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Insulated skin temperature as a measure of core body temperature for individuals wearing CBRN protective clothing

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Abstract. This study assessed the validity of insulated skin temperature (T_{is}) to predict rectal temperature (T_{re}) for use as a non-invasive measurement of thermal strain to reduce the risk of heat illness for emergency service personnel. Volunteers from the Police, Fire and Rescue, and Ambulance Services performed role-related tasks in hot (30 °C) and neutral (18 °C) conditions, wearing service specific personal protective equipment. Insulated skin temperature and micro climate temperature (T_{mc}) predicted T_{re} with an adjusted r^2=0.87 and standard error of the estimate (SEE) of 0.19 °C. A bootstrap validation of the equation resulted in an adjusted $r^2 = 0.85$ and SEE = 0.20 °C. Taking into account the 0.20 °C error, the prediction of T_{re} resulted in a sensitivity and specificity of 100 % and 91 %, respectively. Insulated skin temperature and T_{mc} can be used in a model to predict T_{re} in emergency service personnel wearing CBRN protective clothing with an SEE of 0.2 °C. However, the model is only valid for T_{is} over 36.5 °C, above which thermal stability is reached between the core and the skin.

Keywords

Insulated skin temperature; non-invasive temperature measurement; rectal temperature; heat strain; protective clothing

1   Introduction

Emergency service (ES) personnel can be placed under considerable physiological and thermal strain during routine operational tasks due to the physical demands of the job, and the protective clothing and breathing apparatus worn. In addition to their regular duties, ES personnel are also required to respond to chemical, biological, radiological and nuclear (CBRN) threats which require an additional level of protection in the form of a fully encapsulated impermeable personal protective equipment (PPE). This potentially creates an environment of uncompensable heat stress which occurs when the heat loss required to maintain heat balance exceeds the maximum evaporative capacity of the clothing system. The clothing restricts evaporative heat loss preventing individuals from dissipating their metabolic heat, which prevents a thermal equilibrium being reached and core body temperature (T_c) continues to increase to exhaustion (Givoni and Goldman, 1972).

It is well documented that by adding CBRN clothing to an already physically demanding job the level of heat strain is exacerbated. McLellan et al. (1993) showed that work tolerance time (WTT) decreased by 41 % when participants wore the highest level of protective clothing worn by the Canadian Forces compared to a lower level of protection. Montain et al. (1994) also showed that WTT decreased by 54 % when full PPE was worn during treadmill walking in a desert environment, compared to partial clothing. Although final T_{re} was lower in the full clothing condition in both these studies, final skin temperature (T_s) was higher, resulting in a lower temperature gradient between the skin and the body core, impaired heat loss and a greater sense of thermal strain. This is particularly true for ES personnel; for example in a study which examined the physiological strain associated with firefighters working in CBRN PPE reported a mean increase in T_c of 1.2 °C during 30 minutes of drill (Ilmarinen et al., 2004). Similar temperatures

were reported for police officers during simulated CBRN firearms house entry, with an increase in T_c of 1.3 ± 0.1 °C in 38 minutes and a sweat loss of 1.3 L·h^{-1} (Blacker et al., 2012).

Monitoring T_c during CBRN incidents could reduce the risk of heat illness within ES personnel; however, the measurement of T_c during occupational deployments is complex, balancing practicality against validity of T_c measurement. There are numerous direct measures of T_c, the most accurate and reliable being the most invasive. These direct measures include rectal temperature (T_{re}) and oesophageal temperature (T_{es}) (Lee et al., 2000, Moran and Mendal, 2002). While being the preferred methods to use in a laboratory environment, these measures are impractical for use in the field due to the associated discomfort, difficulty to safely maintain insertion and hygiene issues (Lee et al., 2000). As other less invasive methods such as tympanic, aural, temporal, oral, axillary and forehead temperatures show less reliable associations with T_{re} and T_{es} (Ganio et al., 2009) it might be more practical to use a non-invasive measure of T_c, which predicts or estimates deep T_c.

The possible convergence of T_c and skin temperature (T_s) during exercise and/or heat strain indicates T_s may be a viable alternative method for the prediction of T_c. When clothing permeability, in combination with exercise and heat stress, creates a hot, humid microclimate, the conditions are thought to be created for T_s to approximate T_c, even without the presence of thermal insulation (Pandolf and Goldman, 1978). However, even in protective clothing heat transfer is still possible provided there is a positive temperature gradient between the skin and the environment. The diffusion of moisture via evaporation from the skin to the clothing occurs as a result of higher vapour pressure at the skin due to greater skin temperature (Lotens et al., 1995). In addition, any temperature gradient will also allow heat transfer via dry heat exchange. Therefore, even in protective clothing, using an insulation material over the skin thermistor may be necessary to prevent heat loss from the skin at the site of the temperature measurement. The importance of insulating the skin site was highlighted by Buono and Ulrich (1998). Participants walked on a treadmill under three different conditions, with T_s measured at the chest, calf and forearm. Skin thermistors were either covered with foam and tape, or left exposed to the environment. The covered probes resulted in a significantly higher T_s in all three conditions, the greatest difference between T_{re} and T_s (1.3 °C) being in a thermoneutral condition (23 °C). The author concluded that covering the probe attenuates heat transfer (particularly conduction, convection and radiation) from the covered area, and drives insulated skim temperature (T_{is}) closer to T_c. While there is little information in the literature on the use of T_{is} as a predictor of T_c, the studies available suggest T_{is} has the potential to estimate T_c non-invasively (Taylor et al., 1998, Bernard and Kenney, 1994) and is worthy of investigation for use in the occupational setting.

The aim of this study was to assess the validity of T_{is} to predict T_{re} in police, firefighters and ambulance personnel wearing their respective CBRN PPE.

2   Methods

All participants were verbally briefed, issued with a participant information sheet, and gave written informed consent. Ethics approval for the study was granted by the University of Birmingham research ethics committee. Three emergency responder groups participated in the trial, wearing their specific operational CBRN PPE. Twelve participants were recruited from each of the Police and Fire and Rescue Service, and nine were recruited from the Ambulance Service. All participants were medically screened by an occupational physician to ensure they were medically fit to work as determined by the guidelines used by their respective services and were therefore capable of participating in the study.

2.1   *Experimental protocol*

Three separate five-day trials were carried out; one for each ES group, resulting in 10 to 14 data sets collected for each ES group. Participants from each ES wore their respective occupational CBRN PPE. Police wore the civil responder 1 (CR1) (Remploy Frontline, Merseyside, UK), a tri-layered ensemble with a negative pressure respirator for respiratory protection. Fire and rescue service personnel wore the gas-tight suit (GTS) (Respirex International Ltd, Redhill, Surrey, UK), a one-piece suit worn over the breathing apparatus (BA), in this case being Extended Duration Breathing Apparatus. Ambulance personnel wore the powered respirator protective suit (PRPS) (Respirex International Ltd, Redhill, Surrey, UK) which is also a one-piece suit containing an integral powered respirator system. Underneath the GTS and PRPS participants wore their own choice of clothing as would be standard in a 'live' scenario. In all cases this included either shorts or tracksuit trouser, and a t-shirt. The CR1 incorporates a base layer; therefore Police participants wore only their underwear in addition to the PPE.

Each participant completed four trials in their respective CBRN PPE, on consecutive days. Each trial lasted 60-minutes for the GTS and PRPS groups, and 120-minutes for the CR1 groups. These deployment durations were based on the standard operating procedures for each service in their respective CBRN PPE. Two of the deployments were performed in a 'neutral' thermal environment (~18 ℃) and two in a 'hot' environment (~30 ℃). These ambient temperatures were chosen to represent typical conditions in the UK. As the trial took place in a large garage style building, it was not possible to manipulate the relative humidity. Each deployment was split into 30 minute circuits (table 1) which included various work-related simulations and rest periods, to simulate a typical "heavy" work schedule replicating a realistic deployment training scenario. Each task lasted 3 minutes and was separated by a 1 minute rest period. The exercise intensity was

modified (e.g. by manipulating the number of shuttles, height of step) throughout the first trial to ensure the participants were all exercising at the approximately same relative exercise intensity, based on each individual heart rate (HR). The stepping pace was regulated using a metronome. After the first trial, the same circuit schedule was carried out each subsequent day to standardize the exercise challenge.

Table 1. Example of a circuit.

Task
Brisk walk (5 shuttles·min^{-1} – 15 m for GTS and PRPS and 20 m for CR1
Stepping – 30 cm step at rate of 15 steps·min^{-1}
30 m walking shuttle, alternating with and without a Powerbag (15 kg) placed on 0.9 m table at end of shuttle
Brisk walk (5 shuttles per min – 15 m for GTS and PRPS and 20 m for CR1
Stepping – 30 cm step at rate of 15 steps·min^{-1}
30 m shuttle, alternating with and without 2 10 kg water containers
Brisk walk (5 shuttles·min^{-1} – 15 m for GTS and PRPS and 20 m for CR1

GTS = gas tight suit; CR1 = civil responder 1 and PRPS = powered respirator protective suit

2.2   Measurements

All participants were monitored for both HR and T_{re} during each deployment. Heart rate was measured using the Polar Team 2 system, (Polar Oy, Kemple, Finland) and T_{re} was measured using a flexible probe (Grant Instruments Ltd, Cambridge, UK). Insulated skin temperature (Figure 1) was measured at the lower neck between C7 and T2 (spinous process), consisting of a skin thermistor connected to a Squirrel SQ800 data logger (Grant Instruments Ltd, Cambridge, UK). The probe was covered by a 5 cm x 5 cm x 1 cm block of closed-cell cross linked polyethylene foam (Rubber Astic International, Birmingham, UK), which was secured around the probe head and onto the skin surface by use of a 5 cm x 5 cm double-sided adhesive patch (3M Health Care, UK). A further layer of 11 cm x 11 cm single-sided adhesive patch (woven spun lace tape 1776, 3M Health Care, UK) was used to cover the polyethylene block and provide additional skin adhesion. Each insulated skin patch had a second probe attached to the outer surface of the patch to monitor the temperature of the microclimate (T_{mc}) directly on top of the skin patch.

Prior to the start of the study all temperature sensors were checked for accuracy over 35 °C to 41 °C using a precision water bath (GD 100-P12, Grant Instruments, Cambridge, UK) and United Kingdom Accreditation Service Calibrated precision thermometer (T600i, Digitron Ltd, Torquay, UK). All thermistors used in the study were within 0.5 °C of the precision thermometer after 5 minutes of submersion.

On day 1 of each test week the participants stature (Seca, Birmingham, UK), body mass (Kern ITT 150K5IP, Kern) and body composition (Harpenden callipers, HaB Intl Ltd, Warwickshire, UK) were determined. Estimated body fat was calculated using the Durnin and Womersley (1974) 4-site method. All participants completed a multi-stage fitness test to estimate their aerobic fitness ($\dot{V}O_2$ max) (Ramsbottom et al., 1988). Participants then performed a complete rehearsal of one circuit of the deployment (~30 minutes) in their regular work clothing of the circuit and fitted their PPE to ensure the sizing was correct. On each day of the deployment participants arrived 90 minutes prior to the start of the trial and were instrumented with HR, T_{re} and T_{is} monitors and donned their PPE. The circuit was carried out with six participants at a time, working in teams of three.

There were four reasons for which a test could be terminated: a) attainment of T_{re} of ≥ 39.5 °C, b) low air pressure in the breathing apparatus sets in the GTS or low battery to the powered respirator in the PRPS, c) if for any reason the paramedic or support staff felt it was unsafe for the participant to continue, and d) if for any reason the participant felt unable to continue.
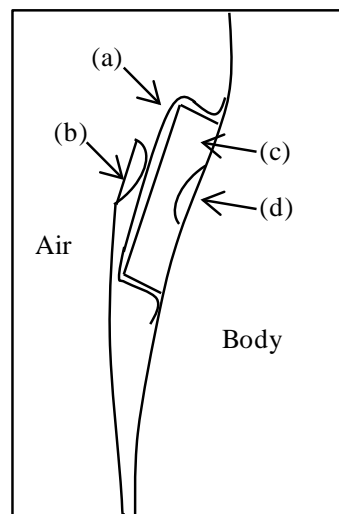

Figure 1 – Insulated skin temperature monitor: (a) 11 cm x 11 cm single-sided adhesive patch, (b) thermistor for monitoring micro-climate temperature, (c) 5 cm x 5 cm x 1 cm block of closed-cell cross linked polyethylene foam secured to the skin using a double-sided adhesive patch, and (d) temperature thermistor secured at the lower neck under the foam patch.

2.3   *Statistical analysis*

All data are expressed as mean ± SD. Standard regression analysis techniques were used to determine the association between T_{is} and T_{re} using SPSS (version 18.0; SPSS Inc., Chicago, Illinois, USA) (Bland, 2000). Where the relationship between T_{re} and the primary variable in the

equation was better described as a curvilinear model, the covariates were centred (c) to reduce colinearity (Bland, 2000). The agreement between measured and predicted T_{re} was assessed using Ordinary Least Squared (OLS) regression, reporting the adjusted (adj) r^2 and the standard estimate of the error (SEE). The level of error between T_{is} and T_{re} that would be operationally acceptable by the emergency services was determined a-priori as a SEE of 0.2 °C.

The model was validated using a bootstrap technique, in which the model was developed on the data set from all but one individual, and then the equation was validated on the data set that was not used in the development of the model. To assess the validity of the model further, the sensitivity and specificity for identifying individuals over a T_{re} of 39 °C was determined.

3   Results

Participant characteristics are shown in table 2. The ambient temperature was 31.0 ± 1.1 °C and 18.3 ± 0.8 °C and the relative humidity was 27.9 ± 6.0 % and 56.2 ± 5.5 % for the hot and neutral conditions over all the three Services' trials, respectively. The mean temperature and relative humidity within the GTS and PRPS throughout the trial were 30.0 ± 1.8 °C and 89.3 ± 6.4 %, and 30.6 ± 3.2 °C and 88.0 ± 8.1 %, respectively, in the hot conditions; and 25.4 ± 0.7 °C and 87.0 ± 8.0 %, and 25.0 ± 21. °C and 90.8 ± 10.0 %, respectively, in the neutral conditions. Table 3 shows the average HR and % HRR during the trial for each PPE under each environmental condition.

Table 2. Physical and physiological characteristics of the participants (mean ± SD).

	CR1 (n = 12)	GTS (n = 12)	PRPS (n = 9)
Age (years)	41.1 ± 6.1	37.2 ± 6.4	35.2 ± 6.0
Body mass (kg)	83.7 ± 9.0	82.0 ± 13.4	79.6 ± 12.4
Height (cm)	177.9 ± 6.9	176.2 ± 7.0	176.0 ± 10.2
Body fat (%)*	26.9 ± 3.5	24.5 ± 6.7	21.6 ± 6.0
$\dot{V}O_2$ max (ml·kg^{-1}·min^{-1})**	43.9 ± 5.1	45.9 ± 8.1	44.4 ± 5.1

*estimated from four-site skin-fold measurement (Durnin and Womersley, 1974)

**estimated from the multi-stage fitness test

CR1 = Civil Responder 1 (Police), GTS = Gas Tight Suit (Fire and Rescue service), PRPS = Powered Respirator Protective Suit (Ambulance Service)

Table 3. Average heart rate (HR) and % HR reserve (% HRR) for each PPE in hot (31 °C) and neutral (18 °C) conditions (mean ± SD).

	CR1 (n = 12)	GTS (n = 12)	PRPS (n = 9)
Hot			
HR (b·min^{-1})	126 ± 15	135 ± 16	137 ± 17
HRR (%)	57 ± 11	60 ± 12	59 ± 13
Neutral			
HR (b·min^{-1})	99 ± 7	120 ± 10	120 ± 12
HRR (%)	33 ± 3	49 ± 7	46 ± 9

3.1 Comparison between T_{re} and T_{is}

Figure 2 shows the raw data of T_{re} and T_{is} for each group in both hot and neutral conditions (only the first hour of the CR1 trial is included for comparison). The Figure shows that for the GTS and PRPS conditions, T_{re} and T_{is} converged over the first 20 min to 30 min before stabilising. In the CR1 conditions, T_{re} and T_{is} had stabilized prior to the start of the trial so there was no apparent convergence.
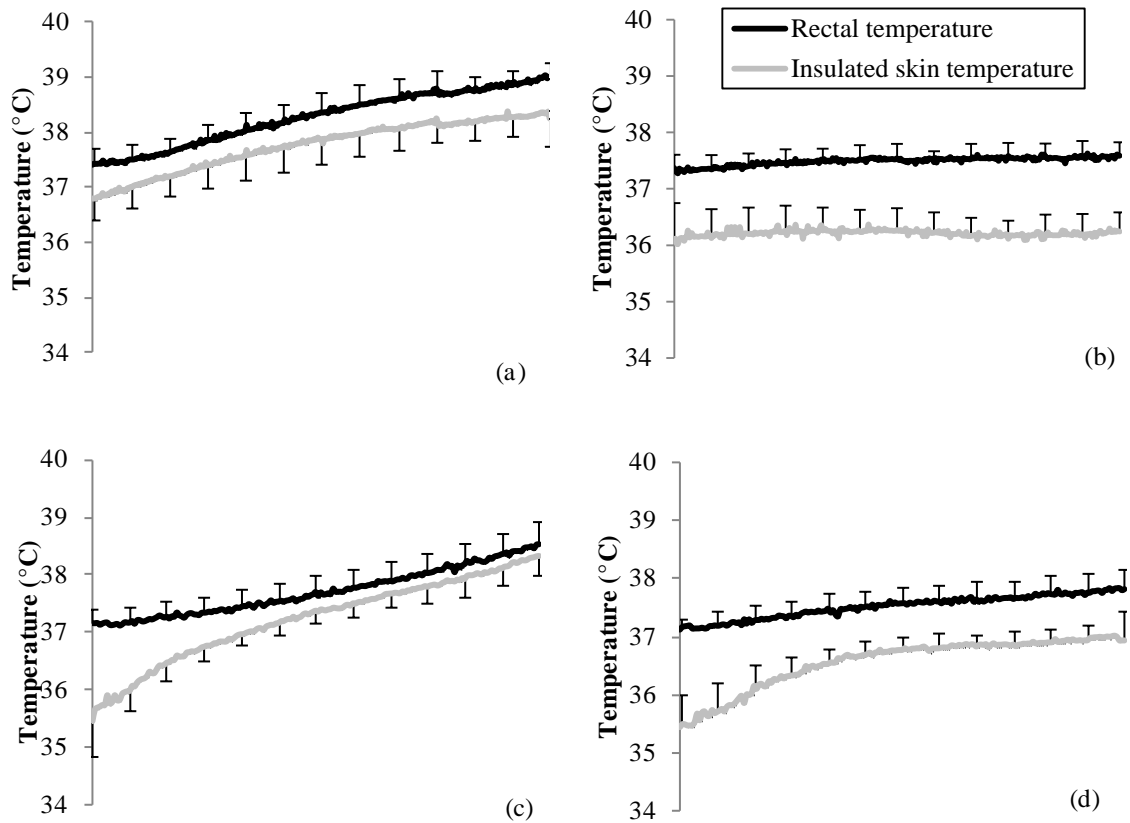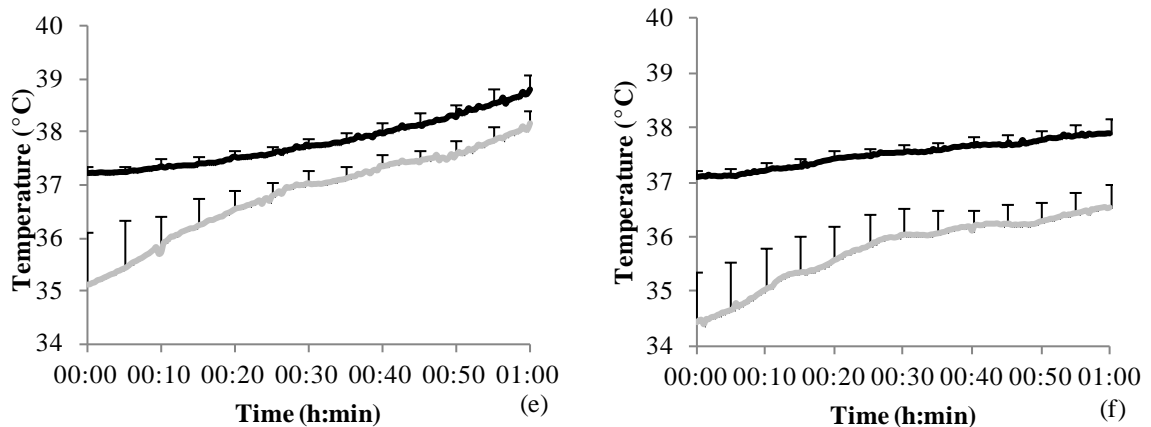
Figure 2 (a-f) - Raw mean data with standard deviation shown every 5 min for clarity for; (a) Civil Responder 1 (CR1) in hot conditions (b) CR1 in cool conditions (c) Gas Tight Suit (GTS) in hot conditions (d) GTS in cool conditions (e) Powered Respirator Protective Suit (PRPS) in hot conditions (f) PRPS in cool conditions. It should be noted that in the CR1 hot and cold conditions the insulated skin temperature (Tis) and rectal temperature (Tre) had converged by the start of the curcuit whereas this did not occur until ~25 min in the GTS and PRPS conditions. This could have been caused by the CR1 ensemble being donned 30 min before the start of the exercise circuit compared to 5 min before for the GTS and PRPS ensembles.

Figure 3 shows all the data (at 10 minute intervals) for all deployments combined. The relationship between T_{re} and T_{is} was better described as a quadratic equation ($r^2 = 0.77$) than a linear equation ($r^2 = 0.64$). The SEE in predicting T_{re} from T_{is} alone is 0.64 °C. If T_{is} values below 36.5 °C are removed then there is little difference between the quadratic ($r^2 = 0.80$) or the linear ($r^2 = 0.78$) equation. Thus, the SEE in predicting T_{re} from T_{is} (> 36.5 °C) using a linear equation was 0.29 °C.
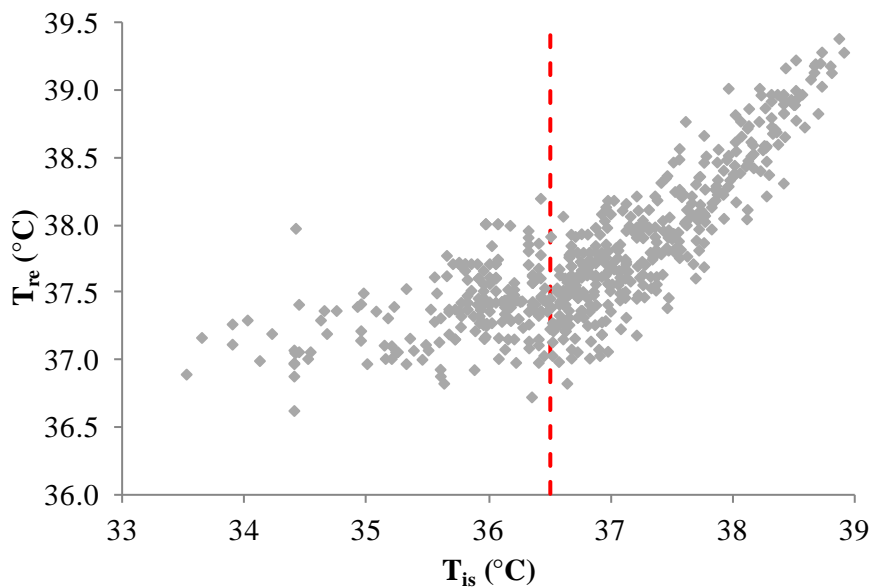
Figure 3 - Relationship between insulated skin temperature (T_{is}) and rectal temperature (T_{re})

3.2 *Developing a prediction equation*

The data from all conditions (PPE and environmental conditions) at 10 minute intervals were entered into the regression analysis. Due to the curvilinear nature of the relationship between T_{is} and T_{re}, T_{is} was entered into the analysis as a quadratic variable after centring to reduce colinearity, giving an SEE = 0.25 °C and an $adjr^2 = 0.79$.

Using stepwise multiple linear regression the following equation was developed:

$$T_{re} = 37.63 + (0.604 * [cT_{is} - 36.82]) + (0.130 * [cT_{is}^2 - 1292]) - (0.070 * [cT_{mc} - 32.16]) \quad (1)$$
$adjr^2 = 0.79$; SEE = 0.25 °C

Heart rate and 'PPE' did not sufficiently improve the variability in the prediction model to warrant their inclusion (SEE = 0.24 °C). While 'participant' resulted in an improvement in the model ($adjr^2 = 0.84$ and SEE = 0.22 °C), it was not included as it would not be practical to have an equation that required individual calibration.

As it was not possible to develop a generic equation to within the pre-defined practical limit of a SEE of less than 0.2 °C, the relationship between T_{is} and T_{re} was investigated in a sub-set of the data. Figure 3 shows that above a T_{is} of 36.5 °C the relationship between T_{is} and T_{re} was linear ($r^2 = 0.88$). Therefore further analysis was conducted to develop a linear equation using only T_{is} data points $\geq$ 36.5 °C (Equation 2).

$$T_{re} = 7.07 + (0.905 * T_{is}) - (0.088 * T_{mc}) \quad (2)$$

$adjr^2 = 0.87$; SEE = 0.19 °C;

3.3 *Validating the equation*

Twenty seven separate regression equations were developed, each leaving out a different participant from the analysis. Rectal temperature was then predicted for each participant using the equation which was developed without the inclusion of their data set. Figure 4 shows the regression line for predicted (using the 27 equations from the validation of equation 2) against measured T_{re}. The equations were developed using only T_{is} data above 36.5 °C, giving $r^2 = 0.85$ (p<0.05) and SEE = 0.20 °C. Figure 4 also shows the sensitivity and specificity of predicted T_{re}, with a theoretical upper T_{re} limit of 39 °C. Taking into account the error in the model (0.2 °C), to protect 97.5 % of individuals from exceeding a T_{re} of 39 °C, participants would need to stop exercising at a predicted T_{re} of 38.6 °C, which protected all participants from exceeding the limit (sensitivity 100 %). In protecting most individuals from possible heat illness, many individuals

would be stopped at an actual T_c of well below (between 38.2 °C and 39 °C) the designated T_{re} limit (bottom right quadrant of Figure 4) (specificity 89 %). If the known error was not taken into account, and all individuals were stopped at a predicted T_{re} of 39 °C, the sensitivity and specificity would be 65 % and 100 %, respectively.

Taking the mean value of the coefficients from the 27 equations, the following equation was created:

$$T_{re} = 7.07 + (0.905 * T_{is}) - (0.088 * T_{mc}) \tag{3}$$
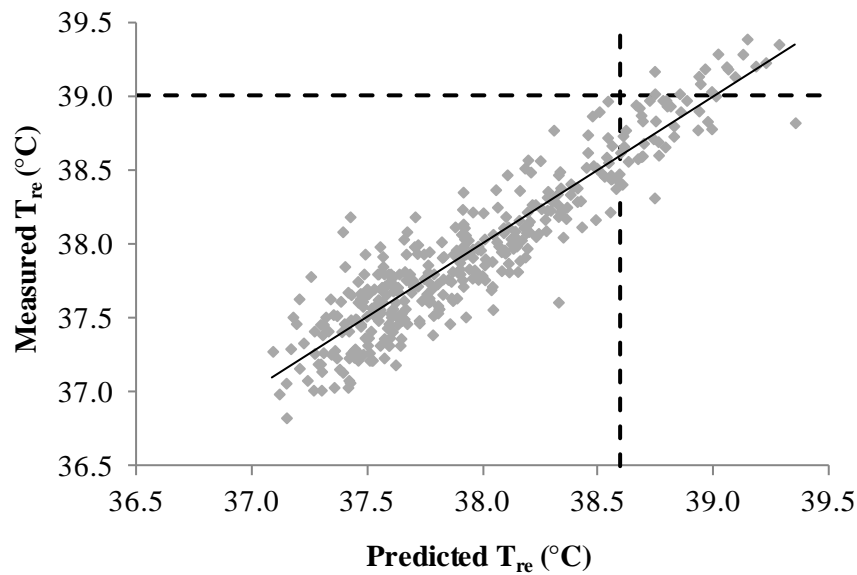$$\text{adj} r^2 = 0.85; \text{SEE} = 0.20 \text{ °C}$$

Figure 4 - Predicted vs. measured rectal temperature (T_{re}) (°C). The dashed lines show participants would need to be stopped at a predicted T_{re} of 38.6 °C to prevent 97.5 % of the population exceeding actual 39 °C.

4 Discussion

The aim of this study was to investigate the validity of using T_{is} to predict T_{re} in ES personnel wearing CBRN PPE. A prediction model using T_{is} and T_{mc} was developed for the prediction of T_{re} within a predetermined practical target SEE of ≤ 0.2 °C. Validation of the model using bootstrapping techniques showed that the equation could be applied to a separate cohort, within the target SEE of 0.2 °C.

Although there are no studies which use T_{is} to develop a heat strain index, the concept of using T_s to derive information about the thermal status of the body core is not novel. In 1971, Fox and Solman proposed a new method of body temperature measurement, based on heat insulation and equalisation of the skin and deep temperatures (Fox and Solman, 1971). If heat dissipation from the core to the environment is minimized either by insulation of the skin or due to conditions of uncompensable heat stress, T_s will converge with T_c and the temperature of the skin will eventually reflect changes in the core temperature (Pandolf and Goldman, 1978). The data from the current study show that T_s converges towards T_{re} when heat loss from the skin is minimized, and the difference between the two temperature measurements eventually stabilizes. The onset of exercise causes an increase in metabolic heat production which is accompanied by a rise in internal temperature. Above a certain threshold, thermoregulatory responses are evoked (Johnson and Park, 1982), including cutaneous vasodilation which promotes an increase in skin blood flow for dry heat loss from the skin to the environment. The extent to which T_s and T_{re} converge (ranging from 0.1 °C to 1.5 °C in the current study) depends upon the temperature of the microclimate (Kenefick et al., 2010), but once thermal equilibrium between the two measures is reached, T_{re} and T_s should rise in parallel. In GTS and PRPS, T_{is} and T_{re} converged for the first 20 to 30 min of exercise, after which they increased in parallel for the remainder of the trial. In CR1 there was no convergence, with T_{is} and T_{re} tracking each other in parallel for the entirety of the trial. The difference in time taken to reach thermal equilibrium between the ensembles was due to the fact that the GTS and PRPS were donned immediately prior to the start of exercise in order to conserve air from the BA (GTS) or conserve the battery life of the powered respirator (PRPS). The CR1 ensemble was donned 30 minutes before the participants started the exercise circuit (excluding the respirator, which is donned immediately prior to deployment). This is due to the more complex procedure of dressing in three layers of the CR1 in comparison to the one layer GTS and PRPS ensembles, which were donned 5 minutes before the start of the exercise circuit. This allowed a thermal equilibrium between T_{re} and T_{is} to be reached prior to the start of exercise in the CR1 conditions (Figure 2). Smolander et al. (1984) showed that T_s converged with T_{re} for the first 20 minutes of exercise in protective clothing, before reaching thermal equilibrium, with participants exercising at 41 % $\dot{V}O_{2\,max}$ in a 24 °C environment. Nunneley et al. (1992) also showed that T_s and T_{re}

reached thermal equilibrium after 20 min of exercise for participants wearing protective clothing, even when the high ambient temperature (38 °C) caused T_s to rise to a higher temperature than the core. These studies suggest that 20 minutes should allow for thermal equilibrium (equal difference between skin and core over time) to be reached in protective clothing, although this study shows this could be closer to 30 min depending on exercise intensity and environmental conditions.

Despite the convergence and apparent stability between T_{re} and T_{is}, T_{is} as a stand-alone measurement resulted in an SEE of 0.29 °C and therefore could not predict T_{re} with the desired precision of 0.2 °C. Other studies investigating the prediction of T_c from T_{is} have also questioned the error associated with the relationship. Although these studies will provide useful insight into a measure for which there is little research available, the protocols have little in common with the current study; thus, this caveat must be considered when drawing comparisons between studies. Bogh and colleagues (1994) compared T_{is} measured at the chest and axillia against T_{re} during a study to examine the effect of circadian rhythm on body temperature. Despite some agreement between T_{re} and T_{is} at the chest, the study concluded the T_{is} measurement could not act as a substitute for T_{re}, particularly during physical activity. The authors suggested that the cotton wool insulation material used was not adequate and questioned whether this could be improved due to inconvenience to the participant of a thicker insulation material and possible allergic reaction to additional adhesive. In another similar study investigating the circadian rhythm of adult women, the correlation between T_{re} and T_{is} was found to be variable and the authors concluded it should not be considered a substitute for T_{re} (Thomas et al., 2004). One study has found that T_{is} alone is a surrogate measure of T_{re} (Bernard and Kenney, 1994). In that study a device was designed that consisted of a 2.5 cm thermally conducting copper disk, covered with insulator that was 4.2 cm in diameter and 0.8 cm thick. There was a high correlation between T_{re} and disk temperature (r = 0.93) with an SEE of 0.2 °C.

Although the current study has shown it is not possible to use T_{is} alone as a predictor of T_{re}, a regression equation which included T_{mc} was developed that did provide a viable and practical non-invasive measure of T_{re}. Only Taylor (1998) has previously used a regression equation that was developed for the prediction of T_{es} using T_{is} (measured at the spinous process). Three equations were developed, one for each of three environmental conditions (25 °C, 33 °C and 40 °C), with strong correlations reported ranging from 0.8 to 0.9 across all conditions. In the current study, T_{mc} was found to improve the error in the prediction of T_{re}. Figure 2 showed that the difference between T_{re} and T_{is} varies depending on the ambient temperature; lower ambient temperature is associated with a larger difference between T_{re} and T_{is}. This was also shown by McLellan et al. (1993) where the difference between T_{re} and mean T_s was 1.3 °C and 2.2 °C when ambient temperatures were 30 °C and 18 °C, respectively, for firefighters carrying out heavy work in CBRN

PPE. Microclimate temperature clearly has a direct impact on the degree to which T_{is} and T_{re} converge (McLellan et al., 1993, Kenefick et al., 2010), and the inclusion of T_{mc} in the equation (equation 3) improves the prediction of T_{re}. However, T_{mc} is subtracted, or inversely in the equation, which is counterintuitive based on the assumption that as T_{mc} increases, capacity for heat loss decreases, which is likely to result in an increase in T_{re}. To the contrary, this equation (equation 3) suggests that a higher T_{mc} has the effect of reducing T_{re}, but the reasons and unclear from the results of this study.

Unfortunately, the exercise protocol used in the current study limits the extent to which one can generalize the findings to other exercise scenarios. In the current study, despite short rest periods between exercise bouts, the overall trend in all physiological responses was to increase. While representative of a short deployment in CBRN according to standard operating procedures enforced by the ESs, this is not representative of all working situation, in which an individual may be working in a high heat stress condition discontinuously for several hours, including many periods of work and rest (Blacker et al., 2012). For a non-invasive monitor to be valid under these circumstances, it must be able to predict T_{re} during both increases and decreases in body temperature. Further work is required to determine the validity of T_{is} to predict T_{re} under other conditions and patterns of work and rest.

4.1 *Application of the model in a working environment*

The impact of the error in predicting T_{re} on the workforce must be considered, and will depend very much on the safety criteria set and the risk the employer is willing to take. Collapse from heat stroke is usually associated with a T_c of > 40 °C (Armstrong, 2003). While in reality many individuals will cope at temperatures between 39 °C to 40 °C, this is not an acceptable upper limit in a working environment, especially taking into consideration that the critical T_c for individuals working in conditions of uncompensable heat stress is often reported as 38.5 °C (Montain et al., 1994, Selkirk and McLellan, 2001). Using this criterion (38.5 °C), and the SEE of 0.20 °C, individuals would have to be removed from work at a predicted T_{re} of 38.1 °C. While this would mean only 2.5 % of the population risk being above 38.5 °C, another 2.5 % would also be stopping at below 37.7 °C, having an adverse effect on work productivity. By increasing the T_c limit, work productivity could be improved, but this must be balanced against the additional risk of heat illness to the work force. Another option is to change the probability of risk to 1 SD rather than 2 SD, and in doing so protect 84 % of the population. This would result in workers being stopped at a predicted T_{re} of 38.3 °C, but would mean that 16 % of the population would be working above 38.5 °C. There is no definitive solution to this safety dilemma, and opinion varies. Gant et al. (2006) cited 0.3 °C (95 % limits of agreement [approximately ± 2SD]) as an acceptable error between T_{re} and gastro-intestinal temperature, with Gunga et al. (2009) accepting an error (95 % limits of

agreement [approximately ±2SD]) of 0.5 °C between T_{re} and a heat-flux sensor. Conversely, Muir et al. (2001) stated that an SD of 0.1 °C was required to ensure the accuracy of prediction between T_{re} and aural temperature. Ultimately the decision and consequent trade-offs lie with the employer, but the application of the model must be considered by the researcher to determine the viability of the surrogate measure.

4.2   Conclusion

The results from this study suggest that T_{is} and T_{mc} can be used in a model to predict T_{re} in ES personnel wearing different CBRN PPE ensembles within an SEE of 0.20 °C. The model is only applicable when T_{is} is over 36.5 °C, above which thermal stability is reached between the body core and the skin. Future work should involve determining the viability of using this non-invasive method in other physically demanding occupations performing different work-rest scenarios in different climatic conditions.

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