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Do one-hour exposures provide a valid assessment of physiological heat strain?

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Abstract

For time- and cost-efficient heat stress assessment procedures at workplaces or in experimental studies, short-time measurement periods (e.g. 1 h) are sometimes employed in lieu of whole shift observations assuming that the short time period will provide valid figures of equilibrium physiological responses. We studied the influence of exposure duration on physiological heat strain considering the modifying effects of clothing and heat acclimation using a database of 564 climatic chamber exposures performed by 28 young males under heat stress conditions with widely varying air temperature and humidity levels. We compared heart rates, rectal and mean skin temperatures, and sweat rates recorded after 1 h with the values averaged over the third hour of exposure representing steady-state. One-hour measurements agreed with equilibrium values for rather low strain levels only, with heart rates below 100 bpm and rectal temperatures below 37.2 °C. On average, one-hour values underestimated all heat strain parameters. This underestimation error was only moderately influenced by clothing and heat acclimation status, but increased significantly with air temperature and humidity, reaching considerable magnitude under hot-humid conditions associated with elevated heat strain. Regression analyses of the prediction error depending on the equilibrium response revealed that underestimation increased with equilibrium strain level. This correlation was strongest for heart rate and core temperature, and was shown to potentially cause a misclassification of hazardous working conditions as safe by given heat strain criteria.

Practical Relevance: The severe underestimation of heat strain due to short measurement periods, as observed under hot-humid conditions and/or when associated with high physiological strain, will immediately impact the exposed personnel, but will also inform occupational health professionals and standard writers regarding the heat stress assessment for work shifts with high activity levels or with protective clothing.

Keywords Thermo-physiology · Heat stress · Humidity · Clothing · Heat acclimation

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Reichen einstündige Messungen zur Beurteilung physiologischer Hitzebeanspruchung aus?

Zusammenfassung

Aus Effizienzüberlegungen werden im Hinblick auf Dauer und Kosten von Messungen bei Untersuchungen zur Gefährdung durch Hitzebelastungen ganzschichtige Datenerhebungen häufig durch kurzzeitige, etwa einstündige Beobachtungen unter der Annahme ersetzt, dass die verkürzte Beobachtungszeit zur Beurteilung eines thermoregulatorischen Gleichgewichts der physiologischen Beanspruchung ausreicht. Zur Untersuchung des Einflusses der Beobachtungsdauer auf die Hitzebeanspruchung unter Berücksichtigung von Bekleidung und Hitzeakklimatisation in 564 Klimakammer-Versuchen mit 28 jungen männlichen Probanden wurden die in der dritten Expositionsstunde registrierten Mittelwerte mit den nach 1 h registrierten Rektal- und Hauttemperaturen, Herzschlagfrequenzen sowie Schweißraten verglichen. Die Werte nach einer Stunde stimmten nur auf niedrigem Beanspruchungsniveau mit den Gleichgewichtswerten überein, unterschätzten aber im Mittel für alle Größen sowie Akklimatisations- und Bekleidungsbedingungen die Beanspruchung. Dieser Fehler nahm mit steigender Lufttemperatur und -feuchte, und damit einhergehender gesteigerter Beanspruchung, statistisch signifikant zu. Regressionsanalysen des Fehlers in Abhängigkeit vom „Steady-State“ belegten zudem insbesondere für Herzschlagfrequenz und Rektaltemperatur eine mit ansteigender Beanspruchung zunehmende Unterschätzung, die in vorgegebenen Beurteilungsverfahren zur Hitzearbeit dazu führen kann, dass Gefährdungen fälschlich als sicher eingestuft werden.

Praktische Relevanz: Die mit steigender Beanspruchung zunehmende Unterschätzung der Gefährdung bei Hitzearbeit durch zu kurze Beobachtungszeiten kann insbesondere für Arbeiten mit erhöhtem Energieumsatz oder unter Schutzkleidung bedeutsam sein und sollte insbesondere bei den für die Gefährdungsbeurteilung Verantwortlichen, den Verfassern von Vorschriften, sowie den direkt betroffenen Beschäftigten Beachtung finden.

Schlüsselwörter Thermophysiologie · Hitze · Luftfeuchte · Bekleidung · Akklimatisation

1 Introduction

1.1 Background and literature review

Climate change will pose escalating risks associated with heat stress to both the general and working population (Casanueva et al. 2020; ILO 2019; Morris et al. 2021; Watts et al. 2021). This triggers a raised awareness and need for assessment procedures considering risks to health and safety (ISO 7243 2017; ISO 7933 2004), but also to heat related productivity issues during work (Bröde et al. 2018; Foster et al. 2021).

A major strain criterion applied in heat related health risk assessment procedures is equilibrium core temperature, usually measured in the rectum (Malchaire et al. 2000), which should not exceed a specified threshold value, e.g. 38 °C as applied by ISO 7933 (2004). The level of this equilibrium core temperature will only depend on workload within the so-called 'prescriptive zone' (Fig. 1), a term coined by Lind (1963). Above the 'Upper Limit of the Prescriptive Zone' (ULPZ), core temperature will still maintain an equilibrium, but at a higher level determined by the climatic conditions in the 'poikilothermic zone' (Fig. 1). If core temperature equilibrium cannot be sustained, heat stress will become uncompensable and exposure time must be limited in order to ensure the worker's health and safety (Cheung et al. 2000; ISO 7933 2004). As performing a corresponding hazard assessment will require time-consuming and cost-intensive observations at workplaces (ISO 15265 2004), the measurement time required for reliable risk evaluation becomes an important parameter for planning such a study.

Historically, research estimating equilibrium values of heat strain relied on long-term observations. E.g., Yaglou (1927) conducted exposures at rest from more than two up to 4 h, and Wenzel (1976) chose durations of exposures comprising treadmill exercise "*... in such a way that the subject was able to tolerate the given condition for at least two, usually four, and sometimes for up to six hours, without becoming completely exhausted*".

Fig. 2 illustrates the differences in the time course of heart rates (*HR*), rectal (T_{re}) and skin temperatures (T_{sk}) as well as sweat rates (*SR*) recorded with a semi-nude, acclimated, young male participant performing treadmill work for more than three hours under warm-dry (Fig. 2a) and hot-humid conditions (Fig. 2b), respectively (Kampmann 2000).

Some influential studies employed shorter exposure times of one hour, e.g. Lind (1963), when estimating "*thermal environmental limits for everyday work*". In this study, each experimental period lasted for 1 h or for long enough to establish thermal equilibrium as judged by an increase in T_{re} below 0.03 °C over a period of 15 min. Even shorter working periods were studied, e.g. "*the values at the end of each 30-min period were used as these usually approached steady-state values*" (Havenith and van Middendorp 1990), but more frequently 60 min exposures (Havenith et al. 1998, 1995a, b). In a recent publication the physical work output

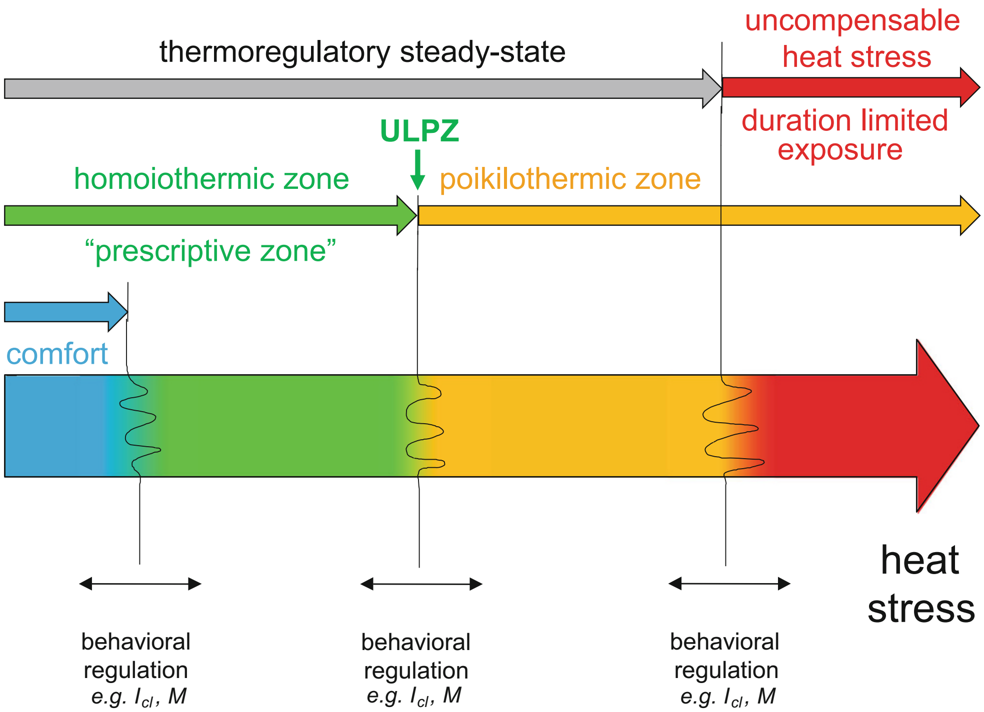

Fig. 1 Scheme of zones with heat stress increasing from the left to the right. The boundaries between the zones are not fixed and depend as well on individual characteristics of exposed subjects as they also may be shifted voluntarily by adjusting e.g. clothing insulation (I_{cl}) or metabolic rate (M). ULPZ gives the "Upper Limit of the Prescriptive Zone", a term introduced by Lind (1963). (Figure modified from Kampmann 2000)
Abb. 1 Schematische Darstellung der betrachteten Bereiche mit von links nach rechts zunehmender Hitzebelastung. Die Bereichsgrenzen variieren in Abhängigkeit von individuellen Merkmalen der Exponierten und können sich auch durch Verhaltensanpassung, z. B. Änderung der Bekleidungsisolation (I_{cl}) oder Arbeitsschwere (M), verschieben. ULPZ kennzeichnet das von Lind (1963) eingeführte „Upper Limit of the Prescriptive Zone". (Bild modifiziert nach Kampmann 2000)

during one-hour treadmill work was measured, clamping heart rate to 130 bpm by adjusting the workload for assessing changes in physical work capacity in response to a wide range of heat stress conditions in comparison to a 'neutral' reference (Foster et al. 2021).

If the focus is on the position of the ULPZ rather than on the level of heat strain within the poikilothermic zone, progressive stress protocols may estimate the ULPC by stepwise increasing a single climatic parameter (e.g. temperature or humidity) until T_{re} raises from an equilibrium. Bernard et al. (2008) used a progressive stress protocol for detecting the ULPZ for different clothing ensembles. Participants walked on a treadmill until they reached a thermal steady-state (no change in T_{re} and HR for at least 15 min). Then, air temperature was increased by 0.8 °C every 5 min until T_{re} raised by more than 0.1 °C per 5 min for 15 min. The climatic condition 5 min before the inflection point marked the "*critical condition*", i.e., the ULPZ for each of the different clothing ensembles.

The time needed for alignment of a thermoregulatory steady-state will depend on several parameters. Cooling by evaporation of sweat is essential for sustaining heat exposures (Cheung et al. 2000; Parsons 2014), while the sweat rate itself is influenced by core temperature as well as by skin temperature (Nadel et al. 1971). The dynamics of sweat rate responses to constant heat stress can be described by a first-order system (Malchaire 1991) reaching 95% of the steady-state value after the triplicated time constant as system parameter. While Grucza et al. (1985) estimated time constants for sweat rate of 8.8 min for women and of 7.5 min for men, 10 min is assumed in ISO 7933 (Malchaire et al. 2001), which might increase up to 25 min for conditions inducing low sweat rates (Malchaire 1991). If the skin is progressively covered by sweat, hidromeiosis may show up with initially increasing and then again decreasing sweat rates due to elevated skin wettedness (Brown and Sargent 1965; Nadel and Stolwijk 1973). From a teleological perspective, hidromeiosis reduces the dripping portion of sweat that does not contribute to evaporative body cooling. This portion varies with heat acclimation (Candas et al. 1980) and appears to be more pronounced in unclothed compared to clothed persons (Candas and Hoeft 1995). Thus, it may well take up to 3 h until sweat rate may settle in hot-humid climatic conditions for semi-nude subjects, as illustrated by Fig. 2b.

Further factors potentially modifying the dynamic responses to heat stress are the adaptive changes in the thermoregulatory system due to heat acclimation, characterized

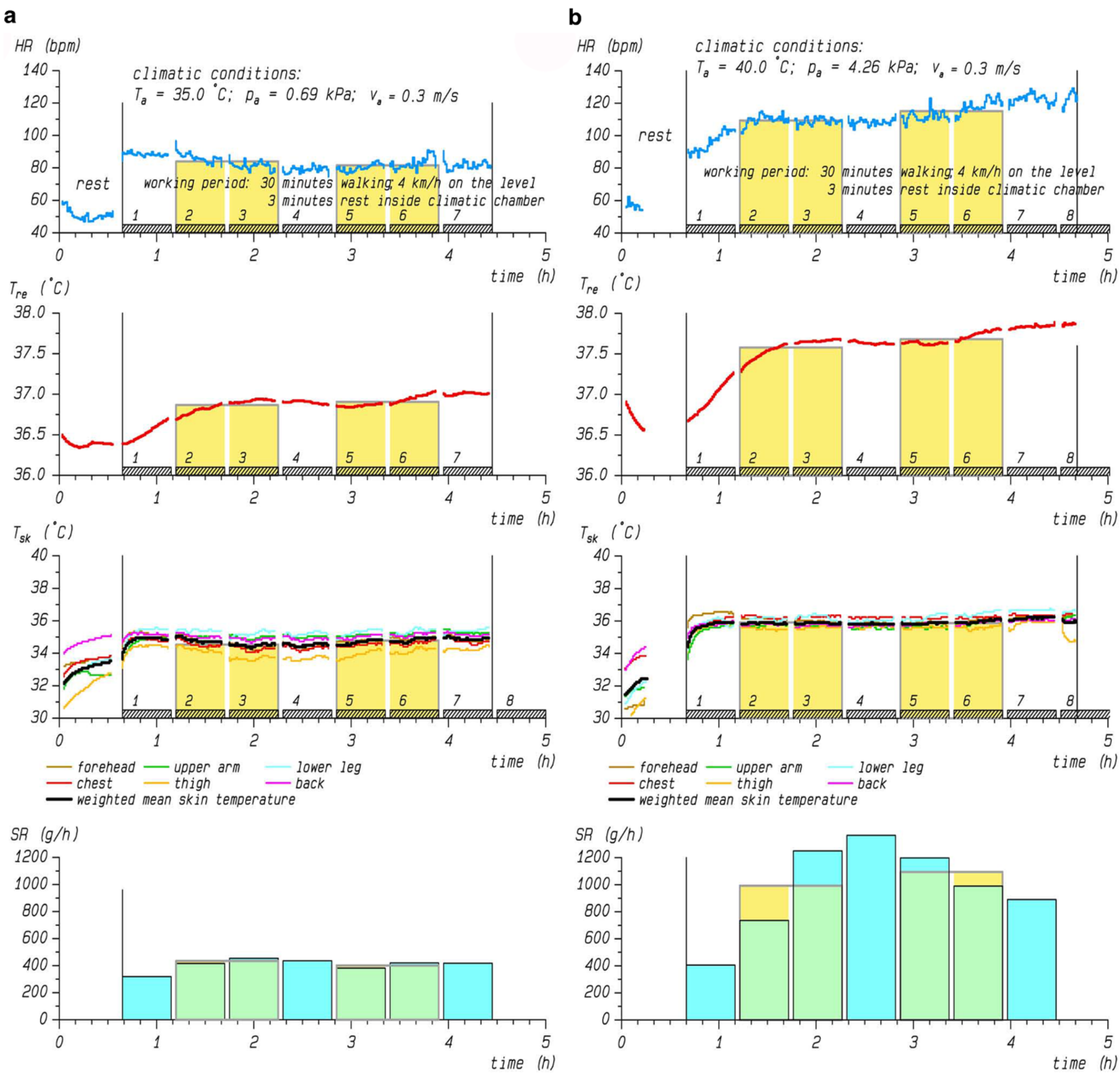

Fig. 2 Example of the development of heart rates (*HR*), rectal (T_{re}) and skin temperatures (T_{sk}), and sweat rates (*SR*) of a semi-nude, acclimated participant in heat stress exposures under warm-dry (**a**) and hot-humid (**b**) conditions, respectively. The yellowish shaded areas mark the time intervals averaged for comparing values after 1 h with those during the third hour of exposure with bar heights corresponding to the mean values

Abb. 2 Zeitliche Entwicklung der Herzschlagfrequenzen (*HR*), Rektal- (T_{re}) und Hauttemperaturen (T_{sk}) sowie Schweißraten (*SR*) eines unbekleideten (I_{cl} = 0.1 clo: Shorts, Socken und Turnschuhe), akklimatisierten Probanden unter trocken-warmer (**a**) bzw. feucht-heißer (**b**) Hitzebelastung in der Klimakammer. Gelblich eingefärbte Abschnitte markieren die Zeitintervalle, die für den Vergleich der Werte nach einer Stunde mit den in der dritten Stunde registrierten Werten herangezogen werden, wobei die Höhe der Rechtecke dem Mittelwert entspricht

by increased *SR* in connection with lowering of T_{re} and *HR* after repeated exposures to heat (e.g., Bröde et al. 2009; Kampmann 2000; Kampmann and Bröde 2019; Kampmann et al. 2008). In addition, for clothed persons, the absorption of sweat during heat exposure within the fabric will modify the clothing's thermal properties and consequently physiological strain (Bröde et al. 2008; Gebhardt et al. 2007; Havenith et al. 2008; Lotens and Havenith 1995).

For evaluating the validity and reliability of the results from studies employing short-time exposures, sometimes accompanied by dynamically changing conditions as in progressive stress protocols, it is crucial to understand how thermal strain will vary over time. Considering the assessment of heat stress in occupational settings, the representativeness of short-time observations for equilibrium values of strain in the poikilothermic zone (Fig. 1) is of special interest.

1.2 Study objectives and hypotheses

From the literature review, we hypothesized discrepancies between short-term and equilibrium heat strain measurements especially under high heat stress, e.g. hot-humid conditions, which might also depend on clothing and acclimation status.

Therefore, the aim of this study was to compare short-time measurements (1 h) of physiological strain experienced over a wide range of heat stress conditions to long-term responses observed during the 3rd hour (3 h) of climatic chamber exposures considering the potentially modifying influence of clothing and heat acclimation.

2 Material and methods

Our analyses rely on the heat strain database of climate chamber exposures conducted previously at *IfADo* (Ilmarinen 1978; Kampmann 2000; Piekarski and Kampmann 1982; Wenzel 1976; Wenzel et al. 1989) following the ethical principles of the Declaration of Helsinki after approval by *IfADo's* local Ethics Committee. This database consists of physiological heat strain responses averaged over consecutive 30 min working periods (Fig. 2) which had been collected in several thousand climate chamber exposures following a standardized protocol involving young male participants performing treadmill work under widely varying heat stress conditions (Kampmann 2000). Minute-by-minute values of heat strain recordings, as illustrated by Fig. 2, were only available for a small portion of all exposures.

2.1 Data

We only briefly summarize the procedures because detailed descriptions are available elsewhere (Kampmann 2000). Each trial consisted of treadmill work with constant workload of walking 4 km/h on the level for at least three hours organized in 30 min work periods, which were interrupted by 3 min breaks for determining body weight loss, from which sweat rates (*SR* in g/h) were calculated taking into account drinking ad libitum (Fig. 2). Rectal temperatures (T_{re} in °C) were recorded continuously using a thermistor probe (YSI 401, Yellow Springs) inserted 10 cm past the anal sphincter. Further, another type of thermistors (YSI 427, Yellow Springs) recorded skin temperatures at the forehead, chest, back, upper arm, thigh, and lower leg, which were used to calculate mean skin temperature (T_{sk} in °C) as area weighted average. During the early years of investigations, rectal and skin temperatures had been measured by means of thermocouples. Heart rates (*HR* in beats per minute, *bpm*) were determined from the recordings of ECG electrodes. Data of *HR*, T_{re}, T_{sk} and *SR* averaged over the two working periods of the third hour of exposure (3 h), deemed representing equilibrium strain levels, were chosen for further analyses. For comparison, we chose values averaged over the second and third working period representing the values after 1 h of exposure in good approximation for a roughly linear time trend (Fig. 2).

We searched our database for series of experiments performed with varying levels of air temperature (T_a) and air humidity expressed as water vapour pressure (p_a in kPa), but restricted to low air velocity (v_a = 0.3 or 0.5 m/s) and mean radiant temperature equaling air temperature. We stratified our search for heat acclimation (*HA*) status (acclimated vs non-acclimated) and clothing (*clo*) condition (semi-nude vs clothed with one-or two-layer work wear). We refer to recent publications concerning details of the heat acclimation protocol (Kampmann and Bröde 2019) and the clothing characteristics (Ilmarinen 1978) with basic clothing insulation (I_{cl}) of the work wear varying between 0.7–1 clo (1 clo = 0.155 K·m²/W) whereas "semi-nude" refers to I_{cl} = 0.1 clo (shorts, socks, sneak-

Table 1 Distribution of number of exposures, participants, exposures per participant and range of temperature and humidity conditions related to clothing condition and heat acclimation
Tab. 1 Anzahl der Expositionen, Teilnehmer, Expositionen pro Teilnehmer sowie die untersuchten Temperatur- und Feuchtebereiche nach Bekleidungsbedingungund Hitze-Akklimatisations-Status

clo	HA	Exposures	Participants (Series)	Exposures per participant (min–max)	T_a (°C) (min–max)	p_a (kPa) (min–max)
No	*Yes*	223	14	7–26	25–55	0.4–5.0
No	*No*	166	13	4–30	25–55	0.3–5.1
Yes	*Yes*	78	5	11–26	25–60	0.5–4.4
Yes	*No*	97	9	6–23	25–55	0.6–4.0

clo clothing condition (*no*: semi-nude, *yes*: clothed), *HA* heat acclimation status (*no*: non-acclimated, *yes*: acclimated), T_a air temperature, p_a water vapour pressure, *min* minimum, *max* maximum

Table 2 ANCOVA results for the effects of air temperature, humidity, clothing and heat acclimation on the differences of physiological heat strain responses after one hour to the values averaged over the third hour of exposure. Statistically significant results are displayed in bold

Tab. 2 ANCOVA-Ergebnisse zum Einfluss von Lufttemperatur, -feuchte, Bekleidung und Hitzeakklimatisation auf die Differenzen der physiologischen Beanspruchungsgrößen nach einer Stunde zu den in der dritten Expositionsstunde registrierten Werten. Statistisch signifikante Ergebnisse sind fett hervorgehoben

			$\Delta_t HR$		$\Delta_t T_{re}$		$\Delta_t T_{sk}$		$\Delta_t SR$	
Effect	NDF	DDF	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*
T_a	1	521	209.01	**<0.0001**	207.19	**<0.0001**	62.65	**<0.0001**	46.76	**<0.0001**
p_a	1	521	124.35	**<0.0001**	113.65	**<0.0001**	3.80	0.0519	119.66	**<0.0001**
clo	1	37	0.03	0.8727	1.72	0.1978	9.06	**0.0047**	6.80	**0.0131**
HA	1	37	2.63	0.1132	6.77	**0.0133**	12.95	**0.0009**	2.66	0.1112
*clo*HA*	1	37	0.05	0.8197	0.00	0.9986	0.43	0.5167	0.19	0.6645

NDF nominator degrees-of-freedom, *DDF* denominator degrees-of-freedom, *F* F-value, *P* P-value, T_a air temperature, p_a water vapour pressure, *clo* clothing condition (semi-nude, clothed), *HA* heat acclimation status (acclimated, non-acclimated), Δ_t difference 1 h–3 h, *HR* heart rate, T_{re} rectal temperature, T_{sk} mean skin temperature, *SR* sweat rate

ers). Overall, we retrieved 564 exposures from 28 young male participants with following average individual characteristics (mean ± SD): age 20.8 ± 1.1 years, body height 1.83 ± 0.04 m, body weight 71.3 ± 7.3 kg, body surface area 1.92 ± 0.10 m², and 48.5 ± 8.8 mL/min/kg of maximum oxygen consumption rate. Table 1 summarizes the distribution of exposure conditions stratified for *clo* and *HA*.

2.2 Statistical analysis

For each physiological strain variable (*HR*, T_{re}, T_{sk}, *SR*), we computed the differences between 1 h- and 3 h-values ($\Delta_t = \Delta_{1\,h-3\,h}$). Thus, Δ_t will represent the prediction error, with positive values indicating overestimation while negative Δ_t specify underestimation of the long-term (3 h) responses by short-term (1 h) observations.

Separately for *HR*, T_{re}, T_{sk}, *SR*, we analyzed the influence of the factors *clo* and *HA* on Δ_t adjusting for the continuous covariates T_a and p_a, and accounting for the repeated measurements by mixed model ANCOVA using SAS® version 9.4 (Littell et al. 2006).

In addition, we analyzed the dependency of the physiological strain on heat stress levels defined by the combinations of T_a and p_a with penalized two-dimensional regression splines fitted by generalized additive models (GAM), which provide a flexible modelling framework for irregularly distributed data (Wood 2017) allowing for non-linear (Zuur et al. 2009) and random effects (Wood 2013b). By including so called factor smooth interactions (Wood 2017) of the two-dimensional regression splines with the time of measurement (1 h vs 3 h), we obtained not only predictions of the physiological response variable, but also for Δ_t in the T_a–p_a–plane supplemented by P-values (Wood 2013a), which were then visualized in a difference plot (Fasiolo et al. 2020). The analyses were performed separately for the four heat strain variables (*HR*, T_{re}, T_{sk}, *SR*) and the four strata defined by *clo* and *HA* using the packages *mgcv* (Wood 2017) and *mgcViz* (Fasiolo et al. 2020) of R 4.1.0 (R Core Team 2021).

In supplemental analyses, we obtained regression equations relating Δ_t to the physiological strain after 3 h for the pooled 41 series from the four strata as defined by *clo* and *HA* by fitting linear mixed models considering the within-series correlation using the R package *lme4* (Bates et al. 2015).

3 Results

The ANCOVA results revealed that Δ_t for all physiological variables were significantly related to T_a and p_a (Table 2, with borderline significance of p_a for $\Delta_t T_{sk}$) and were on average negative for all clothing and acclimation condi-

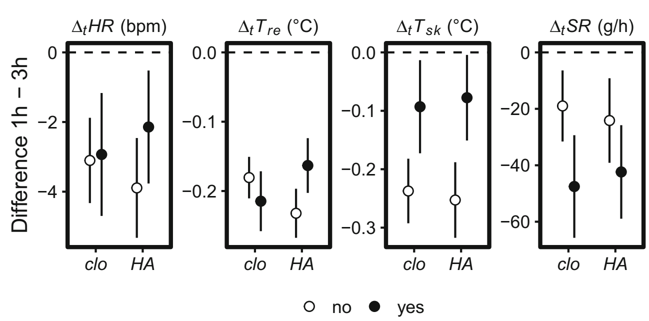

Fig. 3 Least-square means with 95%-confidence intervals estimated by ANCOVA (cf. Table 2) for the main effects of clothing condition (*clo*, coded semi-nude = 'no', clothed = 'yes') and status of heat acclimation (*HA*, 'no' vs. 'yes'), respectively, on the difference between 1 h- and 3 h-values (Δ_t) of heart rate (*HR*), rectal (T_{re}) and mean skin temperature (T_{sk}) as well as sweat rate (*SR*)

Abb. 3 Mit ANCOVA (vgl. Tab. 2) ermittelte Kleinste-Quadrat-Schätzer von Mittelwert und 95%-Konfidenzintervall der Haupt-Effekte von Bekleidung (*clo*, unbekleidet = ‚no', bekleidet = ‚yes') und Hitze-Akklimatisation (*HA*, ‚no' vs. ‚yes') auf die Differenz der nach einer bzw. in der dritten Stunde registrierten Werte (Δ_t) der Herzschlagfrequenz (*HR*), Rektal- (T_{re}) und mittleren Hauttemperatur (T_{sk}) sowie der Schweißrate (*SR*)

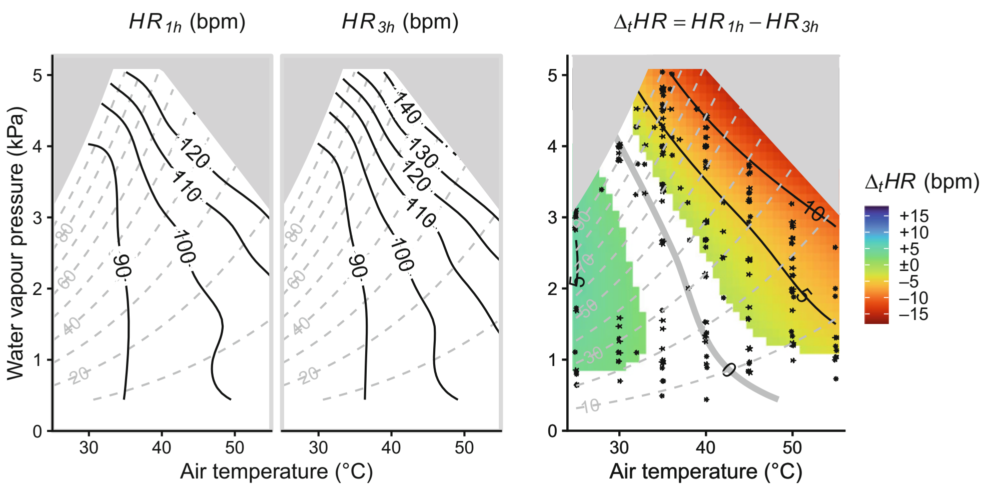

Fig. 4 Contours of heart rates (*HR*) after 1 h (left panel) and averaged over the third hour (3 h) of exposure (mid panel) in relation to air temperature and water vapour pressure as well as their differences ($\Delta_t = \Delta_{1h-3h}$, right panel) predicted by GAM for semi-nude, acclimated participants. Dashed reference lines indicate relative humidity (%). Asterisks in the right panel mark the conditions of the 223 exposures. Coloured regions show statistically significant non-zero differences ($P < 0.05$), while grey areas indicate temperature-humidity combinations not supported by our data
Abb. 4 Mit GAM in Abhängigkeit von Lufttemperatur und Wasserdampfdruck geschätzte Äquivalenzlinien der nach einstündiger (1 h) Exposition gemessenen bzw. über die dritte Expositionsstunde (3 h) gemittelten Herzschlagfrequenzen (*HR*, linke Seite und Mitte) sowie der Differenzen ($\Delta_t = \Delta_{1h-3h}$, rechte Seite). Gestrichelte Referenzlinien markieren die relative Feuchte (%). Auf der rechten Seite markieren Punkte die Bedingungen der 223 Versuche mit unbekleideten, akklimatisierten Probanden. Statistisch signifikant von Null verschiedene Differenzen sind farblich gekennzeichnet. Grau hinterlegte Bereiche indizieren Temperatur-Feuchte-Kombinationen, die durch Daten nicht hinreichend gestützt sind

tions (Fig. 3), indicating that short duration observations significantly underestimated the physiological strain averaged over the 3rd hour of exposure. While *clo* and *HA* did not significantly affect $\Delta_t HR$ (Table 2), the averaged underestimation error increased by 29 g/h regarding *SR* for clothed compared to semi-nude persons, by 0.1 °C regarding T_{re} for non-acclimated compared to acclimated persons, and by 0.1–0.2 °C regarding T_{sk}, when comparing semi-nude to clothed and non-acclimated to acclimated persons, respectively (Fig. 3).

Fig. 4 visualizes the results of the GAM fitted to the *HR* data from the semi-nude acclimated participants as an illustrative example for similar results obtained with the other indicators of heat strain and strata defined by *clo* and *HA*, respectively. The contour lines for both 1 h- and 3 h-values are bended leftwards, which indicate that *HR* increased with both temperature and humidity. In accordance with the ANCOVA results (Table 2), the difference plot in the right panel indicates that $\Delta_t HR$ increased with both T_a and p_a. At moderate conditions, slight overestimation of the 3 h-values by the short-term observations occurred for low strain levels with *HR* below 90 bpm, and good agreement was obtained with zero prediction errors approximately following the contours for $HR = 100$ bpm (in accordance with the results presented by Fig. 6 below). In contrast, strong underestimation of long-term heat strain levels was observed for hot-humid conditions associated with *HR* above 120 bpm.

Fig. 5 summarizes the corresponding difference plots presenting the GAM estimates of the prediction error Δ_t related to temperature and humidity for all heat strain variables and strata defined by *clo* and *HA*. They emphasize the strong underestimation of heat strain under hot-humid conditions amounting to more than 15 bpm for *HR* and more than 0.4 °C for T_{re}, while there was only small to moderate underestimation of T_{sk} and of *SR*, for the latter especially with non-acclimated persons, thus confirming the ANCOVA results (Fig. 3).

As the results presented so far suggest an increased underestimation error under hot-humid conditions, which were associated with higher physiological strain as shown in Figs. 4 and 5, we analyzed the dependency of the error Δ_t on the long-term (3 h) heat strain response level for the pooled 41 series from the strata defined by *clo* and *HA* in Fig. 6. We found statistically significant negative correlations indicating increased underestimation error with raised physiological strain for all heat strain indicators. These correlations were weaker for T_{sk} and *SR* (Fig. 6c, d), but showed a strong relationship for *HR* and T_{re} (Fig. 6a, b) representing heat storage and resulting cardiac strain with underestimation starting at low strain levels below 100 bpm and at 37.2 °C, respectively.

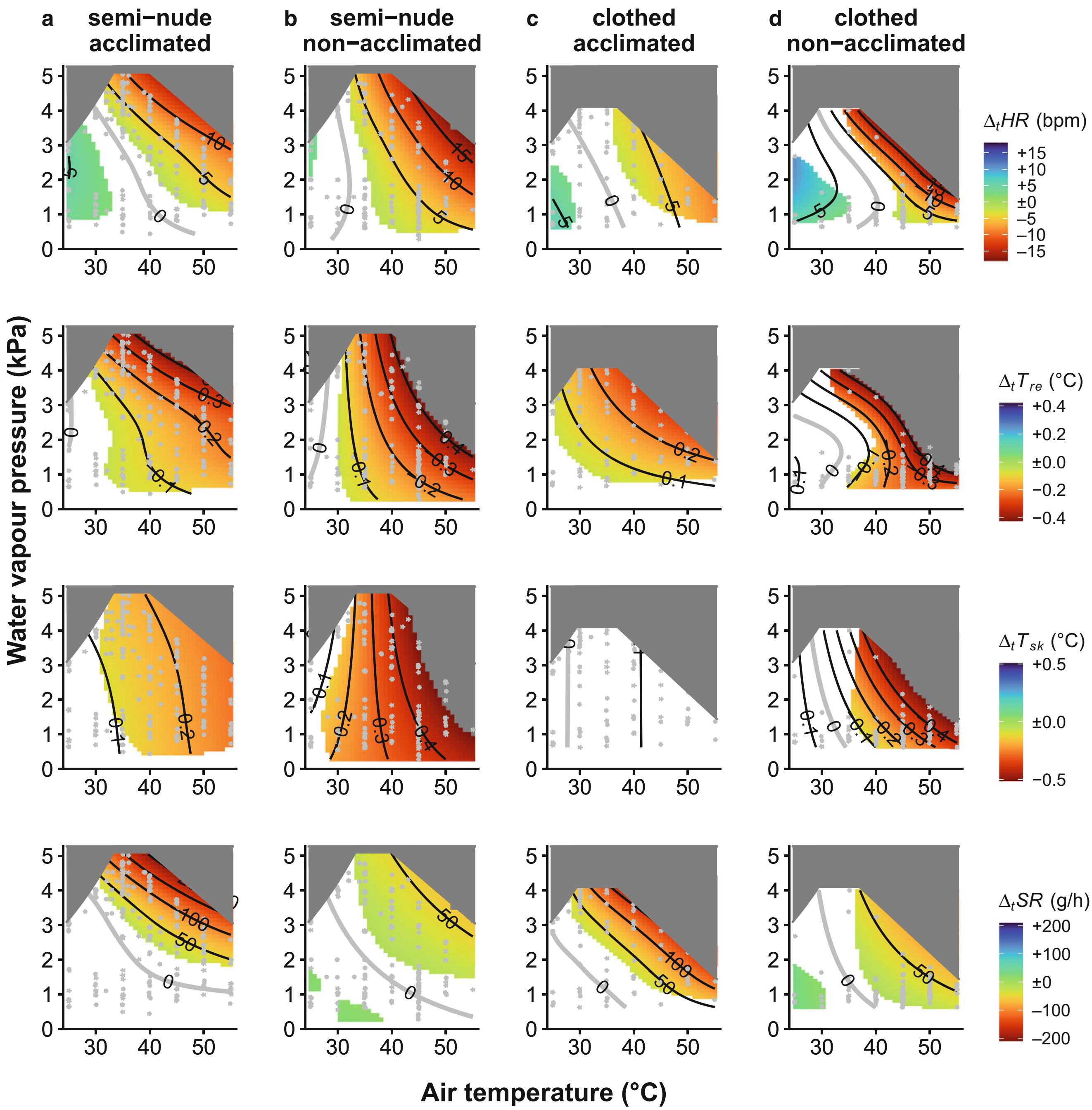

Fig. 5 Contours for the GAM estimates of the differences between 1 h- and 3 h-values (Δ_t) of heart rates (*HR*, row 1), rectal (T_{re}, row 2) and mean skin temperatures (T_{sk}, row 3) and sweat rates (*SR*, row 4) in relation to air temperature and water vapour pressure for semi-nude acclimated (**a**) and non-acclimated (**b**) as well as for clothed acclimated (**c**) and non-acclimated (**d**) participants. Asterisks in the right panel mark the exposure conditions. Coloured regions show statistically significant non-zero differences ($P < 0.05$), while grey areas indicate temperature-humidity combinations not supported by our data

Abb. 5 Äquivalenzlinien der mit GAM geschätzten Differenzen zwischen Werten der ersten und dritten Stunde (Δ_t) der Herzschlagfrequenz (*HR*, 1. Zeile), Rektal- (T_{re}, 2. Zeile) und mittleren Hauttemperatur (T_{sk}, 3. Zeile) sowie Schweißrate (*SR*, 4. Zeile) für unbekleidete akklimatisierte (**a**) und nicht-akklimatisierte (**b**) sowie bekleidete akklimatisierte (**c**) und nicht-akklimatisierte (**d**) Probanden in Abhängigkeit von Lufttemperatur und Wasserdampfdruck. Punkte markieren die in den einzelnen Versuchen eingestellten Bedingungen. Statistisch signifikant von Null verschiedene Differenzen sind farblich gekennzeichnet. Grau hinterlegte Bereiche indizieren durch Daten nicht hinreichend gestützte Temperatur-Feuchte-Kombinationen

4 Discussion

4.1 Methodological concerns

Re-analyzing previously recorded physiological heat strain responses instead of conducting original experiments constitutes a limitation of this study. On the other hand, the sample of 564 exposures under a well-defined heat stress and exercise protocol employing established strain measurements provided a sound data base for applying advanced statistical methods to analyze the impact of temperature and humidity on the prediction error Δ_t (Figs. 3, 4 and 5).

Concerning our approach to analyze the error Δ_t depending on the long-term (3h) heat strain response, it had been recently suggested to use for the abscissa the average of both measurements, i.e. of the 1h- and 3h-values (Bland and Altman 1995). Repeating the analyses according to this recommendation yielded almost identical figures (data not shown), thus confirming the results as presented by Fig. 6.

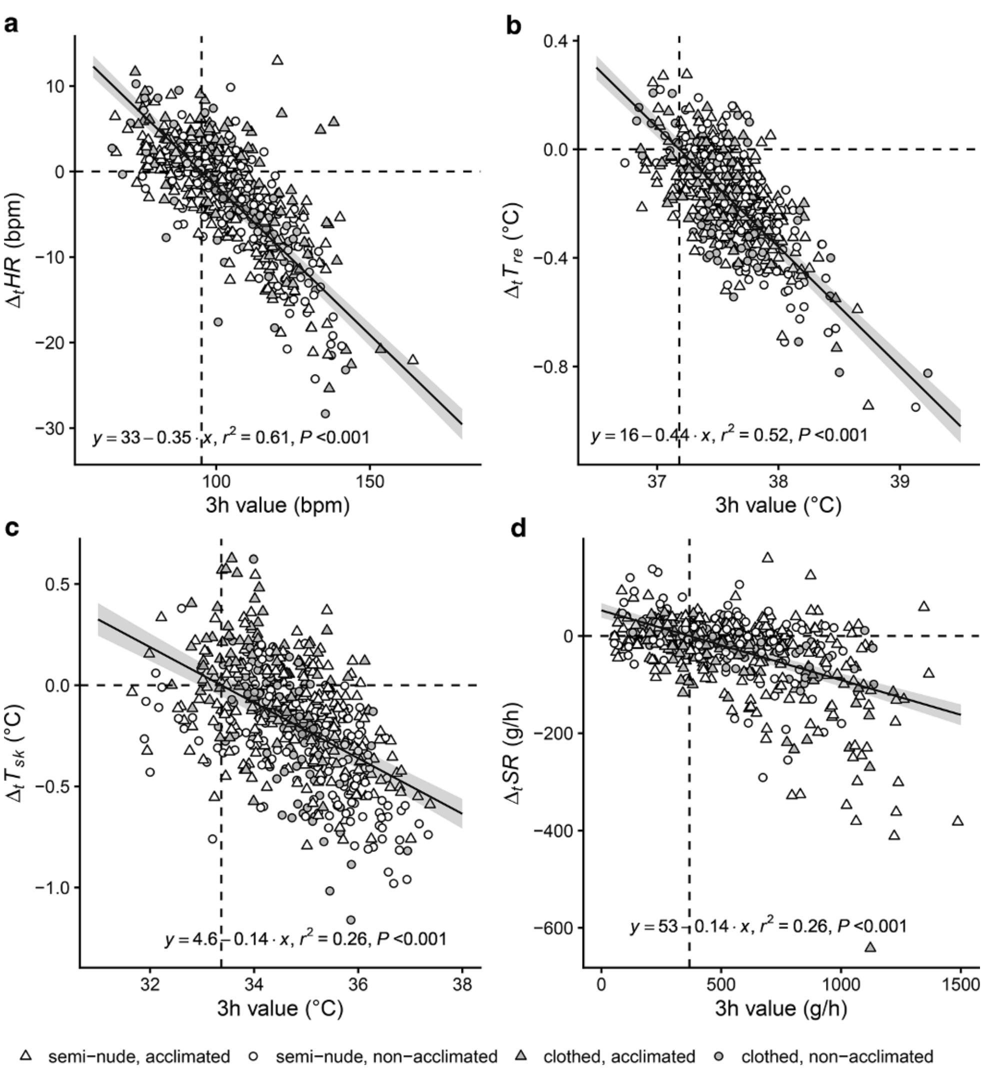

Fig. 6 Differences between 1h- and 3h-values (Δ_t) related to the physiological strain during the 3rd hour of exposure for **a** heart rates (*HR*), **b** rectal temperatures (T_{re}), **c** mean skin temperatures (T_{sk}), and **d** sweat rates (*SR*). Regression lines with 95%-confidence bands for the pooled series with semi-nude and clothed participants, who were either acclimated or non-acclimated to heat, were obtained by fitting linear mixed effects models with random regression coefficients. Vertical reference lines indicate the heat strain response level of the 3rd hour associated with zero prediction error for short-term observation

Abb. 6 Differenzen zwischen Werten der ersten und dritten Stunde (Δ_t) der Herzschlagfrequenz (*HR*) (**a**), Rektal- (T_{re}) (**b**) und mittleren Hauttemperatur (T_{sk}) (**c**) sowie Schweißrate (*SR*) (**d**) in Abhängigkeit vom 3-Stunden-Wert. Regressionsgeraden mit 95%-Konfidenzbändern für die zusammengefassten Daten für bekleidete und unbekleidete, jeweils akklimatisierte bzw. nicht-akklimatisierte Probanden wurden mittels Anpassung von linearen Modellen mit zufälligen Regressionskoeffizienten ermittelt. Vertikale Referenzlinien markieren den 3-Stunden-Wert, oberhalb dessen die einstündige Beobachtung die Beanspruchung unterschätzt

4.2 Relevance to heat stress management and research

Exposure duration is a decisive factor in occupational heat stress assessment (Bröde et al. 2017; Kampmann 2000; Malchaire et al. 2000; Parsons 2014), which requires the consideration of physiological strain experienced over the whole work shift, especially concerning the risk for dehydration due to excessive sweating (Bröde et al. 2018; ISO 7933 2004; Kampmann 2000; Malchaire et al. 2002). Therefore, it is crucial for heat stress assessment procedures relying on short-time observations, that these periods will be representative for long-term strain experienced during a work shift. Our results suggest that, with respect to one-hour exposures, this requirement only holds for low to moderate equilibrium strain levels of heart rates ranging below 100 bpm and rectal temperatures below 37.2 °C.

On the other hand, we found strong underestimation of heat strain with short-term (1 h) observations compared to values during the 3rd hour of exposure when assessing hot-humid conditions under moderate workload, concordant with earlier results for a higher treadmill speed of 5.6 km/h (Lind 1970). This will put the worker at higher risk for experiencing heat-related disorders, if the 1 h-values are considered representing a 'steady-state', when in fact the experienced long-term heat strain might become higher or even uncompensable (Fig. 1). This is supported by Meade et al. (2016), who showed that even in case of rectal temperatures being well below the threshold limit value of 38.0 °C after 2 h, heat balance was not achieved, and so the projected rectal temperatures (based on the average rectal temperature increase recorded over the last hour of each working bout) could be expected to be considerably higher after 4 h than the assumed threshold limit value of 38.0 °C.

For instance, by applying the regression equations in Fig. 6, a long-term T_{re}-value of 38 °C, representing the core temperature limit applied by the Predicted Heat Strain (PHS) index (ISO 7933 2004; Malchaire et al. 2001), would coincide with a value below 37.7 °C for the 1 h-observation. Similarly, an equilibrium core temperature of 38.5 °C, the suggested limit value for personal monitoring by physiological measurements (ISO 9886 2004), would correspond in our setting to a 1 h-value below 38 °C. Thus, in both examples the one-hour observation period would erroneously point to safe working conditions.

Further, a recent study (Foster et al. 2021) developed a model predicting physical work capacity in response to a wide range of heat stress conditions by measuring the physical work output during one-hour treadmill work clamping heart rates to 130 bpm by adjusting the workload. According to our results, this would correspond to more than 10 bpm higher heart rates associated with lower physical work capacity for longer lasting exposures. These effects might even be larger under hot-humid conditions compared to the applied 'neutral' reference with $T_a = 15$ °C, indicating a potential for too optimistic estimates by that model.

Of course, these considerations are most relevant for the assessment of whole work shifts and may be less applicable to short term exposures with high metabolic demands, e.g. when considering time trial performance of elite cyclists (Tatterson et al. 2000). Another example is work with protective clothing and equipment, like self-contained breathing apparatus (SCBA) where oxygen supply may be the time limiting factor (Griefahn et al. 2003). In addition, uncompensable heat stress will likely occur in such situations (Cheung et al. 2000) characterized by high metabolic rates due to the equipment weight, and by hampered heat and vapour transfer through the clothing (Bröde et al. 2008; Havenith et al. 2008).

Nevertheless, the underestimation of physiological responses by too short observation periods, which predominated in our study under heat stress conditions, had also been reported in thermal comfort research. E.g., studies considering the skin temperature and subjective responses to draught, the unwanted local cooling due to air movements (Griefahn et al. 2002; Wang et al. 2012) advocated for 45–60 min periods for establishing a steady-state. This was in contrast to earlier experiments employing a progressive stress protocol increasing air velocity every 15 min (Fanger et al. 1988), which might have underestimated the response, but served as basis for the development of an international standard assessing draught risks (ISO 7730 2005).

Slight overestimation errors under moderate heat stress associated with initially increased and then again decreasing levels were observed for *HR* under all clothing and heat acclimation conditions, and for *SR* with nude and clothed non-acclimated persons (Fig. 5). These may indicate an initial overshooting response of the thermoregulatory system, as exemplified for *HR*, and less pronounced for *SR*, in Fig. 2a. Concerning sweating, overestimation could be expected due to hidromeiosis (Brown and Sargent 1965; Kampmann 2000; Kampmann et al. 2013), a reduction of sweat rate after one or two hours of exposure, which, however, predominantly appears under hot-humid conditions (Candas and Hoeft 1995). The example from Fig. 2b shows the typical time course of *SR* indicating hidromeiosis, but the averaged values even increased from 1 h to 3 h by about 100 g/h, which could be ascribed to the time intervals chosen for analysis. As its effects had in addition increased following heat acclimation in earlier studies (Candas et al. 1980), hidromeiosis seems to be an unlikely explanation for the *SR* overestimation observed in our study only for non-acclimated persons under moderate heat stress. Another factor contributing to the temporally decreasing heat strain observed with clothed persons might be the wetting of the fabric by absorbed sweat, which will lower the clothing's thermal and evaporative resistance (Bröde et al. 2008; Lotens and Havenith 1995), as well as further enhance evaporative cooling by moisture transfer to outer layers due to wicking. The resulting lower skin wettedness and additionally enlarged area where sweat may evaporate from the fabric (Havenith et al. 2008) will consequently reduce heat strain over time (Gebhardt et al. 2007; Lotens and Havenith 1995) and retard the development of a steady-state at a lower level.

Studies employing short observation periods (1 h) or progressive stress protocols for detecting the ULPZ (Fig. 1) with exercising (Bernard et al. 2008) or sedentary participants (Gagnon et al. 2016; Ravanelli et al. 2015) will have to scrutinize their protocols for validity and reliability (Cottle et al. 2022), especially concerning the time course of the physiological response under constant heat stress conditions for ensuring the establishment of a steady-state. Otherwise, these procedures may underestimate the strain level.

Concluding, we like to emphasize the statement from a recent study concerning the upper limit of the thermal neutral zone (Henderson et al. 2021), which may be considered as the ULPZ regarding resting metabolic rate, "*Differences in exposure time are a likely cause of different interpretations in the literature …*".

5 Conclusions

Our results indicate that short-time measurements might lead to severe underestimation of the physiological responses to heat stress at workplaces, especially under hot-humid conditions and/or when associated with high heat strain levels.

As the latter will likely occur, e.g. during summertime in outdoor work situations with high activity levels or with protective clothing, when heat stress is prone to become uncompensable (Cheung et al. 2000), this will not only immediately impact the workers concerned, but will also inform occupational health professionals responsible for risk assessment and prevention (ISO 15265 2004) as well as standard writers drafting corresponding guidelines for heat stress management (ISO/CD 8025 2021).

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