INDIRECT MEASUREMENT OF CORE TEMPERATURE DURING WORK CLOTHING AND ENVIRONMENTAL INFLUENCES

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INTRODUCTION

Since thermal tolerance impacts upon worker performance and health, the measurement of environmental stress and physiological strain are critical health considerations. However, field measurements of strain, particularly body-core temperature (T_c), are substantially harder than within the laboratory, and routine T_c measurement is rare. For industrial and military applications, direct T_c measurement may not be practical, or even possible. Consequently, surrogate indices of thermal strain have been sought. Clinical devices have been developed to evaluate T_c from surface measurements (see 1), and similar approaches have been used for field applications, attempting to exteriorize T_c (2), both with varying degrees of success. While skin temperatures (T_{sk}) are quite variable, it is feasible some shell tissues may approach T_c, if environmental influences are minimized. The current project re-evaluated this possibility, using **an** insulated T_{sk} in exercising, clothed, men and women.

Six pre-experimental factors were considered the T_{sk} of the chosen site must, in its uninsulated state, be inherently stable and closely approximate T_c; since T_{sk} is influenced by subcutaneous adipose and skin blood flow, sites should not be located over large fat deposits, but, if practical, could be located over large blood vessels; such skin sites should be exposed to minimal air movement and have a relatively *dry* **skin** surface with minimal radiant heat exchange; since T_{sks} are more homogenous under hotter conditions, then air temperature is critical to its successful application; skin site(s) chosen must not impede worker performance; and the degree of thermal strain experienced will affect the signal to noise ratio of the technique, such that when heat storage drives T_c upwards, the impact of inherent noise will be minimized.

MATERIALS AND METHODS

We completed 87 trials across **5** thermal loads: unclothed subjects (n = 17 men; 15°C, 28°C, **40°C)**, continuously cycling at 25%, 39% and 57% of peak aerobic power (3x30 min); and clothed subjects (n = 12 **(4** women); 25°C, **33°C, 40°C;** 50% RH). In the latter trials, subjects wore a disruptive-pattern combat uniform (mass ~2 kg, insulation ~0.035 $m^{-2}\cdot K\cdot W^{-1}$) and performed a 2-stage exercise-rest protocol (2% grade walk/run-rest). Stage one elevated T_c to ~38°C

(5 min at 3 km·hr^{-1}, 1 km·hr^{-1} increase every 10 min), followed by seated rest to lower Tc to ~37.5°C. Stage two continued exercise-induced T_c elevation to ~39°C (5 min at 4 km·hr^{-1}, 5 min at 5 km·hr^{-1}, 1 km·hr^{-1} increase every 10 min), followed by 15 min rest. Tests were performed in a balanced order between subjects and at the same time of day within subjects. The Human Research Ethics Committee (University of Wollongong) approved all procedures, and all subjects provided informed consent.

Core temperature was measured at the esophagus (T_{es}), rectum (T_{re}) and auditory canal (Edale Instruments, Cambridge, UK). Skin temperatures were recorded at 8 uninsulated sites (forehead, scapula, upper chest, arm, forearm, hand, anterior thigh, calf) and 4 insulated sites (forehead, over jugular vein, spinous process (T2-T4) and ventral wrist; EU type, Edale Instruments, Cambridge, UK). Skin thermistors were attached with waterproof tape. Insulated sites were also covered with closed-cell foam (4 cm * 4 cm, 8 mm thick) and cottonwool (4 cm * 4 cm, –2 mm thick), and secured with waterproof tape. All temperatures were recorded at 5-s intervals (1206 Series Squirrel, Grant Instruments Ltd., UK). Sweat rate was approximated from mass change. Cardiac frequency (fc) was measured at 5-s intervals (PE4000, Polar Electro SportsTester, Finland). Thermal sensation, thermal discomfort and physical exertion (RPE) were recorded every 5 min.

It was assumed that, for field application of this technique, T, would be derived using predictive equation(s), obtained from linear modeling of the laboratory-derived T_c and insulated skin temperature ($T_{sk\text{-}insul}$) relationships. For this reason, the accuracy of such T_c predictions was evaluated using linear regression analyses (least squares, best fit) across all conditions.

RESULTS AND DISCUSSION

Unclothed trials. Cool exposure (15°C) resulted in a mean T_{es} change from 37.02 °C to 37.57°C, with poor, and generally unacceptable (r=0.79) correlations between T_{es} and insulated T_{sk}. This was due to T_{sk} reductions during the first 30 min of the cool exposure. In the temperate state (28°C), mean T„ rose 0.50°C, while T_{re} increased by 0.83°C, and the relationship between T„ and jugular $T_{sk\text{-}insul}$ was strong (r = 0.97). For trials at 40°C, with T_c progressively rising (ΔT_{es} = 1.58°C), jugular $T_{sk\text{-}insul}$ started wanner and tracked T_c changes more rapidly. Esophageal temperature could be predicted from the average change in both jugular and spinal $T_{sk\text{-}insul}$, with a standard error of the estimate of 0.06°C (r = *0.99): at* 40 °C: T„ = ($T_{sk\text{-}insul}$ - 7.688 °C) / 0.791.

Thus, *95%* of the actual T„ fell within 0.12°C of the value predicted using the surrogate T, index. However, these data related to continuous exercise, during which T_c climbed progressively. They tell us little concerning the effectiveness of surrogate measures in intermittently exercising, clothed subjects, where T_c may be rising or falling.

Clothed trials. Subjects exercised for 95.6 min (23.0) and rested 28.2 min (10.2), with trials averaging 124 min (23.0). When analyzed across conditions, T_{es}, fc and treadmill speed peaked in the following ways: stage one—38.1°C (0.2), 159.6 $b \cdot min^{-1}$ (8.3), 8.4 $km \cdot hr^{-1}$ (1.6); and stage two—39.2°C (0.3), 183.7 $b \cdot min^{-1}$ (8.6), 9.4 $km \cdot hr^{-1}$ (1.6), respectively. Terminal mass change averaged 1.68 kg (0.70), and final effort sense (RPE) was 17.4 (1.8: very hard). Thus, this protocol induced significant thermal strain, under conditions ranging from slow walking to running and approached maximal tolerable exercise for the imposed conditions.

Following thermal equilibration, $T_{sk\text{-}insul}$ at each site increased with T_{es} and tracked resting and recovery falls in T_{es}. While temperatures were offset by as much as 2°C in the temperate state, they converged in the heat, particularly when T_{es} approached 39°C, making these indices more useful for detecting the onset of heat strain, though less effective in the thermoneutral range. Close inspection of rest and recovery data showed that T_{es} decreased almost immediately when exercise was terminated, due to the rapid reduction in heat production. However, $T_{sk\text{-}insul}$ rose transiently, before also decreasing. This continued rise was due to delayed heat flux, and the peaks in T_{es} and $T_{sk\text{-}insul}$ were out of phase at this time. When exercise resumed, the T_{es} to $T_{sk\text{-}insul}$ association returned to its previous relationship. That is, within individuals, the link between T„ and $T_{skin\text{-}insul}$ may be adequately described by a single linear function, for both continuous and discontinuous exercise.

The $T_{sk\text{-}insul}$ site showing the poorest relationship with T_c, across conditions, was the ventral Wrist, followed by the jugular $T_{sk\text{-}insul}$. The latter may be attributable as much to the difficulty of ensuring constant skin attachment, as it was to the facility of the site. The poor relationship with the wrist $T_{sk\text{-}insul}$ was a function of the time taken for T_c exteriorization. That is, even under hot conditions, skin temperature is not uniform, with more distal sites generally being cooler and approximating T_c only after an elevation in both T_c and T_{sks}. Notwithstanding a temperature offset between the forehead and spinal sites, both sites appeared equally capable of tracking T_{es}. However, from a practical perspective, the back may be best suited for T_c monitoring in the worker.

Since the prime concern for industrial and military applications is the relationship between $T_{skin\text{-}insul}$ and T_{es}, when T_{es} is increasing, data for the exercise periods were extracted. Esophageal temperature was regressed against $T_{sk\text{-}insul}$ within each condition (Table 1), for all subjects simultaneously, yielding the following predictions:

at 25°C: $T_{es} = 20.01°C + 0.49 *$ spinal $T_{skin\text{-}insul}$;
at 33°C: $T_{es} = 3.87°C + 0.91 *$ spinal $T_{skin\text{-}insul}$; and
at 40°C: $T_{es} = 9.11°C + 0.76 *$ spinal $T_{skin\text{-}insul}$.

Table 1: Correlation matrix for $T_{sk\text{-}insul}$ and T_c in clothed **subjects**

T,	**Condition**	Jugular		Forehead	**Spine**
T_{es}	40°C	0.85	0.90	0.94	0.91
T_{ac}		0.89	0.92	0.95	0.94
T_{re}		0.74	0.93	0.85	0.86
T_{es}	**All**	0.82	0.81	0.89	0.86
T_{ac}		0.88	0.84	0.91	0.89
T_{re}		0.80	0.89	0.85	0.85

Several points are noted. First, the insulation procedure largely, but not completely, removed the influence of air temperature. Second, a non-insulated T_{sk} is of little value in predicting T_{es} trends. Third, the correlation between $T_{sk\text{-}insul}$ and T_{es} is site dependent, particularly under cooler environments. Fourth, the $T_{sk\text{-}insul}$ relationship with T_{es} was somewhat dependent upon air temperature. Fifth, the error of predicting T_{es} is largely influenced by the $T_{sk\text{-}insul}$ variability between subjects. Finally, previous groups have focused upon the relationship between skin and T_{re}, yet in > 50% of the current comparisons at 33°C and 40°C, $T_{sk\text{-}insul}$ (spine and forehead) provided an equivalent or better prediction of T_{es} than did T_{re} on its own.

CONCLUSIONS

It may be concluded that surrogate indices of T_c do exist, which, when insulated from environmental influences, may be used to predict changes in T_{es} with substantial accuracy.

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