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Original Article

A Comparative Study of Two Ambulatory Core Temperature Assessment Methods

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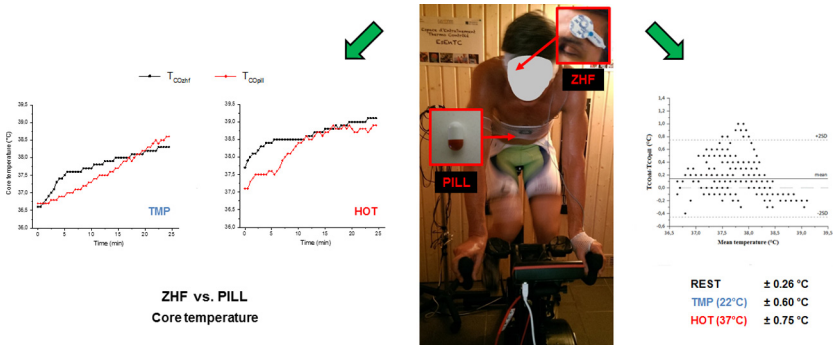
Highlights

- ZHF sensor performance level appears as similar in both ambient conditions.
- ZHF temperature is not reliable with intestinal temperature during exercise.
- Heterogeneity of individual ZHF temperature responses is significant.
- Forehead core-to-skin gradient indicates endurance performance level in the heat.

Graphical abstract



Abstract

Background. Given the need to identify reliable non-invasive solutions for core temperature ambulatory monitoring, the purpose of this study was to evaluate the performance of zero-heat-flux (ZHF) temperature sensor on the forehead (T_{COzhf}) by comparing it with intestinal temperature (T_{COpill}) in different ambient and physiological conditions.

Methods. Seven trained male subjects were followed during a 45-min rest period (STA) and a 25-min self-regulated cycling exercise performed in neutral (TMP, 22.8 °C) and hot (HOT, 38.5 °C) ambient temperature.

Results. T_{COzhf} values differed from T_{COpill} of -0.23 ± 0.13 in STA, 0.15 ± 0.30 °C in TMP and 0.28 ± 0.38 °C in HOT. The 95% limits of agreement showed an acceptable bias between T_{COzhf} and T_{COpill} in STA (±0.26 °C), but not in TMP and HOT (±0.60 and ±0.75 °C).

Conclusion. The non-invasive ZHF sensor gave an accurate estimation of T_{COpill} in steady state but not during exercise. However, complementary results let suppose that ZHF performance is not affected by ambient conditions and could be a relevant alternative for deep body temperature measurement during whole-body heat stress.

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1. Introduction

Continuous non-invasive monitoring of biological vital markers in sports applications has become a major challenge of technological innovations [1]. Progressive spread of heart rate chest belts in the 80's, followed by recent development of new sensors-based wearable devices, provides a relevant approach for athletes training monitoring. In parallel, major sporting events taking place in hot and dry/humid places require innovative solutions to prevent heat-related exhaustion. Further studies indeed demonstrate that aerobic performance decreases as the ambient temperature increases [2]. Core temperature (T_{CO}) values upper to 40 °C are generally associated to physiological heat stress affecting blood perfusion in brain and active muscles, and leading to an early fatigue state [3]. Maintaining a large core-to-skin gradient therefore preserves the thermoregulatory balance during a prolonged exercise. In this framework, the core-to-skin temperature gradient has recently identified as more indicative of performance in heat strain during an incremental exercise to volitional exhaustion [4]. Therefore, T_{CO} follow-up in ecological and ambulatory conditions should be shared from reliable and accurate monitoring.

Pulmonary artery and oesophageal methods have been validated as gold standard for T_{CO} measurement [5], however these assessment techniques are not tolerated in ambulatory conditions. Recent technical evolutions such as miniaturizing of sensors, telemetry and data loggers, provide an ability to estimate T_{CO} from gastrointestinal temperature (T_{COpill}) without causing discomfort. Several studies reported a very low bias (i.e. <0.1 °C) and reliable agreements (i.e. 95% limits of agreement – 95% LoA – in a level of ±0.5 °C) with oesophageal temperature for exercises taking place in warm conditions [6,7]. Heat stress-related haemodynamic responses during exercise might however put in perspective the use of this method during field-based sessions [8]. A suitable non-invasive alternative would be the transcutaneous measurement of deep-body temperature from a zero-heat-flux (ZHF) sensor. Following the first ZHF probe model designed by Fox and Solman [9], technical developments have been progressively brought by new devices [10]. Reliability was validated versus pulmonary artery blood [11] or nasopharyngeal temperature assessment [12] in preoperative general anaesthetic state. But only one study proposed forehead ZHF temperature (T_{COzhf}) measurement before, during and after a physical exercise in the heat, giving acceptable 95% limits of agreement of ±0.4 °C with oesophageal temperature [13].

Therefore, there is an actual need to explore the reliability of this method under different ambient and physiological (i.e. rest vs. exercise) conditions [14]. The purpose of this study was to determine, for healthy subjects, the degree of accuracy and reliability of T_{COzhf} for T_{COpill} estimation in rest and exercise conditions. Self-regulated exercise was reproduced in two different ambient exposures (i.e. neutral/dry vs. hot/dry temperature). We hypothesized, from using Bland and Altman's method, acceptable limits of agreement for T_{COzhf} (i.e. within ±0.5 °C) in all conditions.

2. Materials and methods

2.1. Subjects

Seven healthy and trained male subjects (age 27.3 ± 9.6 yr, height 1.78 ± 0.10 m, body weight 69.8 ± 8.4 kg, body surface 1.87 ± 0.17 m^2, maximal oxygen uptake 61.0 ± 2.5 ml min^{-1} kg^{-1}) were included in the current protocol. Somatic or cardio-respiratory disorders, fever in the last seven days, osteo-myo-articular injury or prior heat acclimation or acclimatization in the last month were considered as exclusion factors. All subjects were informed about constraints and risks related to the experimental protocol and gave written voluntary consent prior to the study. All experimental procedures were conformed to the Declaration of Helsinki and were approved by the local ethics committee of the University of Toulon.

2.2. Experimental protocol

In the current protocol, subjects were invited to come to the laboratory on four separate sessions. Prior written instructions were given as to drink a sufficient water volume, limit all consumption of caffeine, nicotine and alcohol for 24 hours prior to each session, and have the same diet for the two meals preceding each session. All trials started at the same hour of the day (±1 hour) in order to limit circadian rhythm effects on physiological variables and gastrointestinal transit time. Subjects completed this experimental protocol in 5 weeks with a minimum period of 72 hours between visits.

The inclusion visit allowed to take some anthropometrics measurements and to complete a familiarization with the experimental procedures. Peak power output (PPO) and maximal heart rate (HR_{max}) were determined through an incremental test (6-min warm-up at 100 W + 30 W per 2-min stage) until volitional exhaustion, using an electronically braked cycle ergometer (Schoberer Rad Messtechnik, Jülich, Welldorf, Germany).

On the three following separate sessions, subject wore a cycling short, synthetic socks, his own cycling shoes and were bare-chested. Upon his arrival at the laboratory urine density (SG) was measured, subject was thus considered as euhydrated if SG ≤1.02 g/ml. Then he was equipped of a heart rate monitor and temperature sensors.

Initial rest measurements were achieved during the first session (STA). Subjects remained for 45 min seated in front of a personal computer, in a neutral and comfortable ambient environment (22.4 ± 1.9 °C), for watching of an emotionally neutral documentary film previously chosen by the experimenters.