Infrared cameras overestimate skin temperature during rewarming from cold exposure

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Abstract

Objective

The primary aim of this study was to assess the accuracy of an infrared camera and that of a skin thermistor, both commercially available. The study aimed to assess the agreement over a wide range of skin temperatures following cold exposure.

Methods

Fifty-two males placed their right hand in a thin plastic bag and immersed it in 8 °C water for 30 minutes whilst seated in an air temperature of 30 °C. Following hand immersion, participants removed the bag and rested their hand at heart level for ten minutes. Index finger skin temperature (T_{sk}) was measured with a thermistor, affixed to the finger pad, and an infrared camera measured 1 cm distally to the thermistor. Agreement between the infrared camera and thermistor was assessed by mean difference (infrared camera minus thermistor) and 95 % limits of agreement analysis, accounting for the repeated measures over time. The clinically significant threshold for T_{sk} differences was set at ±0.5 °C and limits of agreement ±1 °C.

Results

As an average across all time points, the infrared camera recorded T_{sk} 1.80 (SD 1.16) °C warmer than the thermistor, with 95 % limits of agreement ranging from -0.46 °C to 4.07 °C.

Conclusion

Collectively, the results show the infrared camera overestimated T_{sk} at every time point following local cooling. Further, measurement of finger T_{sk} from the infrared camera consistently fell outside the acceptable level of agreement (i.e. mean difference exceeding ±0.5 °C). Considering these results, infrared cameras may overestimate peripheral T_{sk} following cold exposure and clinicians and practitioners should, therefore, adjust their risk/withdrawal criteria accordingly.

Keywords

Infrared thermography; temperature measurement; thermoregulation; cold exposure; instrument validity

Introduction

Measurement of skin temperature (T_{sk}) is routinely conducted in research investigating human responses to environmental extremes. Measuring T_{sk} enables researchers to profile and calculate a wide variety of responses. Examples include mean body temperature (Hardy and Du Bois, 1938; Jay et al., 2007), body heat content (Burton, 1935), and relatively newer calculations such as the adaptive physiological strain index (Buller et al., 2018; Hunt et al., 2019).

Measurement of T_{sk} may be conducted with a wide variety of devices that are broadly classified as conductive or infrared. Conductive devices, primarily thermistors, are often the preferred method for measuring T_{sk} (Bach et al., 2015b, 2015a; James et al., 2014). Most thermistor-based systems have a negative temperature coefficient. That is, their resistivity decreases with increasing temperature. In a thermistor-based system, a signal of 35 mV per °C is typical; nearly 1000 times greater than a thermocouple-based system (Bull, 2008). Thermistors are known for their long-term stability (Togawa, 1989), producing an error of ~0.1 °C (Bull, 2008). In contrast, infrared thermography is a non-contact technique, which transforms the energy radiated from objects in the infrared band into an electronic video signal that can be displayed on a computer and stored (Hildebrandt et al., 2010; Meola and Carlomagno, 2004).

Infrared cameras have added advantages over conductive devices. For example, they are able to capture (image or video) and store large quantities of data, meaning different areas of skin can be analysed retrospectively (Fernández-Cuevas et al., 2015; Moreira et al., 2017). In contrast, conductive devices are fixed to a specific skin site.

Additionally, most conductive devices are wired and, therefore, participants or patients are tethered to a data logger and their movement potentially restricted.

As a result of the improved accuracy of infrared devices over recent years, and despite the increased cost relative to conductive devices, their use has become more frequent in human physiology research. Example studies include local cold exposure (Brändström et al., 2008; Costello et al., 2012b, 2012a; Hope et al., 2014), identification of sporting injuries (Hildebrandt et al., 2010), testing individuals with non-freezing cold injuries (NFCI) (Ahle et al., 1990; Eglin et al., 2013) or Raynaud's phenomenon (Ring and Ammer, 2012; Shepherd et al., 2019), as well as during medical operations (Mercer et al., 2010). However, under controlled laboratory conditions during exercise and/or warm environmental conditions, thermal imaging technology to date has shown not to be acceptable; that is T_{sk} is under- or overestimated compared with a number of conductive devices (Bach et al., 2015a, 2015b; Buono et al., 2007; Fenemor et al., 2019; James et al., 2014).

Even though infrared cameras have been utilised to measure T_{sk} during cold exposure (Costello et al., 2012a; Hope et al., 2014; Maley et al., 2014), the accuracy of infrared cameras for measuring T_{sk} <33 °C is not well established. Several studies have compared T_{sk} results between an infrared device and a conductive device during cold exposure; however, these studies are limited by sample size, the methodology of cold application and incomplete statistical analysis to properly assess the validity of infrared devices (Buono et al., 2007; Kelechi et al., 2011; Korukçu and Kilic, 2009).

If T_{sk} is cooled to <15 °C for a prolonged period then the risk of peripheral cold injuries is significantly increased (Eglin et al., 2013; House et al., 2000; Maley et al., 2017, 2014; Thomas and Oakley, 2001). Considering this, the accuracy of infrared devices in measuring T_{sk} is paramount in order to not expose an individual to an increased risk of peripheral cold injuries. Given the need for valid monitoring of cooled T_{sk} across a wide range of sport, medical and occupational settings, this investigation set out to compare the agreement of T_{sk} between a conductive device with that of a non-contact infrared device during recovery from cold exposure.

Methods

This study was given ethical approval from the University of Portsmouth Science Faculty Ethics Committee and complied with standards set in The Declaration of Helsinki (2013). The participants were made aware of the purpose, procedures and risks of the study before giving their informed written consent. Fifty-two male participants volunteered in the study; their physical characteristics are as follows (mean [SD]): age 20 [2] years, height of 177.5 [7.7] cm, body mass of 75.5 [13.2] kg and hand length of 20.3 [1.2] cm. Participants' height and body mass were measured using a stadiometer (Leicester, Bodycare, UK) and digital weighing scales (Ohaus I-10, Ohaus Corporation, USA), respectively. Length of participants' right hand was measured using a segmometer (Segmometer 4, Rosscraft, Canada).

Participants entered the climate controlled chamber (mean [SD] dry-bulb: 30.3 [0.9] °C, wet-bulb: 22.9 [0.9] °C, wet-bulb globe temperature: 25.1 [0.9] °C) and rested in a semi-recumbent position for 25 minutes whilst being instrumented. During the 25 minute rest period, a skin thermistor (Type EUS-U, Grant Instruments, UK), connected to a data logger (Squirrel 2020, Grant Instruments, UK), was affixed onto the participant's second finger pad of the right hand using a small piece of breathable tape (Transpore Tape, 3M™, USA). Participants then placed their hand into a plastic bag, immersed it to the styloid process in a water bath maintained at 35.0 [0.2] °C for five minutes. Following this, participants removed their hand from the water, still within the plastic bag, and immediately placed it in a stirred water bath maintained at 8.1 [0.1] °C. After 30 minutes of cooling, participants removed their hand from the water bath and plastic bag to allow spontaneous rewarming for ten minutes. During this period, participants rested their hand at the level of the heart. A calibrated infrared camera (A320G, FLIR Systems, UK) was positioned on a level tripod perpendicular to the participant's hand at a distance of one meter in line with published guidelines (Moreira et al., 2017). The camera was calibrated within 12 months of use. Data were recorded to dedicated software (ThermaCAM™ Researcher, FLIR Systems, UK) to allow offline analysis. Emissivity (0.98) and distance (1 m) was set in object parameters within the software in line with published guidelines (Moreira et al., 2017). T_{sk} was measured immediately distal to the thermistor using the spot measurement tool.

The same thermistor was used for each participant and checked for accuracy before experimental use at eight water temperatures (5 °C to 40 °C, at increments of 5 °C). The thermistor was held at these temperatures in a precision water bath (Grant Instruments, UK) and compared to a UKAS calibrated precision digital thermometer (T600, Digitron Ltd, UK). Across the temperature range, the thermistor deviated by 0.11 (0.03) °C from the UKAS calibrated precision digital thermometer.

Statistical Analysis

The difference in T_{sk} following hand immersion was evaluated with a repeated-measures analysis of variance with Tukey's tests for multiple comparisons. Statistical significance was accepted at $\alpha < 0.05$. Agreement between the infrared camera and thermistor was assessed by the mean difference (infrared camera minus thermistor) and 95 % limits of agreement analysis, accounting for the repeated measures over time (Bland and Altman, 2007). The clinically significant threshold for T_{sk} differences was set at 0.5 °C (Bach et al., 2015a; Marins et al., 2014; Niu et al., 2001; Selfe et al., 2008).

Therefore, an acceptable level of agreement would be a mean difference of <0.5 °C and 95% limits of agreement of 1 °C.

Results

A statistically significant interaction was observed between the measurement devices over time ($F_{9,459} = 26.29$, $P < 0.001$). Post-hoc analysis revealed the infrared camera was significantly higher than the thermistor at every minute during rewarming following hand immersion (Figure 1). As an average across all time points, the infrared camera recorded T_{sk} 1.80 (1.16) °C warmer than the thermistor, with 95 % limits of agreement ranging from -0.46 °C to 4.07 °C (Figure 2). At no time point was the acceptable level of agreement met (Table 1). At each minute, and as an average, mean differences were outside the acceptable level of agreement (Table 1).

Table 1. Mean difference and 95 % limits of agreement (LoA) for each time point and average

Time (min)	Mean Difference (°C)	Standard Deviation (°C)	Lower 95 % LoA (°C)	Upper 95 % LoA (°C)
1	2.55	1.32	-0.04	5.14
2	2.56	1.19	0.22	4.90
3	2.43	1.38	-0.27	5.14
4	2.04	1.12	-0.15	4.23
5	1.85	1.12	-0.35	4.04
6	1.61	0.99	-0.32	3.54
7	1.38	0.88	-0.34	3.11
8	1.24	0.65	-0.03	2.51
9	1.23	0.68	-0.10	2.57
10	1.15	0.66	-0.14	2.43
Average	1.80	1.16	-0.46	4.07

Note: mean differences calculated as infrared camera minus thermistor.

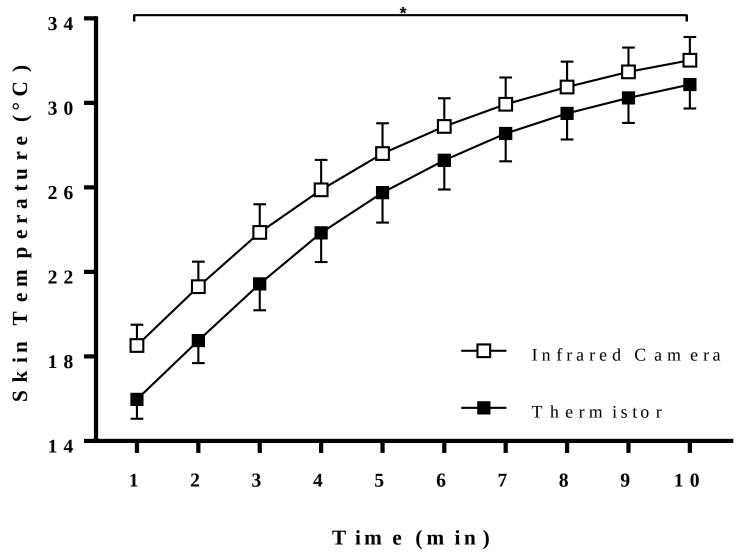

Figure 1. Mean (95 % confidence intervals) finger skin temperature measured by infrared camera and thermistor following cold exposure

[*]statistical difference between the infrared camera and thermistor ($P < 0.001$).

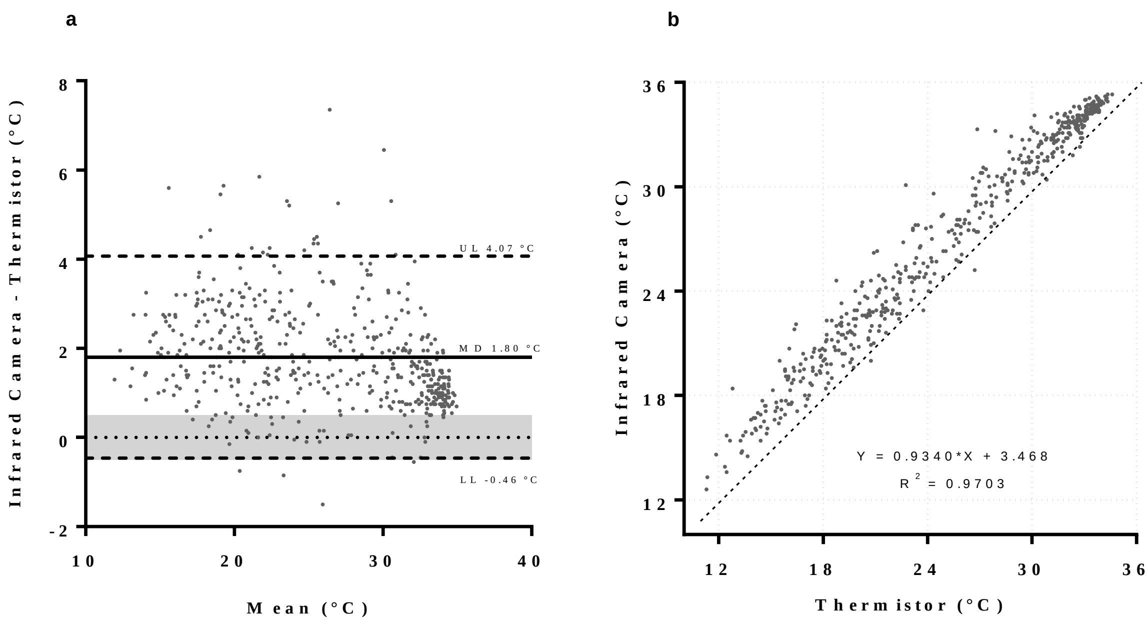

Figure 2. Scatterplot (a) and Bland-Altman plot (b) of the agreement between the infrared camera and thermistor for all time points

Note: MD, Mean difference; UL, Upper 95 % limits of agreement; LL, Lower 95 % limits of agreement. Grey band indicates a priori acceptable mean difference of 0.5 °C.

Discussion

The primary aim of this study was to assess the accuracy of an infrared camera with that of a skin thermistor, both of which are commercially available. The study aimed to assess the agreement over a wide range of T_{sk} following cold exposure; this was achieved as T_{sk} ranged from 16 °C to 31 °C. Collectively, the results show the infrared camera overestimated T_{sk} at every time point following local cooling (Figure 1). Further, measurement of T_{sk} from the infrared camera consistently fell outside the acceptable level of agreement (i.e. mean difference >0.5 °C) (Table 1, Figure 2b).

Few studies have previously assessed the accuracy of infrared devices with that of conductive devices during skin cooling. Buono et al. (2007) utilised a handheld infrared thermometer and contact thermistor to assess weighted mean T_{sk} during rest at air temperatures of 15 °C and 25 °C in six participants. They reported no statistical difference in T_{sk} between devices. Unfortunately, incomplete statistical analysis was conducted, preventing any meaningful interpretation of agreement between devices. Korukçu *et al.* (2009) tested facial T_{sk} of three participants using an infrared camera and contact thermocouple during mild car cabin cooling. Similar to Buono *et al.* (Buono et al., 2007), small sample size and inadequate statistical analysis were conducted preventing proper interpretation of agreement between devices, with authors summarising results of a <2 °C difference between the two devices. Finally, Kelechi *et al.* (2011) recruited 17 participants and compared a handheld infrared device with a thermistor during local skin cooling of the legs. Following cooling, most measurements (71 %) had a mean difference of >0.5 °C between devices. However, raw T_{sk} values are not provided which, similar to previous studies, makes interpretation of results difficult.

To the authors' knowledge, this is the first study to assess the agreement between infrared and conductive devices over a wide range of cool T_{sk} during a dynamic situation using a large sample. In this study, the infrared camera overestimated T_{sk} compared with the contact thermistor, which may have safety implications. As aforementioned, infrared devices have been used to measure T_{sk} following cryotherapy (Costello et al., 2012a, 2012b; Selfe et al., 2014) and assess injury severity in NFCI patients (Ahle et al., 1990; Eglin et al., 2013; Thomas and Oakley, 2001). Cooling T_{sk} to <15 °C for a prolonged period exposes an individual to local cold injuries, such as NFCI (Eglin et al., 2013; House et al., 2000; Maley et al., 2017, 2014; Thomas and Oakley, 2001). Thus, if a study uses an infrared camera to assess T_{sk} during or following cooling there is an increased risk of exposing that individual to lower than expected skin temperatures that may lead to NFCI. The authors are aware T_{sk} within this study did not reach <15 °C but we can only speculate that the mean difference between devices would also be different at these lower skin temperatures.

The present study is not without limitations. Within the infrared camera software, the spot tool was chosen to record T_{sk}, which was distal to the contact thermistor location; meaning there was a difference in the location where T_{sk} was measured from. However, the authors are confident that the difference of around 1 cm between device measurement locations is not the reason for the overestimation of T_{sk} from the infrared camera (Maniar et al., 2015). The authors considered the possibility the contact thermistor was experiencing substantial thermal inertia, which may have explained why the thermistor consistently measured cooler T_{sk} compared with the infrared device.

However, based on pilot studies, the response rate of the thermistor (Δ15 °C·min^{-1}) used far exceeds T_{sk} rewarming rates in this study.

Conclusion

In conclusion, the infrared camera utilised in this study overestimated T_{sk} between 16 °C and 31 °C. Future research should consider using contact devices, checked for accuracy against a UKAS calibrated thermometer, in order to report accurate T_{sk} and to reduce the potential risk of peripheral cold injuries. Future research is needed to compare infrared and contact devices where T_{sk} is <15 °C.

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Ethical Statement

This study was given ethical approval from the University of Portsmouth Science Faculty Ethics Committee and complied with standards set in The Declaration of Helsinki (2013). The participants were made aware of the purpose, procedures and risks of the study before giving their informed written consent.

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