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Measuring core body temperature with a non-invasive sensor

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ABSTRACT

In various occupations, workers may be exposed to extreme environmental conditions and physical activities. Under these conditions the ability to follow the workers' body temperature may protect them from overheating that may lead to heat related injuries. The "Dräger" Double Sensor (DS) is a novel device for assessing body-core temperature (T_c). The purpose of this study was to evaluate the accuracy of the DS in measuring T_c under heat stress. Seventeen male participants performed a three stage protocol: 30 min rest in a thermal comfort environment (20–22 °C, 50% relative humidity), followed by an exposure to a hot environment of 40 °C, 40% relative humidity −30 min at rest and 60 min of exercise (walking on a treadmill at 5 km/h and 2% elevation). Simultaneously temperatures measured by the DS (T_{DS}) and by rectal temperature (T_{re}) (YSI-401 thermistor) were recorded and then compared. During the three stages of the study the average temperature obtained by the DS was within ± 0.3 °C of rectal measurement. The correlation between T_{DS} and T_{re} was significantly better during the heat exposures phases than during resting under comfort conditions. These preliminary results are promising for potential use of the DS by workers under field conditions and especially under environmental heat stress or when dressed in protective garments. For this goal, further investigations are required to validate the accuracy of the DS under various levels of heat stress, clothing and working levels.

1. Introduction

In order to increase operational capabilities and to reduce workers' health risks, a perception has been evolved focusing on continuous, non-invasive physiological monitoring systems based on advanced technologies, which could be integrated into the working gear. In various occupations (firefighters, mine-workers etc.) the workers are required to perform under uncompensated heat stress, sometimes while dressed in protective garments, which impair adequate heat dissipation (Havenith et al., 1999; Taylor, 2006). As a result, the operational capabilities of such workers may deteriorate and they might be at the risk to incur various degrees of heat injuries (Epstein and Roberts, 2011; Epstein et al., 2012; Friedl, 2012). It follows that an important parameter that should continuously be monitored is body core temperature (T_c).

Various devices to measure T_c are in use (Mackowiak, 1997), but in most cases they are not practical for routine field application due to wiring, invasiveness, hygiene, difficult to reuse, or uncomfortable for the user. The available systems to measure directly T_c are invasive (rectal probe, esophageal probe). They are difficult to apply in various working scenarios for labors who are exposed to extreme environmental conditions and extensive work loads, and may hamper compliance. Among the simplest non-invasive method in assessing T_c is measuring skin temperature using a surface thermistor or an infrared light absorption technique (Richmond et al., 2013). Noteworthy, skin temperature underestimates T_c (Gagge and Gonzalez, 1996; Mendt et al., 2016). The minimal invasive method to measure T_c is the temperature pill, which is the only method available today for remote core body temperature monitoring (O'Brien et al., 1998; Baillot and Hue, 2015). This method, however, exhibits many limitations, such as high cost, the possibility to be influenced by water and food intake or the difficulty to standardizing the location of the sensor along the gastrointestinal tract. Non-invasive estimated of T_c are based on computational models, which are composed mainly on time-series analysis of heart rate and or in a combination with skin temperature (Buller et al., 2013; Niedermann et al., 2014; Richmond et al., 2015).

In the past several years researches have put effort in the development of new methods for the measurement of T_c by using non-invasive sensors. The common principle of most existing approaches is extracting the temperature from measuring heat flux gradients, using sensors attached to the skin surface (Yamakage and Namiki, 2003; Teunissen et al., 2011; Kitamura et al., 2010; Steck et al., 2011). One of those

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devices is the Double Sensor (DS) that was developed by Dräger (Sattler, 2011), and has already been experimentally been tested in different centers and under various conditions (Gunga et al., 2008, 2009; Kimberger et al., 2009). The principle of the DS is comparing the heat flux between body core to skin surface to that over a known thermal resistance (for more details the reader is referred to Gunga et al., 2008 and Kimberger et al., 2009).

With the understanding that continuous monitoring of T_c plays a major role in preventing heat related injuries among workers exposed to hot climatic conditions or while wearing protective gear the aim of this study was to assess the accuracy of T_c measured by the DS (T_{DS}) in comparison to direct rectal temperature (T_{re}) measurements, which is considered as a "gold standard" for T_c.

2. Material and methods

2.1. Participants

Seventeen healthy young (age: 24.16 ± 2.85 years) male volunteer participants (weight: 67.83 ± 6.27 kg, height: 1.75 ± 0.07 m, fat percentage: 17.24 ± 4.47%, BMI: 22.02 ± 2.18 kg m^{-2}) were recruited for this study. All participants were physically active (maximal oxygen consumption: 51.6 ± 5.9 ml kg^{-1}·min^{-1}) but with no professional or elite sport background. Participants were informed of all experimental procedures, associated risks and discomforts, and signed a consent form as required.

2.2. Experimental protocol

The study protocol and procedures were approved by the Institutional Review board (IRB) of the Sheba Medical Center and the IDF Medical Corps. Each subject visited the laboratory twice, one week apart. On the first visit, the participants' O_2 consumption (VO_{2max}) was measured according to the Bruce protocol using a metabolic chart (ZAN600, nSpire Health Inc. USA). On the second visit, the participants performed the experimental protocol.

Dressed in shorts and tennis shoes the participants were exposed to 30 min at a sitting position under thermal comfort conditions of 20–22 °C and 50% relative humidity (RH). This was then followed by an exposure to 40 °C and 40% RH in a controlled climatic chamber: 30 min at rest (sitting on a chair) and 60 min exercising on a motor driven treadmill at a pace of 5 km/h and 2% incline. All protocols started at the same time of the day (09:30 am). Participants were asked to refrain from intense exercise and alcohol the day before every visit and from caffeine and cigarettes for 12 h before the experimental session. They were also asked to complete 7 h night sleep before each visit.

2.3. Physiological measurements

Rectal temperature (T_{re}) was monitored using a standard rectal thermistor (YSI-401, USA) at a depth of ~10 cm beyond the anal sphincter. During the first phase (resting at comfort climatic conditions) measurements were taken manually at 5 min intervals. During the second and third phases (exposure to heat in the climatic chamber) T_{re} and T_{DS} were monitored and recorded using a computerized at a rate of 1 Hz; data was analyzed at the rate of 1 sample per minute.

Double Sensor temperature (T_{DS}) was measured from a sensor (Dräger, Germany) attached to the subject's forehead on the vertical line above the eye, directly underneath the hairline according to former study (Gunga et al., 2009). The sensor was applied using an elastic headband, ensuring continuous contact in case of head movements while exercising. A small amount of conductive gel was applied between sensor and skin. T_{DS} was continuously monitored and displayed simultaneously with T_{re}.

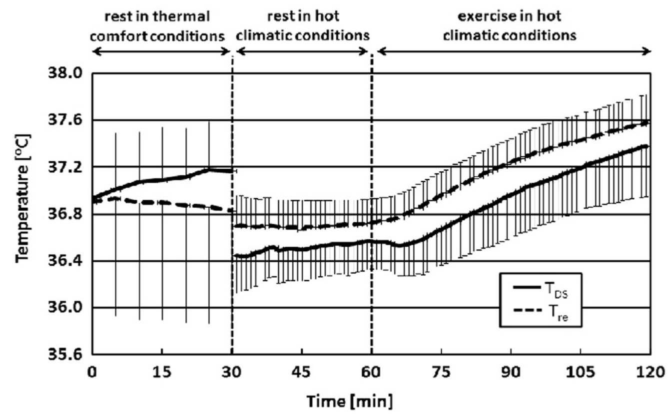

Fig. 1. Mean body-core temperature recorded using DS (T_{DS}) and rectal sensor (T_{re}) during the experimental protocol.

2.4. Data analysis

Under comfortable conditions measurements were taken manually every 5 min. In the climatic chamber (heat exposure) T_{re} and T_{DS} were monitored at a rate of 1 Hz, for the data analysis we used a sample rate of 1 sample per minute. For quantifying the deviation between T_{re} and T_{DS} a Bland-Altman plot (Bland and Altman, 1986) was constructed for all 17 subjects at all three stages. F-test was used, to compare the variance of the two measurements, testing the first stage of exposure separately from the heat exposure. The numerical relationship between rectal and DS measurements was estimated using linear regression. It has allowed us to form a numerical correction and to predict further behavior. Pearson's correlation coefficient was used to indicate the degree of linearity. Where appropriate, data are presented as mean ± standard deviation (SD). Significance level was set at $p < 0.05$.

3. Results

The average T_{re} and T_{DS} of each time period during the entire experimental exposures are depicted in Fig. 1. During the resting period under comfortable climatic conditions mean T_{DS} values were constantly higher than those of T_{re} and tended to increase, while T_{re} decreased ($p < 0.02$). Throughout this stage the mean difference between the two values (T_{re}-T_{DS}) over this period was −0.19 ± 0.10 °C and a maximal difference was −0.33 °C. During the heat exposure session, mean T_{DS} tended to be consistently lower than T_{re} by an average of 0.23 ± 0.04 °C and a maximum of 0.29 °C with no significant difference between variance of the two measurements. A Bland-Altman plot of the raw data (within two standard deviations from mean value) is presented in Fig. 2 and reveals a range of ± 0.6 °C, with 51% of all data points being within ± 0.3 °C. The group of outliers that appear in the Bland-Altman plot are mostly related to the values recorded during the resting period under comfort climatic conditions.

The correlation between the mean values of the two measurements during exercise under heat stress was very high (r = 0.991) (Fig. 3). The linear correlation under heat load enabled a simple adjustment of T_{DS} to T_{re} to match between the two values (Fig. 4).

Following the adjustment to match T_{DS} to T_{re}, the bias and limits of agreement in comparison to the original data point were narrowed. The corresponding Bland-Altman plot ± 2 SD of all data points is within a range of 0.4 °C from the mean difference temperature (Fig. 4); 73% of all data points were within ± 0.3 °C around the mean difference value.

4. Discussion

Given the necessity to develop an easy to use, non-invasive core body temperature monitoring device, the present study evaluated the