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METABOLIC HEAT FLUX DENSITY (M) IN THE HUMAN BIOMETEOROLOGICAL MODELS: CAN M BE PARAMETERIZED BASED ON HEART RATE ESTIMATED BY SMART DEVICES?

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Ács, F., Kristóf, E.: *In this study, we focus on the calculation methods of human metabolic heat flux density (M) and on the applications of these methods in human thermal load models. Special attention was paid to the method that calculates M based on the heart rate (HR). A new M – HR based formula is presented. The connection was determined by measuring the average movement speed (V) and heart rate at the same time and then calculating M from V. The average V was determined by using a stopwatch. The average HR value was measured by using the Applewatch smart watch. The M(V) relationships are taken from the literature. Two persons performed the measurements in Martonvásár (a town close to Budapest), Budapest and Szombathely: a younger woman and an older man. The main lesson of our research is that M – HR based parametrization is individual-specific, despite the fact that the M – HR relationship can be characterized by a general function, which initially increases exponentially and then enters a saturation phase. This type of research will be widespread, given that we are living in the age of smart tools.*

Keywords: *Metabolic heat flux density; Heart rate; Parameterization; Human biometeorology; Smart tools.*

Introduction

In our day and age, energy balance-based models are the dominant models in the science of human biometeorological modelling (Potchter et al. 2018). It should be emphasized that simulating the effect of human factors on the heat balance of the human body is possible only with this type of model. Human factors are the anthropometric data characterizing the human body (body mass, body length, sex and age), the person's activity and the clothing worn. Anthropometric data and activity determine metabolic heat flux density (M) and rate of sweating; the clothing worn is a highly variable parameter, as it depends on both the environmental thermal load and the individual and social rules. In this work, we focus on M.

M is a quantity that must be calculated in every model, but we know little about its determination methods. There are procedures of varying complexity for estimating M (ISO8996 2004, Blazejczyk and Krawczyk 1994). The simplest procedures characterize the "average" person in the case of various occupations or activities (Auliciems and Kalma 1979, Höppe 1999). The M values or value ranges are given in tabular form and are obviously rough estimates (ISO8996 2004, Błażejczyk and Krawczyk 1994). The parameterizations for different activity types (sitting, standing, walking, running) are more complex than these simplest methods, they already use anthropometric data, which are already person-specific (standing; Judice et al. 2016, Amaro-Gahete et al. 2019), walking (Weyand et al. 2010), running (Campbell and Norman 1998). In the case of walking and running, M also depends on the speed. At the same time, there is no parameterization for many activities (let’s mention only the outdoor ones, e.g. gardening, moving, cycling, swimming). In such cases, the recommended method is to use parameterizations based on the M-heart rate relationship. The heart rate means the average heart rate for the given activity and time interval, that is, it does not mean a momentary value. There are few of these parameterizations (Malchaire et al. 2017) and they are quite person-specific.

In light of all this, the goals of this study are the following:

1) to present an M-heart rate type parameterization for 2 people, and

2) to describe the determination methodology in detail. The measurements were carried out by the male and the female researcher of this work, respectively, in Martonvásár, Budapest and Szombathely, Hungary.

Subjects and Methods

Methodology

There are two data collection methods in human biometeorology: the transverse (cross-sectional) and longitudinal method. In the case of transverse data collection, the relationship is examined for many people in the same situation, but in the case of longitudinal data collection, the connection applies to individuals in different situations. This study reports on the method and results of a longitudinal data collection that two persons have been carrying out over the years.

Methodological notes. To determine the relationship between M and heart rate, we gathered the motion speed (V) and heart rate (HR) data simultaneously. Both sets of data characterize the state of the human body. The body state is not for a moment, but for a period of at least half a minute. Obviously, V and HR data represent the average values for the period. The observer was either standing or moving. If the observer was moving, he/she was either walking or running. The observer made sure that his movement was as smooth as possible without higher speed fluctuations. The V varied between 0.5–5 ms^{-1}. Obviously, lower V values refer to longer distances (km), while larger V values refer to shorter (400 m, 800 m) or very short distances (200 m, 110 m). The longest distances were 3–5 km, the shortest distance was 110 m. For distances shorter than 110 m, the heart rate monitoring device no longer gave a signal, presumably due to the shortness of the period.

During our measurements, we used 2 devices: a Junso stopwatch and an Apple Watch smart watch. It should be noted that the Apple Watch smart watch forms a single unit with the Apple smart phone. The devices are presented in Figure 1.

Figure 1: The tools to gather information on human activity (heart rate, average moving speed).

The former device registered the length of the period, while the latter device served to register heart rate in BPM (beat per minute). As we knew the length of the road we have travelled, we easily estimated V from the length of the measured period. It should be noted that the registration of the HR – V connection was the most difficult for large V values, as the load must be continuous, which in our case was usually a minimum of half a minute. Such a registration sequence for large/larger HR – V values can be seen in Figures 2–3 for persons 1 and 2, respectively. In Figure 2, the V_{max} values (averaged V values when sprinting) varied between 4.31–4.62 m/s, and the corresponding HR values (the peaks of the wave-like curves) were between 135–145 BPM. In Figure 3, V_{max} values varied between 3.5–4.5 ms^{-1}, and the corresponding HR values were between 170–180 BPM. As we can see, the two cases are completely different for registered HR values.

Figure 2: Temporal changes in heart rate (beats per minute, BPM) during 10 consecutive sprint-walk exercises based on smartphone data. The distance of both the sprint and walk is 110 m. The sprints were performed by person 1 in Martonvásár on June 3, 2022. The average sprint speed is assigned to the maximum value of the heart rate curve. The descending parts of the curve show the walking periods between sprints.

Figure 3: Temporal changes in heart rate (beats per minute, BPM) during 7 consecutive sprint-walk exercises based on smartphone data. The sprints were performed by person 2 in Budapest on November 2, 2024. The average sprint speed is assigned to the maximum value of the heart rate curve. The descending parts of the curve show the walking periods between sprints.

The location and period of measurements. The location of the measurements of person 1 is Martonvásár (geographical latitude 47.31 ºN, geographical longitude 18.79 ºE), more precisely, the running track surrounding the soccer field. The measurements took place between March 7, 2022 and June 26, 2023. The observed movement states: walking, running at different speeds. We also carried out observations in both lying (resting) and standing positions, respectively, in a home environment. We had a total of 519 measurements, the vast majority of which were during walking and running.

The location of the measurements of person 2 is Budapest along the Rákos stream (geographical latitude 47.50 ºN, geographical longitude 19.15 ºE) and Szombathely (geographical latitude 47.24 ºN, geographical longitude 16.60 ºE). The measurements were taken from June 30, 2023 and February 2, 2025.

Parametrization of M. M is estimated for four different activities: resting, standing, walking and running. We don't differentiate between resting humans' *M* values because the differences are small (ISO8996 2004). In this case, for all humans

$$M_r = 55 \ Wm^{-2} . \tag{1}$$

The human can stand, walk and run. In these cases, *M* (total metabolic heat flux density) is to be calculated as follows,

$$M = M_b + M_a, \tag{2}$$

where M_b is the basal metabolic heat flux density (Wm^{-2}) and M_a is the metabolic heat flux density (Wm^{-2}) associated with activity (standing, walking or running). As we see M_r and M_b values are different, M_r is always somewhat greater than M_b. M_b is parameterized according to Mifflin et al. (1990) for men and women, respectively

$$M_b^{male}[kcal \cdot day^{-1}] = 9.99 \cdot M_{bo} + 6.25 \cdot L_{bo} - 4.92 \cdot age + 5, \tag{3}$$

$$M_b^{female}[kcal \cdot day^{-1}] = 9.99 \cdot M_{bo} + 6.25 \cdot L_{bo} - 4.92 \cdot age - 161. \tag{4}$$

where M_{bo} is body mass (*kg*), L_{bo} is body length (*cm*) and *age* is the age expressed in years. In eqs. (3) and (4), the unit of M_b is *W*, to obtain it in Wm^{-2}, it must be divided by human body surface area *A* (m^2). The well-known Dubois and Dubois (1915) formula is applied,

$$A = 0.2 \cdot M_{bo}^{0.425} \cdot \left(\frac{L_{bo}}{100}\right)^{0.725} . \tag{5}$$

In the case of the standing human, $M_a = M_{st}$. According to the results of Amaro-Gahete et al. (2019) and Júdice et al. (2016), the metabolic heat flux density used up during standing is only slightly higher than the metabolic heat flux density used up while lying down. Based on this, we parameterized M_{st} as follows,

$$M_{st} = 1.1 \cdot M_b. \tag{6}$$

In the case of a walking human, $M_a = M_w$. M_w is parameterized according to Weyand et al. (2010) as follows,

$$M_w = V \cdot \frac{3.80 \cdot M_{bo} \cdot \left(\frac{L_{bo}}{100}\right)^{-0.95}}{A}. \tag{7}$$

where *V* is the walking speed.

In the case of a running human, $M_a = M_{run}$. M_{run} is parameterized according to Campbell and Norman (1997) as follows,

$$M_{run} = M_b \cdot 9 \cdot \left(\frac{V}{V_{max}}\right), \tag{8}$$

where *V* is average speed of running (ms^{-1}) and V_{max} is maximum running speed (ms^{-1}).

Establishing the M-heart rate connection. The M – HR connection can be estimated using the HR – V connection calculating M from V using the above equations. Obviously, the M – HR relationship depends on both the parametrization equations and the measured HR and V values. The relationship is statistical because of the individual scattering of HR values and due to individual fluctuations of V values. It is also obvious that the relationship is individual, but the shape of the regression curve is general (ISO8996 2004).

Anthropometric data

Measurements were carried out by the first and second authors of the paper (hereafter referred to as persons 1 and 2). Their anthropometric data together with the values of M_b and body mass index (BMI) are presented in Table 1.

Table 1. Human state variables as well as basal metabolic heat flux density and BMI values of the persons conducting measurements.

Persons	Sex	Age (years)	Body mass (kg)	Body length (cm)	Basal metabolic heat flux density (Wm^{-2})	BMI (kgm^{-2})
Person 1	male	67–68	89.0	190.5	40.8	24.65
Person 2	female	36–38	70.0	160.5	38.4	27.17

Results

By measuring the HR – V connection, we could also examine the M – V and M – HR connections. Below is the analysis of the point clouds of these relationships.

The relationship between heart rate and movement speed

The point clouds of the HR – V relationship are illustrated in Figure 4. The HR – V point clouds of the 2 people are clearly separated, their points are not mixed. This was caused by person-specific changes in HR and V values. For person 1, HR values, which are close to maximum HR (HR_{max}) values are lower (135–155 BPM) than for person 2 (155–170 BPM). It can also be seen that the heart rate of person 2 is 80-100 BPM when the walking speed is 0.5–1 ms^{-1}. At the same time, person 1 did not walk more slowly than 1 ms^{-1}.

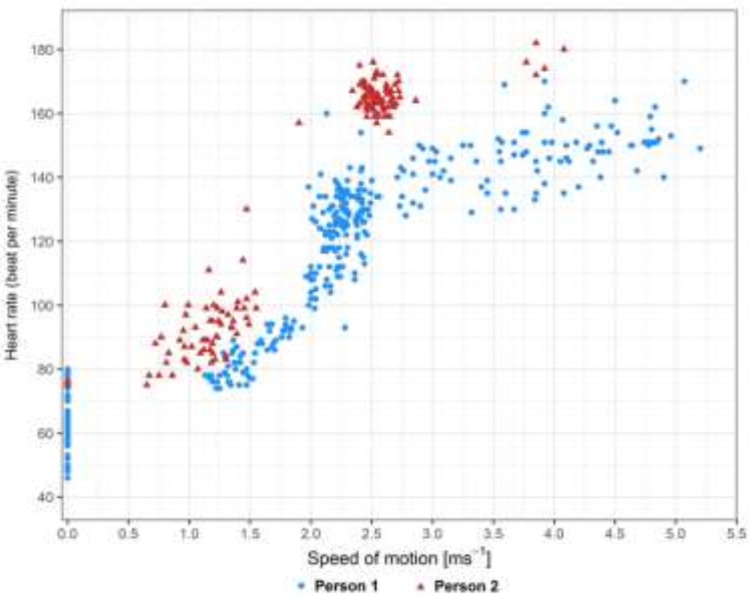

Figure 4: The point cloud of heart rate – average movement speed relationship for persons 1 and 2.

Heart rate values for both standing and slow walking states can be around 75–80 BPM, which is a sign that the function characterising the HR – V connection is continuous. We believe that this is true for both individuals. Based on the point clouds, the HR values of the two persons are distinct from each other. Person 2 has a higher heart rate than person 1, so the HR values of person 2 are greater than the ones of person 1. But the form of function characterising the HR – V connection is similar.

The relationship between metabolic heat flux density and movement speed

The point clouds of the M – V relationship are illustrated in Figure 5. The points are not scattered as the parametrization formulae were used (see section "Parametrization of M"). Three characteristics are noticeable: 1) M – V points form lines for both walking and running; 2) the lines of the person 2 have a slightly greater slopes than the lines of person 1; 3) for walking the slope of the M – V line is somewhat greater than the slope of the M – V line for running. The higher slope of M – V line for walking means that for the same speed V $M_{walk} > M_{run}$. Person 1 noticed this fact.

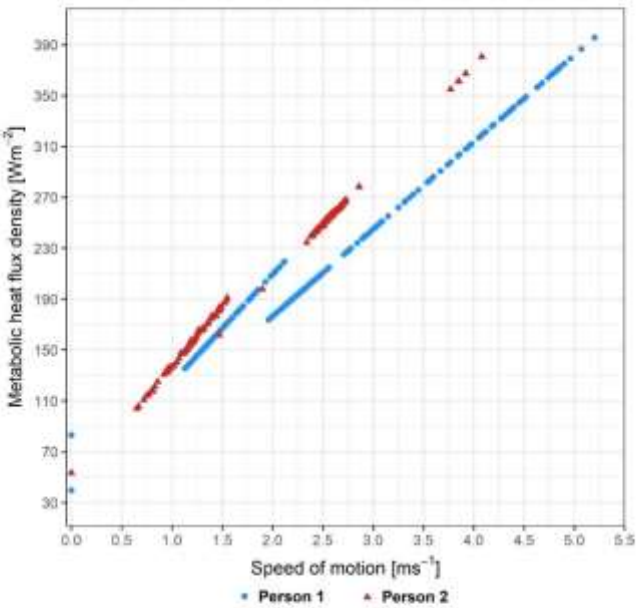

Figure 5: The point-cloud of metabolic heat flux density – average movement speed relationship for persons 1 and 2, respectively.

The relationship between metabolic heat flux density and heart rate

The point clouds of the M – HR relationship are presented in Figure 6. We focus on person 1, as in this case the distribution of M – HR points is more continuous. It is noticeable that the value range of the HR values is continuous. The lowest HR values are between 50–60 BPM in a resting, lying position, the highest HR values are around 160–170 BPM, when person 1 is under maximum load.

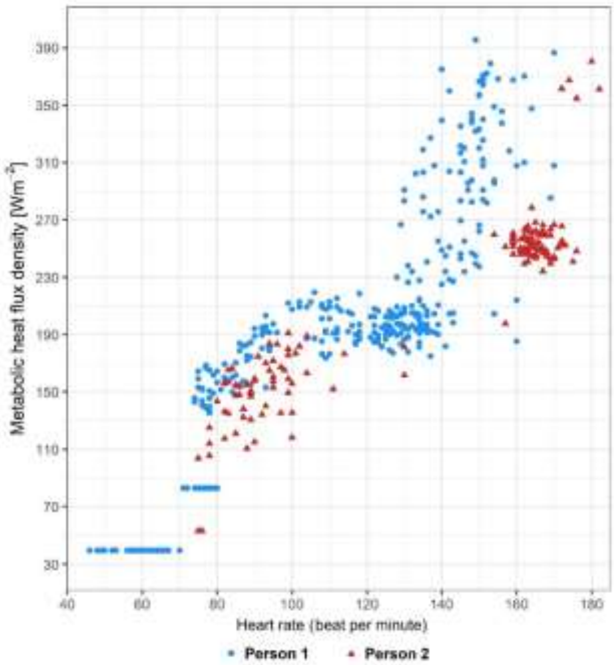

Figure 6: The point-cloud of metabolic heat flux density – heart rate relationship for persons 1 and 2, respectively.

However, the value range of M values is not continuous. The M values are clearly separated, when the person is in resting position (55 Wm^{-2}), or it stands (80–90 Wm^{-2}) or moves (130–390 Wm^{-2}). This, of course, is based on the parametrizations specified (eqs. 1–8). Let's look at the M – HR relationship in more details during walking and running, that is, when one moves. This point cloud can be divided into two parts: a) a part with a smaller slope (segment 1) where the (ΔM/ΔHR) ratio is approximately 40 Wm^{-2}/60 BPM, that is 2/3 Wm^{-2}/BPM (the range of speeds less than 2.5 ms^{-1}) and b) a part with a much greater slope (segment 2) where the (ΔM/ΔHR) ratio is approximately 200 Wm^{-2}/20 BPM, that is 10 Wm^{-2}/BPM (the range of speeds larger than 2.5 ms^{-1}). Despite the great difference between the slopes, the M – HR relationship is continuous. The points of M – HR relationship for person 2 are not evenly distributed.

The set of points for both persons can also be seen as a single set of points. In this case, the scattering of the points will be greater, and the general characteristics will be slightly modified. The slopes of the M – HR lines will change. The slope of the M – HR line in the segment 1 will be somewhat greater but the slope of the M – HR line in segment 2 will be somewhat smaller. In this case, the point-cloud can be approached by the following regression curve,

$$M = 4.13 \cdot 10^{-4} \cdot HR^3 - 1.18 \cdot 10^{-1} \cdot HR^2 + 12{,}08 \cdot HR - 259.8\,. \qquad (9)$$

The correlation coefficient is 0.75.

Discussion

In this study, we deal with parametrization of metabolic heat flux density and related human biometeorological applications. The presented M parametrization is a new parametrization, M – HR based, which is the highest in terms of complexity levels given in the ISO8996 (2004) study. The novelty of the study is in the methodology used, since the M – HR connection was determined based on the measurement of the V – HR connection by calculating M on the basis of V. During the measurement of the V – HR relationship, the weather, clothing, and the observer's mental state obviously varied. During these measurements, we did not register weather variability, as we established that in the case of a healthy person, HR is independent of weather thermal load (Ács et al. 2024). V depends on the quality of the surface, not the weather, apart from extreme weather conditions, in which we did not measure. We observed a slight seasonality in V_{max}. The values are lower in winter and somewhat higher in summer. The clothing worn was always appropriate for the given weather conditions, which obviously varied seasonally. The study of Ács and his colleagues (2023) provides more information on the types of clothing worn and the seasonal changes in the thermal insulation capacity of clothing. Regarding the mental state, it is important to highlight that the person performing the measurements was always motivated, never listless or tired, as if we knew that this was pioneering work.

In addition to the methodology used, the new result is that the slope of the M – HR connection lines is significantly different for the smaller and larger HR values. Our study also shows that the M – HR relationship is person-specific. This means that the course of the point-clouds is similar, but there may be significant differences between HR_{min}, M_{min} and HR_{max}, M_{max} values. Malchaire et al. (2017) also highlight the importance of the extreme values in the M – HR relationship. It can also be noted that the M – HR connection was provided for a person aged 67–68, and such an elderly person is not included in the ISO8996 (2004) study.

Nowadays, PET (Physiologically Equivalent Temperature; Höppe 1999) and UTCI (Universal Thermal Climate Index; Blazejczyk et al. 2010) models are the most commonly used human biometeorological models. In these models, the human is a "reference" human who is walking with a speed of 4 kmh^{-1} (1.1 ms^{-1}). The body shape of reference people is mesomorphic (Zsákai and Bodzsár 2014). The M value of a person with defined activity and body shape is constant. But not all thermal load index models use the concept of a "reference" person (Ács et al. 2021, 2024). In the models that use the concept of "individuals", the M quantity is parameterized, the most commonly parameterizations used have been shown (eqs. 1–8) in the study. But these are basically M – V relationships. There are no M – HR based relationships. This study is intended to partially compensate for this shortage. M – HR based studies are also important because there are many activities that cannot be parametrized by V.

Nowadays we are in the age of smart devices. Without them, this study would not have been made possible, this is especially true for heart rate data. However, people who make measurements and observations are just as important as the device since human biometeorological observations and measurements require free time, motivation and dedication, in addition to having basic meteorological and anthropological knowledge. In our opinion, with the spread of smart devices, human biometeorological analyses will tend to be more individualized.

Finally, let's answer the question in the title! The characterization of the M – HR relationship – even if only in the case of 2 persons – is the first attempt of this type in our country. The M – HR relationship has high interpersonal variability (Bröde and Kampmann, 2019), this is a methodological disadvantage, but its great advantage is that it makes possible to determine M for any activity if the heart rate associated with the activity is known. We assume that the use of HR information will increase with the spread of smart devices.

Conclusion

In this study, we dealt with parametrization methods for calculating metabolic heat flux density and presented a new M – HR based parametrization. We have come to the following conclusions: 1) the appearance of smart devices stimulates the process of individualizing human biometeorological analyses, 2) despite the fact that M – HR based formulae are person-specific, they are capable of approaching the values of M. Obviously, there is a need for doing more similar studies to make for an even more reliable pool of knowledge.

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