Journal of Thermal Biology 45 (2014) 141–149

Contents lists available at ScienceDirect

Journal of Thermal Biology

journal homepage: www.elsevier.com/locate/jtherbio

Reliability and validity of skin temperature measurement by telemetry thermistors and a thermal camera during exercise in the heat

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ARTICLE INFO

Article history:
Received 2 July 2014
Received in revised form
7 August 2014
Accepted 21 August 2014
Available online 3 September 2014

Keywords:
Reliability
Validity
Skin temperature
Thermal camera
Heat stress
Exercise

ABSTRACT

New technologies afford convenient modalities for skin temperature (T_{SKIN}) measurement, notably involving wireless telemetry and non-contact infrared thermometry. The purpose of this study was to investigate the validity and reliability of skin temperature measurements using a telemetry thermistor system (TT) and thermal camera (TC) during exercise in a hot environment. Each system was compared against a certified thermocouple, measuring the surface temperature of a metal block in a thermostatically controlled waterbath. Fourteen recreational athletes completed two incremental running tests, separated by one week. Skin temperatures were measured simultaneously with TT and TC compared against a hard-wired thermistor system (HW) throughout rest and exercise. Post hoc calibration based on waterbath results displayed good validity for TT (mean bias [MB] = −0.18 °C, typical error [TE] = 0.18 °C) and reliability (MB = −0.05 °C, TE = 0.31 °C) throughout rest and exercise. Poor validity (MB = −1.4 °C, TE = 0.35 °C) and reliability (MB = −0.65 °C, TE = 0.52 °C) was observed for TC, suggesting it may be best suited to controlled, static situations. These findings indicate TT systems provide a convenient, valid and reliable alternative to HW, useful for measurements in the field where traditional methods may be impractical.

1. Introduction

Skin temperature (T_{SKIN}) measurement has application for research (Harper-Smith et al., 2010), occupational health (Kim et al., 2013) and clinical monitoring (Sherman et al., 1996). It is through the skin that the body loses or gains heat and as such, T_{SKIN} plays an important role in human thermoregulation. T_{SKIN} is a consequence of dermis microcirculation, which is mediated through activity of the sympathetic nervous system and regulated by the hypothalamus. Typically T_{SKIN} may initially reduce during exercise as a consequence of sweat on the skin surface and blood shifting towards working skeletal muscles (Torii et al., 1992). However, a steady rise is observed during endurance exercise as core temperature (T_{CORE}) increases, with elevated ambient temperatures increasing the rate of T_{SKIN} increase (Roberts and Wenger, 1979). Whilst T_{SKIN} may be interpreted in isolation, it also forms a component of derivative calculations of heat strain, such as body heat content (Jay and Kenny, 2007) and mean body temperature (Jay et al., 2007). Such calculations assist in understanding the mechanisms underpinning practical thermal interventions such as precooling and heat acclimation, by providing an objective measure of whole-body thermal dynamics.

Typically, T_{SKIN} has been measured using thermocouples or wired thermistors with recent literature adopting wired thermistors as the criterion measure when validating new tools (Kelechi et al., 2011; Buono et al., 2007; Burnham et al., 2006). A thermocouple is a temperature-measuring device consisting of two dissimilar conductors that contact each other at one or more joint locations. It produces a measureable electrical potential difference proportional to the temperature difference against another joint which is set at a reference temperature in another part of the circuit. Thermistors are resistors in which resistance varies with temperature, allowing stored calibration data within the circuit to convert this to a temperature. Such devices have been shown to be robust and accurate to 0.045 °C across a range (10–40 °C) of waterbath temperatures (Harper-Smith et al., 2010). Thermistors and thermocouples are non-invasive, but the associated wiring requires familiarisation and a hard-wired connection to a datalogger, making field testing problematic. This in turn, limits the external validity of thermal interventions which are untested in the field.

Recent developments in wireless thermometry provides an alternative to hard-wired systems, particularly as some telemetry devices appear more accurate than wired thermistors (Harper-Smith et al., 2010), require little familiarisation and provide

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http://dx.doi.org/10.1016/j.jtherbio.2014.08.010
0306-4565/

freedom of movement for the person being measured. Harper-Smith et al. (2010) examined wireless iButtons (Maxim Integrated Products Inc., California, USA) in a waterbath as well as on human skin during exercise in hot conditions. Typical error was <0.3 °C, Pearson and Intra-class correlation (ICC) coefficients >0.9 and coefficient of variation (CV) $<1\%$ when compared against wired thermistors which were the criterion measure during exercise. The size and convenience of iButtons undoubtedly affords opportunities for measurements in novel environments, however the lack of real-time data may preclude their use in safety monitoring and research environments. Dermal temperature patches for physiological monitoring systems are wireless and offer live data, but being single-use only, carry significant purchase and consumable costs, which may prohibit use for large sample sizes. Consequently, a newly-developed telemetry system, whereby thermistors are connected to a transmitter worn on the person, may offer the benefits of live data without long, trailing connecting wires or being restricted to the laboratory.

Infrared thermometry is another technique that is used in research (Costello et al., 2012) and clinical environments (Ring and Ammer, 2012) where T_{SKIN} is an important variable to measure. Thermal cameras receive and process infrared radiation emitted from a surface, using this information to display the production and dissipation of heat. The ability of a surface to emit energy by radiation is termed 'emissivity' and allows the temperature of the emitting surface to be calculated. Thermopiles or microbolometers within the cameras absorb this infrared radiation, eliciting a change in electrical resistance that a colour palette can use to display temperatures of an object. Handheld infrared thermometers provide temperature at specific points based on the same principle and are widely used for measuring core temperature via the tympanic membrane and increasingly for T_{SKIN} (Ring and Ammer, 2012). Measurements from such devices demonstrate strong association with wired thermistors, providing valid measures of mean T_{SKIN} at rest ($r=0.95$) and whilst walking in the heat ($r=0.98$, Buono et al., 2007). This technology appears reliable, with mean inter-examiner intraclass correlation of $r=0.88$ (range 0.73–0.99) between T_{SKIN} measurements on consecutive days (Zaproudina et al., 2008). The majority of literature utilising thermal cameras as a measure of T_{SKIN} has involved thermogram images taken at rest being retrospectively analysed using software to identify area average temperatures for specified regions of anatomical interest. Measuring temperature across a region of interest enhances construct validity by helping to avoid inter-individual variation of veins and vascularisation and the consequential non-uniform heat production, a potential confounding error when taking readings from a single spot on an image or from attached thermistors (Chudecka and Lubkowska, 2012). Broadly, this technique has been shown to be valid (correlation range $r=0.71$–0.77, Roy et al., 2006) and reliable (correlation range $r=0.82$–0.97, Selfe et al., 2006), such that it has been recommended for clinical use (Ng et al., 2004; Ring and Ammer, 2012). However, large errors versus a thermocouple during rest and exercise have also been reported (-0.75 °C, Fernandes et al., 2014), making it unclear within which situations it may have application. Recent developments in thermal camera technology permit high speed imaging, offering a real-time thermal image, such that cameras can produce whole images for post hoc analysis as well as instantaneous spot analysis. These improvements allow simultaneous comparison against other T_{SKIN} measures, facilitating an objective assessment of the potential of thermal cameras as a multi-purpose tool for environmental exercise physiology research.

To our knowledge, wired thermistors, telemetry thermistors and a thermal camera have not been compared simultaneously for live T_{SKIN} measurement during exercise in hot environments. Therefore, the aim of this study was to compare the reliability and validity of these measurement tools for live T_{SKIN} measurement in athletes exercising in a hot and humid environment. We hypothesized that telemetry thermistors and a thermal camera would provide acceptable levels of error for both reliability and validity when compared against hard wired thermistors during exercise in the heat

2. Methods

2.1. Experimental design

The study was organised into two parts; a waterbath comparison and human skin temperature measurement during exercise. Both parts of the study assessed validity and reliability of tools. During the waterbath analysis, data was collected for 20 min across seven stable temperatures within the range 25–40 °C. Stability was defined as a deviation of no more than 0.1 °C measured by the criterion thermocouple over 5 min consecutively. Retest reliability was examined on the following day. In order to assess the measurement tools in a relevant context for endurance exercise in the heat, an incremental exercise test was completed on each athlete volunteer. Re-tests of T_{SKIN} measurements were separated by one week to prevent an acclimation effect (Barnett and Maughan, 1993) and taken at the same time of day (Winget, 1985), with the second trial data used for validity analysis.

2.2. Participants

Fourteen male recreational club runners volunteered as participants (mean [SD]): age 38 (11) years, stature 179 (8) cm, mass 77.3 (7.1) kg, sum of skinfolds 33.6 (7.7) mm, $\dot{V}O_{2max}$ 57.3 (4) mL kg^{-1} min^{-1}. Each participant provided written informed consent and stated their recent medical history. Ethical approval was provided by the institutional ethics committee following the principles outlined by the Declaration of Helsinki of 1975, as revised in 2008. Participants were asked to replicate their diet in the 12 h prior to each session and refrain from alcohol, caffeine and strenuous activity for 24 h prior to the measurements as has been previously controlled in similar studies in the field (Harper-Smith et al., 2010).

2.3. Measurement tools

During the waterbath tests, measurements from all thermistors and the thermal camera (TC) were referenced against a multi-point calibrated and certified thermocouple (Type K probe attached to Fluke 51 II instrument, range -200 °C to 1000 °C, divisions 0.1 °C, Washington, US). This thermocouple had been calibrated in a certified laboratory in the last 6 months.

During exercise the criterion measure comprises four hard-wired (HW) skin thermistors (Eltek U-Type EUS-U-VS5-0, Eltek Ltd., Cambridge, UK) connected to a datalogger (Grant Squirrel 1000 series, Grant Instruments, Cambridge, UK). The manufacturer stated accuracy was ± 0.2 °C. This type of device has been adopted as a criterion during similar validity comparisons (Kelechi et al., 2011; Buono et al., 2007; Burnham et al., 2006). The telemetry system (TT) comprises four skin thermistors (ELEU-U-VS-02, Eltek U-Type, Eltek Ltd., Cambridge, UK) connected to a transmitter (Gen II GD38, Eltek, Cambridge, UK, dimensions $6\times8\times5$ cm^3). Data is transmitted wirelessly to a datalogger (Eltek RX250AL 1000 series Wireless Squirrel Logger, Eltek, Cambridge, UK), up to a distance of 2 km. The datalogger was placed outside of the environment chamber approximately 3 m away. The manufacturer stated accuracy was ± 0.1 °C. Both dataloggers were synchronised and