time and decreases power supply.

Comparative analysis. Research on heat flux sensors is scarce, but some promising results have been achieved, especially for clinical use (70; 114-116). Compared to T_{es}, 95% levels of agreement of −0.59 to 0.36°C have been reported during hypothermic therapy (114), while differences of 0.2 ± 0.3°C have been observed during gynaecological surgery (116). The Double Sensor achieved 95% limits of agreement of −0.72 and +0.55°C (115). Future research should investigate the optimal location, improve its performance under different conditions and reduce delay time. In chapter 2 ZHF measurement is discussed more extensively, including the results of newly developed sensor.

Contraindications. Wounded or inflamed skin at the measurement location.

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SAMENVATTING

Meten en manipuleren van lichaamstemperatuur in rust en tijdens inspanning

Een te hoge of lage lichaamstemperatuur kan ernstige gevolgen hebben voor de gezondheid en het prestatievermogen. Het is dus belangrijk om lichaamstemperatuur makkelijk én betrouwbaar in de praktijk te kunnen meten, met name in een medische setting, in bepaalde arbeidsomstandigheden en in de sportwereld. Er zijn vele meetmethoden beschikbaar op verschillende plekken van het lichaam, maar elke methode kent de nodige bezwaren. Vooral het continu meten van (veranderingen in) de lichaamstemperatuur in het veld blijft een uitdaging. Daarom worden in de eerste sectie van dit proefschrift de voor- en nadelen van vier praktisch toepasbare meetmethoden voor de bepaling van kerntemperatuur in rust en tijdens inspanning in kaart gebracht.

In **Hoofdstuk 2** wordt een studie beschreven naar een nieuw ontwikkelde 'zero heat flux sensor', die aan de hand van de warmtestroom op het voorhoofd de temperatuur van de lichaamskern bepaalt. Deze sensor blijkt in een warme stabiele omgeving een betrouwbaar instrument voor het continu meten van de kerntemperatuur, ook bij snelle stijging en daling. Wel heeft de sensor een lange opstarttijd en zijn er verbeteringen nodig in het gebruiksgemak voordat de sensor breed toepasbaar is in de praktijk.

In **Hoofdstuk 3** wordt besproken in hoeverre infrarood warmtebeelden, die onder andere zijn gebruikt voor screening op koorts tijdens recente epidemieën, veranderingen in kerntemperatuur bij gezonde mensen weergeven. Dit bleek nauwelijks het geval en daarom ontraden we het gebruik van deze methode voor schatting van de kerntemperatuur, hoewel verificatie bij koortspatiënten zinvol zou zijn.

Hoofdstuk 4 beschrijft een studie over temperatuurmeting in het oorkanaal met behulp van een in een oorstukje geïntegreerde sensor. Dit zou een praktische methode voor continue schatting van de kerntemperatuur in het veld kunnen zijn, maar de meting bleek gevoelig voor veranderingen in omgevingscondities en individuele verschillen. Daarom is deze oormeting op het moment slechts op groepsniveau bruikbaar en alleen in een warme en stabiele omgeving.

Hoofdstuk 5 bespreekt een studie naar inslikbare temperatuurpillen, die vaak worden gebruikt om kerntemperatuur in het veld vast te stellen. Het huidige experiment testte deze pillen tijdens grote temperatuursveranderingen in korte tijd. De piltemperatuur kwam goed overeen met de enigszins gedempt en vertraagd reagerende rectaaltemperatuur, maar bleek in deze situatie niet geschikt om de snel fluctuerende bloedtemperatuur te monitoren.

Deze hoofdstukken bevestigen de stelling dat er niet één enkele kerntemperatuur bestaat en dat er nog geen universele meetmethode is. Kennis van de voor- en nadelen van sensoren en meetlocaties, erkenning van de natuurlijke thermische verschillen over het lichaam en bewustzijn van het doel en de omstandigheden van een meting, zou moeten bepalen welke methode het meest geschikt is in een bepaalde situatie. Met betrekking tot continue monitoring in ziekenhuizen lijkt de zero heat flux methode veelbelovend. Het blijkt een nauwkeurige methode met een korte responstijd en comfortabel voor patiënten. Voor toepassing in het veld heeft het huidige zero heat flux systeem echter nog veel bezwaren. De in een oorstukje geïntegreerde sensor is in dat opzicht praktischer, maar bleek zeer gevoelig voor veranderende omgevingscondities. Dientengevolge lijkt de temperatuurpil, ondanks praktische bezwaren als de innametijd en de kosten, momenteel nog de aangewezen keuze voor veldmetingen.

De tweede sectie van dit proefschrift richt zich op warmtebelasting tijdens inspanning en de effecten hiervan op het prestatievermogen. Inspanning in combinatie met zware klimatologische omstandigheden en/of het dragen van beschermende kleding betekent een zware thermische en cardiovasculaire belasting voor het lichaam. Meer kennis van de mechanismen die ervoor zorgen dat warmtebelasting het prestatievermogen beïnvloedt alsmede optimale methodes om deze mechanismen te manipuleren, zou kunnen leiden tot een toename van prestatie, welbevinden en veiligheid tijdens inspanning in de warmte. Daarom zijn er drie studies uitgevoerd die de fysiologische, perceptuele en prestatieve effecten van precooling (lichaamskoeling voorafgaand aan de inspanning), wind en beschermende kleding hebben bestudeerd.

Hoofdstuk 6 gaat over de tegengestelde belangen van warming-up en precooling in voorbereiding op een duurinspanning. Warming-up, inname van ijsslurrie en koeling van de schedel werden in verschillende combinaties toegepast voorafgaand aan een 15 km

fietstijdrit in de warmte. Het voorbereidingsprotocol dat resulteerde in de laagste warmte-inhoud van het lichaam en koelste gevoel bij de start van de trial (ijsslurrie + schedelkoeling), bleek het meest voordelig voor het vermogen aan het eind van de trial, hoewel eindtijden niet significant verschilden. Het precoolen van de kern met ijsslurrie bleek effectiever dan het precoolen van de schedel.

Hoofdstuk 7 bespreekt een tweeledig experiment naar de effecten van windkoeling tijdens inspanning in de warmte. Wind verminderde de fysiologische warmtebelasting door het koelen van de huid. Dit leidde direct tot voordelige effecten op de ervaren mate van koelte, comfort en inspanning en resulteerde in een duidelijk snellere eindtijd. Wanneer echter de warmtebelasting constant gehouden werd, door tegelijk met de windkoeling de temperatuur en luchtvochtigheid te verhogen, leidde dit wel tot een koeler gevoel, maar was er geen effect meer op het thermische comfort en de prestatie.

Hoofdstuk 8 beschrijft een verkennend onderzoek bij ijshockey goalies. Zij zouden vatbaar kunnen zijn voor warmteproblematiek vanwege het beperkte warmteverlies door het dragen van beschermende kleding. Tijdens een trainingssessie bleek de kern- en huidtemperatuur echter slechts gematigd toe te nemen. Het lichaamsgewicht was significant afgenomen door vochtverlies, maar dit overschreed de algemeen geaccepteerde limiet van 2% niet. Ook werd er geen achteruitgang in cognitief functioneren en/of prestatie vastgesteld.

De fysiologische warmtebelasting en het gevoel van comfort zijn bepalende factoren voor duurprestaties in een warme omgeving. Het vooraf innemen van ijsslurrie blijkt in die omstandigheden dan ook minstens zo effectief als een gewone warming-up. Ook heeft koeling door wind tijdens een inspanning in de warmte een zeer positief effect op belasting, comfort en prestatie. Grenswaardes voor warmtebelasting (WBGT) houden hier onvoldoende rekening mee en zouden beter afgestemd moeten worden op de windcondities. Wind kan ook een simpel middel zijn om tijdens evenementen of werksituaties in een warme omgeving het welbevinden te bevorderen en gezondheidsrisico’s te verminderen. Ten slotte bevestigde het onderzoek bij ijshockey goalies dat warmtebelasting ook voorkomt tijdens inspanning in koele condities wanneer het warmteverlies beperkt wordt door het dragen van beschermende kleding. Extra koeling lijkt in dit geval echter niet noodzakelijk.

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CURRICULUM VITAE

Lennart Teunissen was born on June 19, 1981 in Amersfoort, The Netherlands. In 1999, he finished secondary school at Stedelijk Gymnasium Johan van Oldenbarnevelt in Amersfoort. After obtaining his premedical exam at Utrecht University in 2000, he travelled for half a year through Australia and Indonesia. Back home in 2001, he started the study of Human Movement Sciences at VU University Amsterdam. This included several activities as student-assistant, a teacher's course and a practical internship at LifeGuard (health & performance management). In 2005-2006, he performed his research internship at the VU concerning the influence of pacing strategy on energy expenditure in high intensity cycling. During this period, he received the Gerrit-Jan van Ingen Schenau Award for Promising Young Scientists. This enabled him to consecutively conduct another research internship at the University of Colorado (USA), studying the independent effects of body weight and body mass on the metabolic cost of running. In 2007, he graduated cum laude. After shortly resuming his work for LifeGuard, he started his PhD project in June 2008. This concerned a cooperative project of the Faculty of Human Movement Sciences (VU University Amsterdam) and research institute TNO at Soesterberg, focused on the topics discussed in this thesis. Next to his scientific interest, he is also engaged in human movement in practice, being sixfold medallist at the national championships triple jump, certified track & field trainer and mentor of novice trainers.