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SHORT REPORT

Agreement among common core temperature indices in defining critical environmental limits for human thermoregulation: a secondary analysis

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Abstract

Global intensification of heat extremes has heightened interest in defining critical environmental limits for human thermoregulation. These limits are commonly estimated from the inflection point in core temperature during progressive heat stress protocols. Esophageal temperature (T_{es}) is the criterion core temperature index, as it reflects right atrial blood temperature and responds rapidly to changes in the body's thermal state. However, measurements of rectal (T_{re}) and gastrointestinal temperature (T_{gi}) are more commonly used due to better participant tolerability. We evaluated agreement between inflection points of these core temperature indices using data from two previously published progressive heat stress protocols. Study 1 measured T_{es} and T_{re} in 11 resting young adults (3 female). Study 2 evaluated T_{re} and T_{gi} in 16 resting or cycling young adults (8 females). Ambient conditions at the identified inflection points were converted to wet-bulb temperature (T_{wb}) and analyzed with Bland–Altman analysis (±1.3°C T_{wb} acceptable agreement range). In Study 1, both the mean bias [0.3°C (95% CI: 0.0°C to 0.6°C)] and the individual limits of agreement (LOA: −0.6°C to 1.3°C) for the T_{es}-T_{re} comparison were within ±1.3°C T_{wb}. In Study 2, the mean bias was also within the acceptable range [0.8°C (0.5°C to 1.1°C)], whereas the limits of agreement (0.6°C to 1.7°C T_{wb}) exceeded this threshold. Although larger confirmatory trials are needed, these findings suggest that T_{re} inflection identified during a progressive humidity protocol closely aligns with that identified using T_{es}. T_{re} and T_{gi} demonstrated acceptable group-level agreement but caution is warranted when interpreting individual responses.

NEW & NOTEWORTHY We assessed agreement in inflection points for esophageal (T_{es}), rectal (T_{re}), and gastrointestinal (T_{gi}) temperatures in young adults during progressive humidity protocols. T_{es} and T_{re} exhibited good agreement on both group (study) and individual levels. Although group-level agreement between T_{gi} and T_{re} was acceptable, individual agreement was poor. These findings indicate that all three techniques are suitable for studies of critical environmental limits, though T_{es} or T_{re} are preferred when assessing individual thresholds.

climate change; environmental extremes; heat balance; heat stress; thermoregulation

INTRODUCTION

The increasing frequency and severity of extreme heat events place a growing proportion of the global population at risk of exposure to combinations of ambient temperature and humidity exceeding critical environmental limits for human thermoregulation. Conditions above these limits denote thermally uncompensable environments (1, 2). A comprehensive understanding of criticial environmental limits is becoming increasingly important for characterizing climate-related risks and informing evidence-based mitigation strategies to prevent adverse outcomes in susceptible populations.

Progressive heat stress protocols (also called thermal-step or core temperature inflection protocols) are a commonly used and validated approach for empirically identifying critical environmental limits for thermoregulation (3, 4). In

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these protocols, participants are exposed to rapidly stepped increases in air temperature or relative humidity in a climate-controlled chamber (e.g., 5–10 min steps of 3% relative humidity at 42°C) while a core temperature index is continuously monitored (3–9). Over a wide range of environments, body core temperature equilibrates in proportion to metabolic heat production, largely independent of environmental factors (10, 11). As the temperature and humidity conditions reach critical limits, an abrupt and rapid increase in core temperature occurs, thought to reflect a failure of heat loss mechanisms to offset heat production and environmental heat gain, leading to a continuous increase in core temperature. This inflection point has been shown to provide an accurate estimate of the transition from compensable and uncompensable heat stress; that is, the environmental conditions beyond which body temperature regulation fails, and core temperature increases rapidly toward dangerous levels (4, 7).

Esophageal temperature (T_{es}) is generally considered the optimal index of core temperature for identifying the core temperature inflection point during progressive heat stress protocols since it provides an accurate estimate of central blood temperature (12) and rapidly responds to changes in the body's thermal state (13). However, most research on critical environmental limits uses alternative core temperature indices, primarily rectal (T_{re}) or gastrointestinal temperature (T_{gi}). These methods are better tolerated by participants but respond more slowly to changes in thermal conditions due to low inertia of heat transfer between the central circulation and the gut (12–14). For example, stable rectal temperatures can lag 30–70 min behind whole body heat balance (determined via direct calorimetry) in resting young adults moved from thermoneutral conditions to ambient conditions of 40°C with 9% relative humidity (RH) (14). Consequently, it has been suggested that using T_{re} or T_{gi} may mischaracterize the core temperature inflection point (15). However, this hypothesis has not been empirically tested. We therefore assessed agreement between estimated critical environmental limits based on inflection points derived from different core temperature indices during progressive humidity protocols.

METHODS

This analysis used previously published data from the Human and Environmental Physiology Research Unit of the University of Ottawa (4) (Study 1) and from data collected at the Vrije Universiteit Amsterdam in the Netherlands in collaboration with the Pennsylvania State University Human Environmental Age Thresholds (PSU HEAT) project (5) (Study 2) to assess the agreement in core temperature inflection points between common measurement techniques. Brief summaries of the experimental protocols are provided in the next two paragraphs, and full details are available in the primary publications.

In Study 1, T_{es} and T_{re} were measured in 11 resting young adults [3 female; mean (interquartile range): 28 (25–32) yr, with a body mass index (BMI) of 26.2 (22.9–30.4 kg/m^2)] exposed to a progressive humidity step protocol. Air temperature was held constant at 42°C. Following a 60-min equilibrium period, RH was increased 3% every 10 min until RH in the chamber reached 70%. T_{es} and T_{re} were measured continuously using general-purpose thermocouple temperature probes (Mon-a-therm General Purpose Temperature Probe, Mallinckrodt Medical Inc.) situated ∼40 cm past the nostril and ∼12 cm past the anal sphincter, respectively. Data were averaged over 1-min intervals and exported as a series of figures. Inflection points for T_{es} and T_{re} were identified by a blinded analyst [for details, see Ref. (4)]. Note that although the published report included 12 participants, our analysis was conducted for a reduced sample size of 11, as one participant did not have both T_{es} and T_{re} inflection data (due to technical difficulties).

In Study 2, 16 young adults [8 female; mean (SD): 23 (4) yr, with a BMI of 23 (3) kg/m^2] were exposed to a progressive humidity step protocol at 38°C air temperature while at rest or performing light cycling (10 W external work). After 30 min of RH at 39.9 ± 2.5%, RH was increased 10% every 10 min, until a clear rise in T_{re} was observed. T_{re} (401 YSI Compatible Reusable Temperature Probe, Yellow Spring Instruments, Yellow Springs, OH) and T_{gi} (myTemp, Nijmegen, The Netherlands) temperatures were measured simultaneously, and inflection points were later identified visually [for details, see Ref. (5)]. Fluid intake was prohibited during experimental trials. Note that although the published report included data for 26 participants, T_{re} and T_{gi} were collected simultaneously for the 16 participants tested in the Netherlands.

Statistical Analysis

Ambient conditions at the inflection point were converted to wet-bulb temperature (T_{wb}) and compared via Bland–Altman analysis using the R (version 4.3.2) package "SimplyAgree" (16) within the RStudio integrated development environment (version 2025.9.2, Posit). For Study 2, a participant identifier was included in the analysis to account for the repeated measures design (rest and cycling). We also evaluated agreement separately for rest and exercise conditions.

The acceptable range for agreement was set at ±1.3°C T_{wb}, representing a meaningful detectable difference (95% confidence level) in the estimated limit for thermoregulation based on reliability data from Cottle et al. (8). From these data, we estimated the standard error of the measurement of core (rectal) temperature inflection using the "SimplyAgree" package for R (16). We then calculated the individual minimal detectable difference using previously described equations (17, 18):

$$\mathrm{MDD} = \mathrm{SEM} \cdot 1.96 \cdot \sqrt{2},$$

where MDD is the meaningful detectable difference (at the 95% confidence level), and SEM is the standard error of the measurement (both in °C T_{wb}).

To evaluate the potential for proportional bias, we interpreted the slope coefficient from a linear model regressing the difference in inflection point between the two techniques against their mean. For Study 2, we also included a random intercept for participant ID.

RESULTS

In Study 1, the inflection points for T_{es} occurred, on average, 0.3°C T_{wb} earlier than the T_{re} inflection point. However, both the mean bias 95% confidence interval (0.0°C to 0.6°C T_{wb}) and the 95% limits of agreement (−0.6°C to 1.3°C T_{wb}) were within the acceptable range of ±1.3°C T_{wb} (Fig. 1*A*). In Study 2, the inflection point for T_{gi} occurred 0.8°C T_{wb} higher on average, compared with the T_{re} inflection point (Fig. 1*B*). Although the mean bias 95% confidence interval fell within the acceptable range (0.5°C to 1.1°C T_{wb}), the upper limit of the 95% limits of agreement fell 1.5°C T_{wb} above the upper bound (−0.8 to 2.4 T_{wb}). Interpretations were similar when analysis was restricted to resting [mean bias: 0.7 T_{wb} (0.5°C to 1.1°C T_{wb}); limits of agreement (−0.9 to 2.3 T_{wb})] or exercise conditions [mean bias: 0.8 T_{wb} (0.2°C to 1.3°C T_{wb}); limits of agreement (−1.3 to 2.9 T_{wb})]. Proportional bias tests were not statistically significant for either study ($P \geq 0.12$).

DISCUSSION

Progressive heat stress protocols are a validated and commonly used empirical approach to identify the environmental conditions marking the transition from compensable to uncompensable heat stress across different populations and metabolic rates (3–9). The protocols rely on continuous monitoring of core temperature as participants are exposed to stepwise increases in ambient air temperature or humidity. When environmental conditions become uncompensable, heat balance can no longer be maintained, resulting in a rapid inflection in core temperature (7). Thus, the validity of these protocols depends on using a core temperature index that accurately and quickly detects a change in body heat content. Our secondary analysis of previously published progressive heat stress data (4, 5) suggests good agreement between esophageal and rectal temperatures at both group mean and individual levels. That is, both the mean bias—which reflects the magnitude of error between techniques at the group or study level—as well as the individual limits of agreement were within the minimal detectable difference in critical environmental limits (±1.3°C T_{wb}). Although T_{re} and T_{gi}

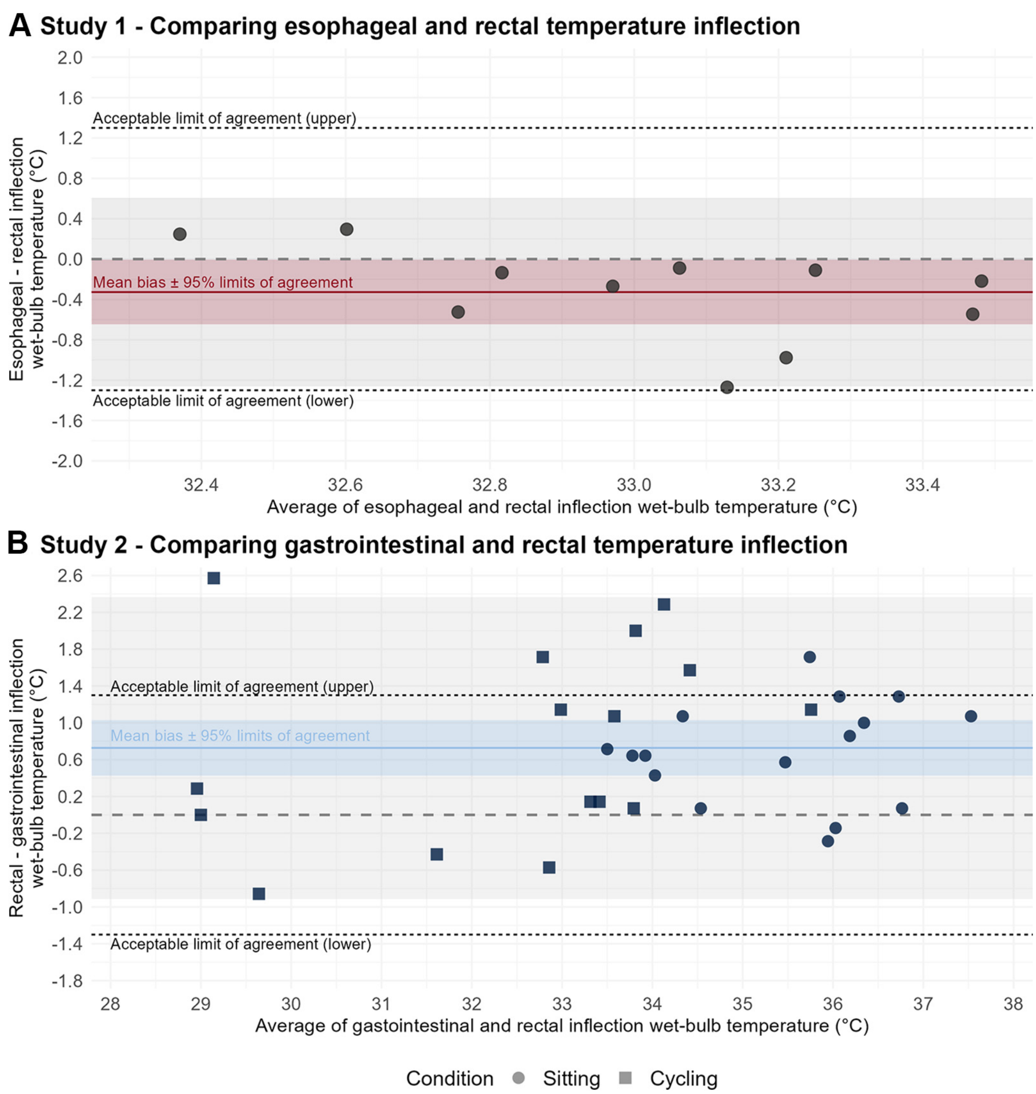

Figure 1. Bland–Altman analysis of agreement between core temperature indices for wet-bulb temperature inflection points. Panels show agreement between esophageal and rectal temperature in 11 young adults during a progressive humidity protocol (*A*) and gastrointestinal and rectal temperatures in 16 young adults during a progressive humidity protocol (*B*) while either resting or lightly cycling. Solid lines indicate mean bias; dark colored bands show the mean bias 95% confidence interval; gray shaded bands show the 95% limits of agreement; dotted lines indicate predefined acceptable limits (±1.3°C T_{wb}).

are reasonably comparable on average, they show greater individual variability.

In mechanistic thermal physiological studies, T_{es} is generally preferred for body core temperature assessment because it accurately reflects central blood temperature (12) and responds rapidly to changes in the body's thermal state (13). By contrast, measurements from more insulated body compartments, such as the rectum or gastrointestinal tract, respond more slowly to sudden changes in the body's internal thermal environment (13, 14, 19). Our analysis supports this interpretation. In Study 1, T_{es} inflected ~0.3°C T_{wb} earlier than T_{re} (Fig. 1*A*). However, the difference between these measures remained within the predefined acceptable range of ±1.3°C T_{wb} at both the group and individual levels based on the day-to-day reliability in core temperature inflection during progressive heat stress protocols [see Meade et al. (4) for details]. Although some studies report discrepancies between T_{es} and deeper body measurements (13, 14), others show acceptable agreement (20, 21). These differences may result from the intensity and duration of heat stress. For example, O'Brien et al. (20) found comparable changes in T_{es}, T_{re}, and T_{gi} during 3 h of warm water immersion at 36°C, with or without exercise. Although progressive heat stress protocols use extremely hot and humid conditions to evaluate thermoregulatory upper limits, changes in thermal conditions occur relatively gradually. For example, in Study 1, relative humidity was increased by only 15% per hour (4). This gradual progression likely minimizes the impact of temporal lags between central circulation and deeper tissues on the identified inflection points.

By contrast, T_{re} and T_{gi} showed less consistent agreement. Although the mean bias and group-level agreement were acceptable, individual-level variability was higher than in Study 1 and the predefined acceptable agreement. This discrepancy could be due to the fact that T_{re} reflects the average temperature of deep body tissues and is strongly influenced by convective heat transfer associated with blood circulation. In contrast, the temperature measured by T_{gi} depends on the sensor's location. Because the capsule in Study 2 was ingested ~1 h before the experiment, it was likely still in the stomach at the start of heat stress. In this position, T_{gi} may respond more like T_{es} and therefore increases earlier and faster than T_{re}. The positive mean bias we observed, an earlier inflection point when measured with T_{gi}, supports this interpretation. Another potential explanation is the shorter step duration in Study 2 compared with Study 1. The substantial individual-level variability observed between T_{re} and T_{gi} demonstrates that these measures are not interchangeable when individual precision is required. This finding has important implications for the use of T_{gi} in evaluating thermal strain or establishing individual thermal limits. Nonetheless, confirmation of this interpretation requires studies directly comparing T_{gi} and T_{es} during progressive heat stress. Overall, these discrepancies are unlikely to meaningfully affect most study-level conclusions, which are typically based on group-level analyses. However, caution is warranted when individual-level precision is required, such as in person-level assessments, model validation, or the evaluation of individual contributors to variability in critical limits, although these applications are comparatively less common.

Our findings have clear implications for designed studies evaluating critical environmental limits for human thermoregulation, particularly regarding the feasibility and practicality of the included measurements. Although T_{es} is considered the reference standard for thermophysiological research (except for maybe central blood temperature), it is not always practical in studies involving older adults, clinical populations, or prolonged heat exposures because it can increase participant burden and discomfort and can yield inaccurate measurements when fluids are consumed. The acceptable group-level agreement among T_{es}, $T_{re,}$ and T_{gi} suggests that participant comfort and experimental ease can be improved without markedly compromising accuracy in core temperature assessment. However, for studies focusing on individual responses, T_{es} or T_{re} remain the preferred measures and prolonged stage durations (~8–10 min) are recommended if T_{gi} is used to minimize lag between compartments. The present analysis is limited by sample size, participant characteristics, and the specific experimental conditions used. Although this secondary analysis provides preliminary evidence of the agreement of these measurement techniques, their agreement needs to be assessed under a greater range of metabolic and environmental conditions.

Conclusions

The findings suggest that T_{es}, T_{re}, and T_{gi} show acceptable agreement for estimating critical environmental limits for human thermoregulation during thermal-step protocols at the group (study) level. In studies involving clinical or vulnerable populations such as older adults, less invasive measures like T_{re} and T_{gi} may therefore be used without compromising the validity of group-level inferences. However, when the objective is to identify or assess individual limits, T_{es} or T_{re} are recommended.

DATA AVAILABILITY

Deidentified data are available upon reasonable request and signed access agreement. Note that separate use agreements for each study are required.

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

AUTHOR CONTRIBUTIONS

R.D.M., F.K.O., H.A.M.D., W.L.K., and G.P.K. conceived and designed research; R.D.M. and F.K.O. performed experiments; R.D.M. analyzed data; O.K.L., R.D.M., T.v.d.B., F.K.O., H.A.M.D., W.L.K., and G.P.K. interpreted results of experiments; R.D.M. prepared figure; O.K.L. and R.D.M. drafted manuscript; O.K.L., R.D.M., T.v.d.B., F.K.O., H.A.M.D., W.L.K., and G.P.K. edited and revised manuscript; O.K.L., R.D.M., T.v.d.B., F.K.O., H.A.M.D., W.L.K., and G.P.K. approved final version of manuscript.

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