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.
REFERENCES

3. Rissanen S. *Quantification of thermal responses while wearing fully encapsulating protective clothing in warm and cold environments*. University of Oulu, Oulu, Finland, 1998.


