

# Accuracy of metabolic rate estimates from heart rate under heat stress—an empirical validation study concerning ISO 8996

Peter BRÖDE<sup>1\*</sup> and Bernhard KAMPMANN<sup>2</sup>

<sup>1</sup>Leibniz Research Centre for Working Environment and Human Factors at TU Dortmund (IfADo), Germany

<sup>2</sup>School of Mechanical Engineering and Safety Engineering, Department of Occupational Health Science, University of Wuppertal, Germany

Received October 4, 2018 and accepted December 17, 2018

Advanced Epub on J-STAGE December 29, 2018

**Abstract :** The standard ISO 8996 provides methods for the determination of metabolic rate from measured oxygen consumption ( $M_{VO_2}$ ), as well as simplified estimation algorithms based on heart rate ( $M_{HR}$ ). We quantified the accuracy of these methods by comparing  $M_{HR}$  with  $M_{VO_2}$  measured in 373 climatic chamber experiments under different workloads and widely varying heat stress conditions. While our results confirmed the 5% accuracy level for  $M_{VO_2}$ ,  $M_{HR}$  considerably overestimated  $M_{VO_2}$  due to the rise in core temperature concomitantly increasing heart rate by approximately 30 bpm/°C resulting in an overall error of 43%. After individually correcting for this bias the accuracy was 10–15% as stipulated by the standard. Thus, methods correcting for the thermal component of heart rate, e.g. by introducing intermittent resting periods of sufficient length of at least five min when investigating heat stress at workplaces, should become a mandatory element in the ongoing revision of the relevant standards.

**Key words :** Heat stress, Activity, Metabolic rate, Heart rate, Standards

In addition to the physical parameters of the thermal environment (air temperature, humidity, air velocity, thermal radiation) and the thermal properties of clothing, the rate of metabolic heat production ( $M$ ) associated with occupational activities is a crucial input to assessment procedures for the thermal environment. This applies to the thermal comfort index  $PMV$  (Predicted Mean Vote, ISO 7730)<sup>1</sup> as well as to the cold stress index IREQ (required clothing insulation, ISO 11079)<sup>2</sup> and to heat stress indices like the  $WBGT$  (wet bulb globe temperature, ISO 7243)<sup>3</sup> and the currently revised  $PHS$  (Predicted Heat Strain, ISO/DIS 7933)<sup>4</sup>.

The international standard ISO 8996<sup>5</sup>) describes methods for the determination of  $M$  at increasing levels of expertise, effort and presumed accuracy. They start at Level 1 (screening) with a simple categorization of workload (resting, low, moderate, high, very high)<sup>3, 5</sup>, and tables of metabolic rates for different professions<sup>6</sup>) associated with a ‘very great risk of error’<sup>5</sup>). Level 2 (observation) uses tables<sup>5</sup>) or predictive equations of energy consumption for simple activities like walking<sup>7</sup>) with an assumed accuracy of 20%. Level 3 (analysis) provides algorithms to estimate  $M$  from heart rates ( $HR$ ) recorded during workplace studies considering the influence of gender, age and body constitution (weight, body fat). A recent review<sup>8</sup>), which will serve as a guideline document for the ongoing revision of ISO 8996, analysed the uncertainty of the different components of the underlying algorithms using

\*To whom correspondence should be addressed.

E-mail: broede@ifado.de

©2019 National Institute of Occupational Safety and Health

Monte Carlo simulations. The authors concluded from the resulting percentage coefficient of variation (*CV*) that the overall accuracy of metabolic rate estimates based on *HR* was 10–15%.

For assessing their accuracy, these estimates should be ideally compared to *M* determined from measured rates of oxygen consumption (*VO*<sub>2</sub>), which are considered Level 4 (expertise) methods and supposed to provide the highest level of accuracy with a typical error of 5%<sup>5</sup>.

As *VO*<sub>2</sub> measurements require sophisticated equipment and expert knowledge, the recording of heart rates with subsequently applied estimation algorithms are considered as a cost-effective alternative with acceptable accuracy<sup>8</sup> and are recommended for the evaluation of the impact of dynamic work when assessing heat strain at workplaces by the revised draft of the *PHS* standard<sup>4</sup>.

However, the widely acknowledged<sup>5, 8, 10, 12</sup> influence of further components, like static work, thermal and mental load etc., that increase heart rate and thus potentially trigger overestimation errors, is not considered in depth by these documents<sup>4, 8</sup>. More specifically, they do not quantify the effects of the rise in core temperature ( $\Delta Tre$ ) under heat stress, which will increase both *M* and *HR*. For the first effect, *Q*<sub>10</sub> coefficients<sup>9</sup> describe the percentage change in *M* (%*M*) due to  $\Delta Tre$  by

$$\%M = (Q_{10}^{\Delta Tre/10} - 1) \times 100 \quad (1)$$

Thus, the common setting *Q*<sub>10</sub>=2<sup>9</sup>) implies that a 1°C increase in core temperature will rise *M* by approximately 7%, which might increase the variability of *M* measured under heat stress. The *Q*<sub>10</sub> effect on *M* will then also lead to a concomitant increase in *HR* for this *M* increment. Independently from this effect, the thermoregulatory response to rising body temperature, an increase in blood flow to the skin, will require an increase in *HR*. This impact of  $\Delta Tre$  on *HR*, called thermal cardiac reactivity<sup>10</sup>) or the thermal component of heart rate ( $\Delta HR_T$ )<sup>5, 10</sup>) or ‘thermal pulses’<sup>11, 12</sup>), will increase *HR* by 30–40 bpm per 1°C rise in *Tre*<sup>8, 10, 12</sup>). This could introduce an overestimation bias and thus inflate the prediction error of *M* estimated from *HR*<sup>8</sup>) under heat stress conditions.

This validation study aimed to assess the claimed levels of accuracy for the different methods to determine *M* quantifying the influence of physiological strain under heat stress conditions by comparing *M* estimates to measured values from controlled climatic chamber experiments.

We compiled a database from human heat stress experiments performed previously<sup>9, 12–15</sup>) in the climatic cham-

bers at *IfADo*, which had been conducted according to the ethical principles of the Declaration of Helsinki. Data originated from 373 laboratory sessions consisting of 11 individual series with 11 to 78 trials performed by six non-acclimated young fit males (Table 1) who had provided informed consent to the studies. Their averaged characteristics (mean  $\pm$  SD) were 20.8  $\pm$  0.9 yr of age, 1.83  $\pm$  0.04 m of body height (*H*<sub>b</sub>), 72.1  $\pm$  8.4 kg of body weight (*W*<sub>b</sub>), 1.9  $\pm$  0.1 m<sup>2</sup> of body surface area (*A*<sub>Du</sub>), 21.5  $\pm$  2.5 kg/m<sup>2</sup> of body-mass-index (*BMI*), and 55.3  $\pm$  8.1 ml/min/kg of peak oxygen consumption (*VO*<sub>2max</sub>).

Following a one-hour bed rest under neutral conditions, the participants donned a cotton coverall combined with underwear, socks and gym shoes providing a thermal insulation of 0.7 clo<sup>13</sup>). Then they moved into the climatic chamber set to heat stress conditions characterized by different combinations of air temperature (range 15–55°C), water vapour pressure (0.4–1.8 kPa), air velocity (0.5–2.0 m/s), and values of mean radiant temperature varying between 0 and 128.5 K above air temperature. The participants performed treadmill work for at least 3 h with three levels of workload: 3 km/h on the level (*W*1), 4 km/h on the level (*W*2), and 4 km/h with 2.5° inclination, corresponding to a grade of 4.4% (*W*3). The protocol included short interruptions (3 min) after each 30 min period for weighing the participants. In addition, rates of oxygen consumption (*VO*<sub>2</sub>) in l/min were determined from the expired air collected in Douglas bags towards the end of each full hour according to ISO 8996<sup>5</sup>). As physiological responses usually stabilized after two hours<sup>12</sup>), we calculated averages over the third hour of exposure from continuously recorded rectal temperatures (*Tre*) and *HR*, thus representing steady-state values. These were matched with *VO*<sub>2</sub> measurements from the third exposure hour. We also computed resting values (*Tre*<sub>0</sub>, *HR*<sub>0</sub>) from the last 15 min of the rest period.

We calculated *Q*<sub>10</sub> coefficients from *Tre* and *VO*<sub>2</sub> for each series as described recently<sup>9</sup>) using an expanded version of (1) shown in (2).

$$VO_2 = VO_{2,ref} \times Q_{10}^{(Tre - Tre_{ref})/10} \quad (2)$$

More precisely, *Q*<sub>10</sub> coefficients were obtained by exponentiating the slopes of the logarithmized equation (2) fitted by linear regression to the measured *VO*<sub>2</sub> using *Tre* as predictor with *Tre*<sub>ref</sub> = 36.8°C. It should be noted that choosing a different value for *Tre*<sub>ref</sub> or applying a multiplicative transformation on *VO*<sub>2</sub>, e.g. calculating metabolic rates using a constant standard energy equiva-

**Table 1. Means (*AM*) and coefficient of variation (*CV*) of metabolic rate from measured oxygen consumption ( $M_{VO_2}$ ) measured in 11 series with six participants (ID1–ID6) under different workload conditions (W1, W2, W3)**

Work-ID	$N_{exp}$	Series			$M_{VO_2}$		Error $M_{HR}$		Error $M_{HR}$ corrected for $\Delta T_{re}$		Error $M_{pan}$	
		$\Delta T_{re}$ (°C)	<i>TCR</i> (bpm/°C)	$Q_{10}$ (nd)	<i>AM</i> (W)	<i>CV</i>	%bias	%rmse	%bias	%rmse	%bias	%rmse
W1-ID1	15	1.0	28.8	1.47	193	11%	63%	66%	0%	14%	-12%	16%
W1-ID2	18	0.9	16.2	1.07	224	4%	41%	45%	0%	14%	-23%	23%
W1-ID3	15	1.0	24.8	1.12	210	7%	61%	63%	0%	11%	-23%	24%
W2-ID1	44	1.0	38.8	1.19	221	11%	56%	60%	0%	14%	1%	11%
W2-ID2	35	1.0	17.9	1.13	265	6%	27%	31%	0%	12%	-14%	15%
W2-ID3	78	1.0	20.9	1.05	242	5%	44%	47%	0%	13%	-11%	12%
W2-ID4	52	0.9	39.3	1.19	289	7%	35%	45%	0%	15%	-0%	7%
W2-ID5	38	0.9	23.3	1.00	272	5%	57%	59%	0%	12%	-7%	8%
W2-ID6	51	0.8	28.7	1.09	277	4%	8%	19%	0%	9%	-5%	7%
W3-ID1	11	0.9	40.4	0.95	323	5%	10%	14%	0%	6%	5%	7%
W3-ID2	16	1.1	11.0	0.97	329	4%	8%	14%	0%	9%	5%	7%
Subtotals for workload												
W1	48	1.0	22.8	1.21	210	7%	54%	57%	0%	13%	-20%	21%
W2	298	0.9	28.0	1.10	260	6%	38%	43%	0%	13%	-6%	10%
W3	27	1.0	23.0	0.97	327	4%	9%	14%	0%	8%	5%	7%
Total	373	1.0	27.0	1.11	258	6%	38%	43%	0%	12%	-7%	11%

Together with averaged rectal temperature increase ( $\Delta T_{re}$ ), thermal cardiac reactivity (*TCR*) representing the slopes from Fig. 1b) and non-dimensional (nd)  $Q_{10}$  coefficients. Percentages of mean prediction error (%bias) and root-mean-squared error (%rmse) for metabolic rates estimated from heart rates ( $M_{HR}$ ) in comparison to the errors after correcting for bias due to rectal temperature increase ( $\Delta T_{re}$ ) using the relationship from Fig. 1a), and to predictions from the Pandolf equation ( $M_{pan}$ ). Subtotals for workload and total figures were calculated from the individual series as means weighted by the number of experiments ( $N_{exp}$ ).

lent as in (3) below, would only affect the intercept  $VO_{2,ref}$ , but result in identical  $Q_{10}$  values.

The metabolic rates in watts from  $VO_2$  measured in l/min ( $M_{VO_2}$ ) were calculated using the standard energy equivalent of 5.68 W/(l/h) according to ISO 8996<sup>5)</sup> as:

$$M_{VO_2} = VO_2 \times 60 \times 5.68 \quad (3)$$

Estimates of metabolic rate based on *HR* ( $M_{HR}$ ) rely on the linear relationship between metabolic or work capacity with cardiac capacity or cardiac reserve. Detailed algorithms considering different populations depending on gender, age and body constitution are provided in the literature<sup>5, 8, 16)</sup>. Here, we will focus on the equations needed for our sample of young fit males and suggested by the standard<sup>5, 8)</sup> as follows:

$$M_{HR} = M_0 + \frac{(MWC - M_0)}{(HR_{max} - HR_0)} \times (HR - HR_0) \quad (4)$$

In (4),  $M_0$  and  $HR_0$  denote resting values of metabolic rate and heart rate, respectively; *MWC* is the maximum

work capacity in watts; and  $HR_{max}$  denotes maximum heart rate. As only *HR* and  $HR_0$  were measured, we estimated the other parameters following the published guidelines<sup>8)</sup> underlying the current revision of ISO 8996. We assumed  $M_0$  for males as 60 W/m<sup>2</sup> and converted it to watts by multiplication with  $A_{Du}$ .  $HR_{max}$  was calculated depending on age in years as  $HR_{max} = 208 - 0.7 \times age$ . *MWC* can be estimated for males depending on age and lean body mass (*LBM*) as:

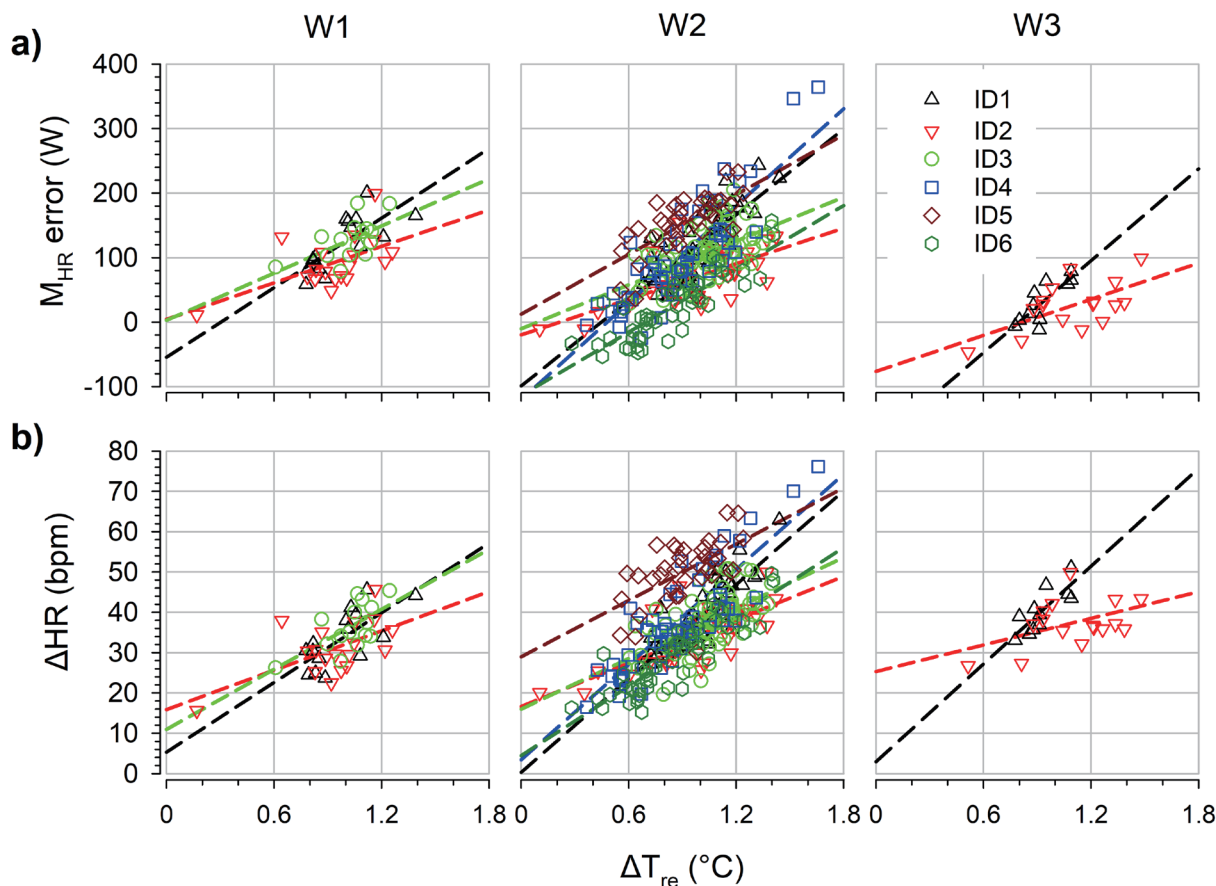
$$MWC = (19.45 - 0.133 \times age) \times LBM \quad (5)$$

As recently reviewed<sup>8)</sup>, there are several options to estimate *LBM*. We adopted the approach as advised for males in the current draft for the revision of ISO 8996 and calculated *LBM* from body weight ( $W_b$ ) and height ( $H_b$ ) as:

$$LBM = \left( 1.08 - \frac{W_b}{80 \times H_b^2} \right) \times W_b \quad (6)$$

In the sample under study, *LBM* thus varied between 77% and 85% of body weight.

Representing a Level 2 method, we also applied the



**Fig. 1.** Influence of the increase in rectal temperature from rest ( $\Delta T_{re}$ ) on a) the prediction error for metabolic rates estimated from heart rates ( $M_{HR}$ ), and on b) the increase in heart rate from rest ( $\Delta HR$ ). Regression lines are shown for the individual series with the six participants (ID1–ID6) under the different workload conditions (W1, W2, W3).

widely used Pandolf equation<sup>7)</sup> for treadmill walking. Equation (7) predicts the metabolic rate ( $M_{Pan}$ ) in watts considering body weight ( $W_b$ ), the load due to the weight of clothing and sensors ( $L=2 \text{ kg}^{13}$ ), the grade of the treadmill ( $G$ ) in %, and walking speed ( $v_w$ ) in m/s, which was calculated by dividing the values given in km/h by 3.6.

$$M_{pan}=1.5 \times W_b + 2 \times (W_b + L) \times (L/W_b)^2 + (W_b + L) \times (1.5 \times v_w^2 + 0.35v_w \times G) \quad (7)$$

For each of the 11 series, based on calculations for each individual session, we determined intra-series means and  $CV$  as presented in Table 1. Mean  $M_{VO2}$  increased with workload from 210 W (W1) over 260 W (W2) to 327 W (W3), whereas  $CV$  showed slightly decreasing values with 7% (W1), 6% (W2) and 4% (W3). A closer inspection revealed that  $CV$  significantly increased with  $Q_{10}$  ( $r=0.81$ ,  $p=0.002$ ). Though rectal temperature increase from rest ( $\Delta Tre = Tre - Tre_0$ ) varied between 0.1–1.7°C (Fig. 1a), we observed sim-

ilar averages of approximately 1°C in all series (Table 1), indicating prevailing steady-state conditions. Together with the overall  $Q_{10}$  of 1.11, this implies an average increase in  $M_{VO2}$  of about 1% due to  $\Delta Tre$  (1), contributing to 6% overall  $CV$ , with  $CV$  values conforming to the accuracy level of 5% claimed by the standard<sup>5)</sup> for  $Q_{10} \approx 1$ , i.e. if  $M$  were independent of  $\Delta Tre$ .

We calculated the prediction  $error = M_{HR} - M_{VO2}$  for all 373 experiments and computed intra-series mean error ( $bias$ ) and root-mean-squared error ( $rmse$ ) summary statistics presented in Table 1 as percentage values relative to mean  $M_{VO2}$ . Metabolic rates calculated from heart rates considerably overestimated  $M_{VO2}$  (Table 1) with mean  $\%bias$  ranging from 54% (W1) over 38% (W2) to 9% (W3). Consequently, overall  $\%rmse$  amounted to 43% (Table 1), which further increased to 64% when replacing lean body mass ( $LBM$ ) by body weight ( $W_b$ ) in eq. (5), as suggested<sup>8)</sup> for the prevailing lean persons in our study. These figures were far above the accuracy level of 10–15% stipulated by

the standard<sup>5</sup>) and guideline document<sup>8</sup>).

The error was highly sensitive to  $\Delta Tre$  as illustrated by Fig. 1a. However, the slopes exhibited a considerable inter-series variability, which mirrored the variation in thermal cardiac reactivity ( $TCR$ ), i.e. the increase in heart rate ( $\Delta HR = HR - HR_0$ ) due to core temperature rise ( $\Delta Tre$ ) shown in Fig. 1b and summarized in Table 1.  $TCR$  varied between 11.0–40.4 bpm/°C, whereas the overall average (27.0 bpm/°C) was close to the value of 33 bpm/°C reported in ISO standard 9886<sup>10</sup>). The slopes of Fig. 1a significantly correlated with  $TCR$  ( $r=0.96$ ,  $p<0.001$ ), suggesting that the bias was largely attributable to the thermal component of heart rate ( $\Delta HR_T$ )<sup>5, 10</sup>), also termed ‘thermal pulses’<sup>11, 12</sup>), which were neglected by the proposed algorithms<sup>8</sup>).

There are procedures to correct for  $\Delta HR_T$ , either using the correlation with core temperature, if those measurements were available<sup>11</sup>), or by estimating  $\Delta HR_T$  from  $HR$  recorded during resting periods intermitting the heat exposure<sup>10, 17–19</sup>). The latter method is advantageous under field conditions, as it does not require any core temperature measurements. The basic idea is to calculate  $\Delta HR_T$  as the difference of the  $HR$  recorded after at least five minutes break from work to  $HR_0$ , which could be measured before start of work or estimated by the 1st percentile of all measured  $HR$ <sup>8</sup>). Linear interpolation approximates intermediate values of  $\Delta HR_T$  over the working periods, which are then subtracted from recorded  $HR$  before estimating  $M_{HR}$ <sup>17–19</sup>).

As  $Tre$  was available in our study, we applied a bias correction to the  $M_{HR}$  estimates for each series using the individual regression functions from Fig. 1a. As shown in Table 1, this did not only remove the bias, but also reduced % $rmse$  considerably to values between 9–15%, thus conforming to the requested accuracy level of 10–15%<sup>5, 8</sup>).

Interestingly, in our study a comparable overall performance was observed for the simple estimates  $M_{Pan}$  (Table 1) using the Pandolf equation<sup>7</sup>) (7), which represents a Level 2 method<sup>5</sup>) for this type of treadmill work in the laboratory.

A recent field study on forest workers<sup>18</sup>) achieved a similar level of accuracy by estimating  $\Delta HR_T$  from intermittent resting periods<sup>17</sup>) and using individual  $M$ -to- $HR$  relations calibrated with procedures deemed representative for forest work<sup>18</sup>). This is important, as the  $M$ -to- $HR$  relationship intra-individually depends on the type of work: for the same heart rate, work with great muscles (legs) shows a metabolic rate 23–30%<sup>8</sup>) higher than activities involving smaller muscles (work with arms), and the dif-

ference may even increase for static muscular work. So the overestimation bias shown in Table 1 for  $M_{HR}$ <sup>8</sup>) may be actually higher in field situations frequently including work of small muscle groups and also static muscular work than for our comparison with walking subjects predominantly concerning leg muscles.

This validation study followed the concept of expressing accuracy levels as  $CV$ <sup>5, 8</sup>), but supplemented this by calculating *bias* in combination with *rmse*, as these quantities provide more appropriate error figures in case of non-zero bias. Adhering to this concept, we could largely confirm the accuracy level of 5% for  $M_{VO_2}$  as stipulated by the standard<sup>5</sup>), although the influence of body temperature on  $VO_2$  was smaller ( $Q_{I0}=1.11$ ) compared to recent studies<sup>9</sup>) with semi-nude subjects showing  $Q_{I0}=2$ .

However, we observed large overestimation by the  $M_{HR}$  algorithm due to thermal cardiac reactivity inflating the overall error up to 43% on average and above 60% for single series. After bias correction at the individual level, the error conformed to the accuracy level of 10–15% found in the recent simulation study assuming zero bias<sup>8</sup>).

Our results reinforce recent findings<sup>11, 16–19</sup>) on two essential requirements for the application of  $M_{HR}$  estimation algorithms to work scenarios. First, individual  $HR$ -to- $M$ -relationships derived from controlled cardiac stress tests are desirable, that should reflect the actual workload and type of work under consideration<sup>8, 11, 18</sup>). Secondly, a correction for the thermal heart rate component is necessary, especially under heat stress conditions. Thus a bias correction, e.g. by introducing intermittent resting periods of sufficient length of at least five minutes<sup>10, 17–19</sup>) should become mandatory for Level 3 studies in ISO 8996<sup>5</sup>) and *PHS*<sup>4</sup>). Otherwise, the accuracy of Level 3 studies might fall behind simpler Level 2 methods, as indicated by the smaller error for  $M_{Pan}$  in our study.

Finally, we like to add that measurement repetition is one method to reach a requested level of accuracy. Based on the  $CV$  of an unbiased estimate, the formula (*actual accuracy level/requested accuracy level*)<sup>2</sup> approximates the required number of repetitions. This implies that two measurements would be necessary to achieve the 10% accuracy level with a method actually providing 14%, while four repetitions would be needed with 20% accuracy, and even 9 with 30%, making such a method inefficient for field applications.

## References

- 1) ISO 11079 (2007) Ergonomics of the thermal environment–

- Determination and interpretation of cold stress when using required clothing insulation (IREQ) and local cooling effects. International Organisation for Standardisation, Geneva.
- 2) ISO 7730 (2005) Ergonomics of the thermal environment—Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria. International Organisation for Standardisation, Geneva.
  - 3) ISO 7243 (2017) Ergonomics of the thermal environment—Assessment of heat stress using the WBGT (wet bulb globe temperature) index. International Organization for Standardization, Geneva.
  - 4) ISO/DIS 7933 (2018) Ergonomics of the thermal environment—Analytical determination and interpretation of heat stress using the predicted heat strain model. International Organisation for Standardisation, Geneva.
  - 5) ISO 8996 (2004) Ergonomics of the thermal environment—Determination of metabolic rate. International Organisation for Standardisation, Geneva.
  - 6) Poulianiti KP, Havenith G, Flouris AD (2019) Metabolic energy cost of workers in agriculture, construction, manufacturing, tourism, and transportation industries. *Ind Health* **57**, 283–305.
  - 7) Pandolf KB, Givoni B, Goldman RF (1977) Predicting energy expenditure with loads while standing or walking very slowly. *J Appl Physiol* **43**, 577–81.
  - 8) Malchaire J, d'Ambrosio Alfano FR, Palella BI (2017) Evaluation of the metabolic rate based on the recording of the heart rate. *Ind Health* **55**, 219–32.
  - 9) Kampmann B, Bröde P (2015) Metabolic costs of physiological heat stress responses—Q10 coefficients relating oxygen consumption to body temperature. *Extrem Physiol Med* **4** Suppl 1, A103.
  - 10) ISO 9886 (2004) Ergonomics—Evaluation of thermal strain by physiological measurements. International Organisation for Standardisation, Geneva.
  - 11) Kampmann B, Kalkowsky B, Piekarski C (2001) Estimation of metabolic rate from cardiac frequency for field studies: correcting for “thermal pulses”. *J Therm Biol* **26**, 437–40.
  - 12) Kampmann B (2000) Zur Physiologie der Arbeit in warmem Klima. Ergebnisse aus Laboruntersuchungen und aus Feldstudien im Steinkohlenbergbau. Habilitation Thesis, Bergische Universität Wuppertal, Wuppertal.
  - 13) Ilmarinen R (1978) Einflüsse verschiedener Bekleidung auf einige physiologische Größen des Menschen bei Körperarbeit in unterschiedlich erhöhter Umgebungstemperatur und Luftfeuchtigkeit. PhD Thesis, Deutsche Sporthochschule Köln, Köln.
  - 14) Forsthoff A, Mehnert P, Neffgen H (2001) Comparison of laboratory studies with predictions of the required sweat rate index (ISO 7933) for climates with moderate to high thermal radiation. *Appl Ergon* **32**, 299–303.
  - 15) Wenzel HG, Mehnert C, Schwarzenau P (1989) Evaluation of tolerance limits for humans under heat stress and the problems involved. *Scand J Work Environ Health* **15** Suppl 1, 7–14.
  - 16) Ueno S, Ikeda K, Tai T (2014) Metabolic rate prediction in young and old men by heart rate, ambient temperature, weight and body fat percentage. *J Occup Health* **56**, 519–25.
  - 17) Vogt JJ, Meyer-Schwartz MT, Metz B, Foehr R (1973) Motor, thermal and sensory factors in heart rate variation: a methodology for indirect estimation of intermittent muscular work and environmental heat loads. *Ergonomics* **16**, 45–60.
  - 18) Dubé PA, Imbeau D, Dubeau D, Lebel L, Kolus A (2016) Removing the thermal component from heart rate provides an accurate VO<sub>2</sub> estimation in forest work. *Appl Ergon* **54**, 148–57.
  - 19) d'Ambrosio Alfano FR, Palella BI, Riccio G, Bartalini M, Strambi F, Malchaire J (2018) Heat stress assessment in artistic glass units. *Ind Health* **56**, 171–84.