Heat Balance and Algorithms Elaborated

Maintaining a relatively constant body temperature requires a fine balance between heat production and heat losses.

*If body temperature is to remain unchanged, increases or decreases in heat production must be balanced by increases or decreases in heat loss, resulting in negligible heat storage within the body. If the body is at constant mass, the whole-body **heat-balance equation** expresses this concept as follows:*

$$\underbrace{(\overset{\text{Metabolism}}{M} - \overset{\text{Work done on environment}}{W})}_{\text{Heat production}} - \underbrace{(\overset{\text{Radiative heat loss}}{R} + \overset{\text{Convective heat loss}}{C} + \overset{\text{Evaporative heat loss}}{E})}_{\text{Heat losses}} = \overset{\text{Storage of heat}}{S}$$

*Metabolism (**M**) is the consumption of energy from the cellular oxidation of carbohydrates, fats, and proteins. For a cyclist, the useful work on the environment (**W**) might be the energy spent in riding a Time Trial or a Granfondo. However, because of a long list of inefficiencies—the inherent inefficiency of metabolic transformations as well as frictional losses (e.g., blood flowing through vessels, air flowing through airways, tissues sliding passed one another)—most metabolic energy consumption ends up as heat production (**H = M – W**).* (c.f. Medical Physiology, 3rd Edition Modes of Heat Transfer).

In our specific case we are, for practical reasons, interested in loosing heat during indoor bike training on a stationary trainer. Usually, one or more fans on the ground face the indoors setup, to cool down the (over)heated body during the workout or during intense virtual races like with Zwift. In that situation you want to minimize the rate of heat change. Front facing airflow around the body, is the best way to minimize sweating, as we all know from cycling outdoors. The faster you go outdoors the better you cool the body. When confronted with your indoor trainer setup, the question remains how hard should the fans have to blow to result in a maximal effect without causing shivering due to overcooling when the exercise is not that intense anymore?

Storage of Heat

$$\Delta S/\Delta t = C_h/A_D * \Delta T_b/\Delta t$$

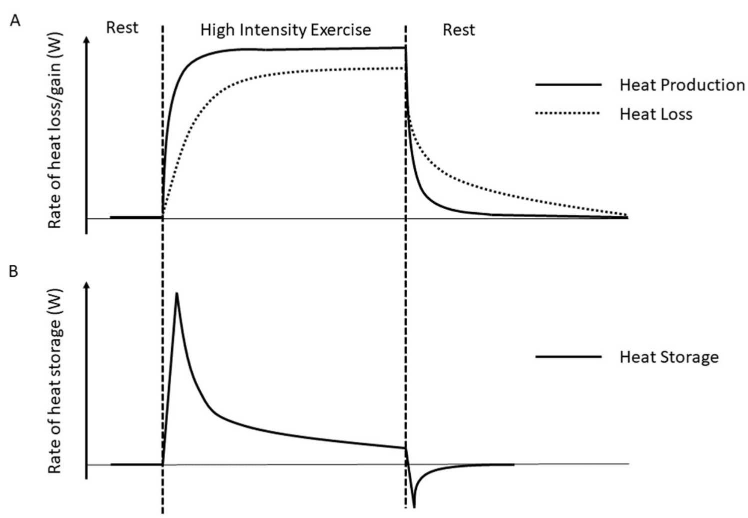
The rate of heat change ($\Delta \mathbf{S}$) stored inside the human body during timespan (Δt) is directly correlated to the rate of body temperature change ($\Delta \mathbf{T_b}$) during exercise time (Δt). $\mathbf{C_h}$ is the heat capacity of the human body, which derives from the specific heat c = 3474 J/°C.kg. C_h = c * Bodymass. $\mathbf{A_D}$ is the DuBois body surface area (m^2); $\mathbf{A_D}$ (m^2) is calculated as: $0.00718 \times Bm^{0.425} \times H^{0.725}$ where Bm = Body mass (kg) and H = height (cm). The Du Bois and Du Bois (1916) body surface area equation is used widely to normalize physiological parameters. All terms in the following heat balance equations are in W/m^2.

Notice that the rate of heat change will vary during a workout with the intensity of the effort (power output) and the heat change can be positive (net heat gain) and negative (net heat loss). We can determine the internally heat stored as the sum of all determinations (1 to n) of $\Delta S/\Delta t$ during the workout time:

$$S_{(W/m^2)} = (\Delta S/\Delta t)_1 + (\Delta S/\Delta t)_2 + (\Delta S/\Delta t)_3 \ldots (\Delta S/\Delta t)_n$$

Where **S** is the heat stored inside the human body during the workout.

Heat internally stored in the human body during and after exercise:



Kenny and McGinn (2017) published an extensive study about the thermoregulation during and after exercise that perfectly shows at what rates internal heat is gained and loosed as depicted in the above figure. (Figure is modified after Kenny and McGinn, 2017)

During exercise, the body stores heat because of an imbalance between the rate of heat gain (internal heat production) and heat loss (heat exchange with the environment). Under compensable conditions, heat balance is achieved within 30 – 45 min of steady-state exercise, with the greatest rate of body heat storage, and therefore increase in core temperature, occurring in the first 15–20 min. During the performance of intermittent exercise, a greater increase in evaporative heat loss occurs following the initial exercise such that the amount of heat stored in the successive exercise bouts is reduced by as much as 40 – 60% under compensable conditions. During the rest phase, there is an abrupt, centrally mediated suppression in the heat loss responses which occurs as the rate of metabolic heat production also returns to baseline levels. However, as recent studies demonstrate, this leads to a sustained elevation of muscle and core temperatures above resting levels for as long as 90 min postexercise. (c.f. Kenny and McGinn, 2017)

Response to internal heat production: thermoregulation

The rise in core temperature during an exercise is due to retention of the internal heat generated by exercising muscles. Internal heat production rises immediately during the initial stage of an exercise and exceeds heat loss at first. Internal body heat storage will result in an increase in the average body temperature (**T_b**), which is a weighted combination of the core temperature (**T_c**) and mean skin temperature (**T_{sk}**). The rise in core temperature (**T_c**) triggers reflexes, via central thermoreceptors, for increased heat loss and will influence heat exchanges through convection, radiation, and evaporation between the shell of the body and the environment. With increased skin blood flow and sweating, the discrepancy between heat production and heat loss starts to diminish. The skin (or body shell) is losing heat to the environment, but core temperature continues to rise until heat loss and heat production are balanced. At some point, core temperature stabilizes at the elevated value and in a semi-steady state.

The mean body temperature can be calculated from T_c and T_{sk}:

$$T_b = (0.64*T_c + 0.33*T_{sk})$$ (Burton, 1935 and Kerslake, 1972)

Where (**T_b**) is the average body temperature, (**T_c**) is the core temperature and (**T_{sk}**) the skin temperature. Units are in degrees Celsius.

Skin temperature can be estimated from air temperature using an <u>oversimplified</u> equation:

T_{sk} (°C) = 0.33 * T_{air} + 20.7 (Brotherhood, 2008; Davies 1979)

However, Mehnert, P. et al. (2000) published an elaborative research that took many more parameters into account that have a direct influence on skin temperature. Fortunately, the set of data was obtained for subjects that were only lightly clothed, like an indoor cyclist would wear! That resulted in the following equation:

$$T_{sk}\,(^{o}C) = 7.19 + 0.064*T_a + 0.061*T_r + 0.198*P_a + 0.348*V_a + 0.616*T_{re}$$ (Mehnert et al. , 2000)

T_a is air temperature; **T_r** is Radiant temperature; **P_a** is Vapour pressure; **V_a** is airflow and **T_{re}** is rectal or core temperature. All parts of this equation can be determined and lead to an accurate estimation of the skin temperature.

The average normal **core temperature** is generally accepted as 37°C. Heat production can potentially raise your core body temperature by nearly 3 degrees Celsius during intense exercise, as was documented recently. During the Time Trial of the 2016 UCI Road World Championships, core temperature was recorded via an ingestible capsule in 40 elite male and female cyclists. 85% Of the cyclists participating in the study (i.e. 34 of 40) reached a core temperature of at least 39°C with 25% of the cyclists (i.e. 10 of 40) having a core temperature exceeding 40°C. (Racinais et al, 2019).

An algorithm with simple heart rate monitors to estimate core body temperature

Continuous ambulatory measurement of core body temperature can be a critical component of human heat strain assessment during strenuous work. However, while personal physiological monitoring technology has developed to the point where multi-parameter sensor systems can be used to collect data in a variety of settings over extended periods of time, the requisite measurement of core body temperature (T-core) remains a challenge.

Medical grade T-core measurement using pulmonary arterial blood temperature is only appropriate in a clinical setting. The traditionally accepted laboratory rectal and esophageal probe methods are impractical for ambulatory settings. Ingestible thermometer pills have been used successfully in field settings and have been within acceptable limits of agreement and bias when compared to esophageal temperatures. However, these thermometer pills have clear drawbacks: (1) they cannot be used by all people due to medical contraindications, (2) can suffer from inaccuracy when hot or cold fluids are consumed, and (3) not very practical in daily life. The difficulty in directly measuring T-core in ambulatory settings has led to the search for a practical alternative technique. cf Buller et al, (2013)

Buller et al, (2013) accomplished a brilliant research on estimating T-core in warm to hot conditions during exercise with simple wearable heart rate monitors. It resulted in a method to use time series observations of heart rate to track T-core over time. The method heavily relies on a Kalman filter (Kalman, 1960) which has been used extensively in engineering tracking problems. Here an item or variable of interest must be tracked from a series of 'noisy' observations, and knowledge of the temporal dynamics. The Kalman filter requires two models defined by linear Gaussian probability density functions. One model relates how the variable to be tracked changes over time, while the other model relates current observations to the variable of interest.

Buller et al, (2013) extended a previous Kalman filter and T-core estimation model in the following ways: (1) they used an extended Kalman filter to allow estimation of T-core up to 41 ◦C, (2) the model's T-core time update and T-core to heart rate mapping functions are derived from a single study with 17 volunteers where T-core ranges from 36 ◦C to over 40 ◦C, and (3) the model is validated against original data sets from laboratory and field experiments where work rates and environment, hydration, clothing, and acclimation states are varied. They succeeded in providing a method of estimating T-core in warm-hot environments that is simple to use, works with equipment that is readily available (with cyclists) and provides a valid estimate of time varying T-core.

Since 2015 the T-core estimate is part of Golden Cheetah (https://www.goldencheetah.org/, implemented by Mark Liversedge) and many Golden Cheetah-users have been consciously working with it since, including myself. The sponsor of the research (USARIEM) published the algorithm for non-commercial use: https://www.usariem.army.mil/index.cfm/research/products/cbt_algorithm.

We have transferred the algorithm code to an Arduino setting and it is used in minute-by-minute measures of heart rate to estimate the core body temperature during exercise.

Heat Production

The heat production depends on where the heat originated in the body. In the heat balance equation, the following terms represent Heat Production:

$$H_{(W/m^2)} = M_{(W/m^2)} - W_{(W/m^2)}$$

Where H = internal heat production (W/m^2), W = external work (W/m^2) and M = metabolic free energy production (W/m^2). Basal metabolic rate <u>at full rest</u> is in the order of 70 kcal/h. Notice that only about 20% of the cycling energy is transferred (by muscles) to actual bike movement, the remainder (4 times (!) the produced cycling **Power**) is released as internal metabolic heat. The human engine is not very efficient. When you push 200 watts on the pedals, 800 watts is released as internal body heat.

Every sport has a different basic efficiency. For cycling the **gross mechanical efficiency** (η) ranges between 19% and 28% depending on the individual. It will be no surprise that the highest values are found with elite riders (world champions and the top ten of Vuelta and/or Tour de France) (Coggan, 2013).

Thus, for a given metabolic rate a more efficient individual will be able to produce more power, and/or will be able to produce a given power output at a lower metabolic rate (= less physiological strain = less heat produced). (Coggan, 2013).

The mechanical efficiency (η) is defined in the equation:

$$\eta = W/ M$$ (Parsons, 1993)

where W = external work (W/m^2) and M = metabolic free energy production (W/m^2). In the previous calculation we assumed a very reasonable value of 20% for the efficiency.

Combining the previous two equations, the heat production can be calculated when the efficiency and M or W is known with the equations:

$$H_{(W/m^2)} = (M * (1- \eta)) * 1/A_D$$ (McIntyre, 1980)

$$H_{(W/m^2)} = (W * ((1/ \eta) - 1)) * 1/A_D$$

where M = metabolic free production (W/m^2), W = work rate (W/m^2) , η = mechanical efficiency and A_D is the body surface area (m^2) (Du Bois, 1916) .

Heat Losses

Metabolic heat generated during exercise (external work) is transferred (by blood and conduction) to the environment from the skin surface via dry (**conduction**, **convection**, and **radiation**) and **evaporative** heat transfer pathways. Parameters within the environment that influence heat exchange include the ambient temperature, water vapor pressure, radiant heat, air movement, and the properties of clothing (insulation and moisture transfer). An important difference between exercise indoors and outdoors is that indoors exercise is more likely to occur in near wind still conditions unless specific equipment is used to produce an adequate facing windspeed, equivalent to what might be expected in outdoors exercise. The presence of an adequate facing airflow will influence the extent of heat loss by both **convection** and **evaporation**.

$$H - Q_{loss} = S$$

S equals the heat stored inside the human body during exercise time (W/m^2). Ideally **S** should equal to zero when the body is in heat balance i.e., heat production = heat loss (NO internal heat storage).

$$Q_{loss}\ (W/m^2) = (R + C + E)$$

R = heat exchange via **radiation** (W/m^2), C = heat exchange via **convection** ($W/\ m^2$), E = **evaporative** heat exchange.

Let us have a closer look at the different terms of Q_{loss}:

$$R\ (W/m^2) = 4.7 * (T_{sk} - T_{db}) \qquad \text{(Kenney 1998)}$$

Where T_{sk} = skin temperature (°C) and T_{db} = dry bulb temperature (°C). In our indoor cyclist practice, T_{db} is the same as the ambient air temperature (Kenney 1998).

Heat exchange by **Radiation** temperature gradient is dependent of and can actively be influenced by how much and what clothing you wear. Less is more radiation. We assume this is all included in the outcome of the equation $E.\sigma.f_{cl}.f_{eff} = 4.7$. Where E = emittance from the outer surface of a clothed body (0.97), σ = Stefan-Boltzmann constant ($5.67 \times 10^{-8}\ W.m^{-2}.K^{-4}$), f_{cl} =clothing area factor (0.92 ND), f_{eff} = effective radiation area of a clothed body (0.71).

Notice that **Radiation** is important to exchange heat with the environment, stay out of the sun and minimize your clothing! Air velocity plays a major role with the heat exchange via **Convection** and **Evaporation**!

$$C\ (W/m2) = H_c * V_a^{0.84} * (T_{sk} - T_{db}) \qquad \text{(Kenney 1998)}$$

V_a is air velocity (m/s), T_{sk} = skin temperature (°C) and T_{db} = dry bulb temperature (°C). H_c ($W/m^2/K$) is the convective heat transfer coefficient. The shell or skin- temperature is several degrees lower than the temperature in the central core. Skin temperature is dependent on the body location, heat, torso, legs or feet! Dry bulb temperature is in our indoor case equal to the ambient temperature. (Notice: **The air velocity exponent is taken from Defraeye et al., 2011**)

$$E\ (W/m2) = H_e * V_a^{0.84} * (P_{sk} - P_a) \qquad \text{(Kenney 1998)}$$

V_a is air velocity (m/s), P_{sk} = saturated water vapor pressure at the wetted skin surface (kPa), P_a is the partial water vapor pressure (kPa). H_e ($W/m^2/kPa$) is the evaporative heat transfer coefficient. **Convection** and **evaporation** are strongly related not only because of the importance of the air velocity but also due to the linear relation of H_c and H_e. (Notice: **The air velocity exponent is taken from Defraeye et al., 2011**)

$$H_e = 16.5 * H_c$$ (Kerslake, 1972)

In the literature different values for **Hc** can be found ranging from 8.0 to 15.0. These values are dependent of the kind of sport and laboratory circumstances. Most of the research is done at still air or low wind speeds < 1 m/s. The same applies for the air velocity exponent that ranges from 0.5 to 0.6 in a lot of literature not specifically aimed on cycling (Kerslake (1972). However, the value of 0.84 is taken from recent work by Defraeye et al. (2011). Defraeye et al. (2011) have done extensive research, focusing on cycling, with different realistic windspeeds and on different cyclist positions! They derived cycling specific results for the V_a exponent (between 0.81 and 0.85) and for **Hc** between 8.5 and 8.1, both dependent on cycling position. We have applied their findings.

Notice that during intense exercise, the body loses 85% of its heat through sweating. Sweating only starts at a core temperature above 36.85 degrees Celsius. The air velocity is the dominant variable and highly determines the efficacy of convection and evaporation rates for given values of the other variables (like humidity, ambient and skin temperature). These terms in the equations (for **E** and **C**) change relatively little during a workout. Air temperature and humidity can be determined at least at the start of a workout or continuously when the circumstances change. In our case the values are continuously measured. We do not measure a skin temperature directly for practical reasons.

Finally, we can derive the requested airflow velocity from the heat balance equation…

We can quite accurately determine the different terms from the heat balance equation. Since we are interested particularly in an optimized measure for the airflow velocity, we will rewrite the heat balance equation accordingly! But first one should realize the following. Stored Heat (**S**) is a serious factor to account for when not all heat is exchanged with the environment, net heat gain exceeds the net heat loss. Since we want to tune the airflow velocity in such a way that **heat balance** is achieved, when net heat gain equals heat loss, we consequently have to account for (1) the internally stored heat (**S**) from previous unbalanced efforts during the exercise **and** for (2) the presently produced heat (**H**) in the exercise. It is the sum of stored heat and produced heat that must be exchanged ideally with the environment through **convection, evaporation,** and **radiation** to end up with a heat balanced situation! Only when the airflow velocity is carefully tuned **heat balance** is achieved!

We rewrite the heat balance equation accordingly for our purpose:

$$(H + S) – (C + E + R) = 0$$

Or with **C** and **E** at the left of the equation:

$$C + E = (H + S) – R$$

C and **E** share the airflow velocity term (**V_a**) and can be rewritten as follows:

$$C + E = V_a^{0.84} * (H_c * \Delta T_{ska} + H_e * \Delta P_{ska})$$

With $\Delta T_{ska} = (T_{sk} - T_{db})$ and $\Delta P_{ska} = (P_{sk} - P_a)$

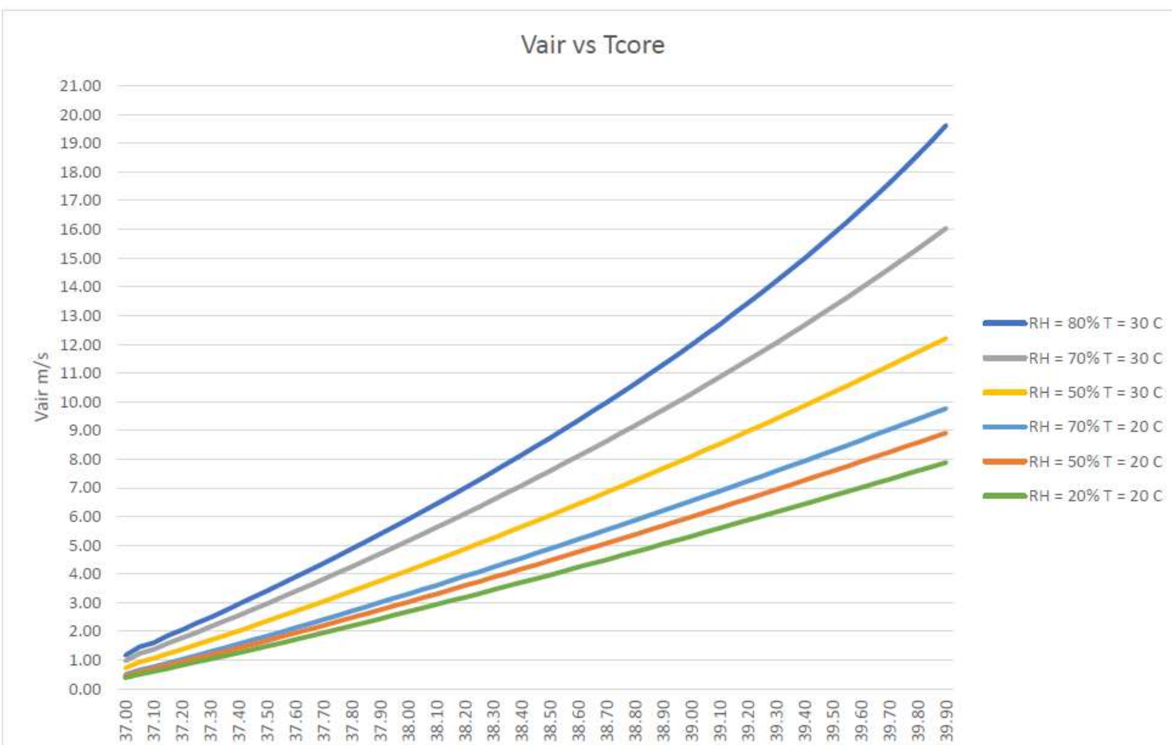
We put this formula in the heat balance equation and rewrite it as follows:

$$V_a^{0.84} = (H + S - R) / (H_c * \Delta T_{ska} + H_e * \Delta P_{ska})$$

The airflow velocity can now be determined, since all terms (at the right side) are known or can be determined instantly during the exercise:

$$\boxed{V_a = ((H + S - R) / (H_c * \Delta T_{ska} + H_e * \Delta P_{ska}))^{1.1904}}$$

All terms of the Heat Balance equation can be determined and consequently the requested airflow velocity calculated to maximize heat exchange with the environment. The requested air velocity drives the duty cycle of the fan(s) and therefore they most effectively cool the indoor cyclist with an airflow, appropriately tuned with the level of the workout and thermo-regulated state of the cycling individual.



In the figure the air velocity is plotted versus core temperature (proportional to internal body heat storage) during a steady-state workout at 200-watt power output. The exponential graphs vary in steepness as a function of relative humidity (%) and ambient temperature (Celsius) as one would expect. (Notice: 8.33 m/s equals 30 km/h or 18.7 miles/h).

The individual of the example has a body height of 175 cm and height of 72 kg. It is assumed that the core temperature increases (despite heat exchange with the environment) with 0.05 Celsius every minute because of an imbalance between heat gain and heat loss! This example is elaborated and presented in more detail in the Appendix file.

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