Ergonomics of the thermal environment :
Evaluation of metabolic rate

I was the main writer (Prof J. Malchaire) of this document which became the international standard ISO 8996. I was never remunerated for this work and I never yielded the royalties to anybody. Therefore, I consider that I have the right to diffuse the document that was sent to ISO to edit the standard.
This document takes into account the modifications brought in 2018

Annex C is based on the article "Evaluation of the metabolic rate based on the recording of the heart rate" that we published in 2017.

1 The units

The metabolic rate associated with a given task is expressed in watts. If the task does not involve displacements and is performed in the same way, the metabolic rate does not vary as a function of the size and the weight of the subject. If it involves displacements, then the weight of the person must be taken into account (see annex B).

As the heat associated to this metabolic rate and produced inside the body must leave it essentially through the skin, thermophysiologists usually express the metabolic rate per unit of body surface (in Wm^{-2}) and the estimations of thermal comfort and thermal constraints described in other standards of this series are always done in Wm^{-2}.

2 The 4 levels of methods for estimating the metabolic rate

The mechanical efficiency of muscular work — called the “useful work” — is low. In most types of industrial work, it is so small (a few percent) that it is assumed to be nil. This means that the energy spent while working is assumed to be completely transformed in heat. For the purposes of this International Standard, the metabolic rate is assumed to be equal to the rate of heat production.

Table 1 lists the different approaches presented in this International Standard for determining the metabolic rate.

These approaches are structured following the philosophy exposed in ISO 15265 regarding the assessment of exposure. Four levels are considered:

- Level 1, *Screening*: a method simple and easy to use is presented to quickly classify as light, moderate, high or very high the mean workload according to the kind of activity.
- Level 2, *Observation*: a time and motion study is presented for people with full knowledge of the working conditions but without necessarily a training in ergonomics, to characterize, on average, a working situation at a specific time:

  A procedure is described to successively record the activities with time, estimate the metabolic rate of each activity using formulas and data presented in Annex B and compute the time weighted average metabolic rate.
- Level 3, *Analysis*: one method is addressed to people trained in occupational health and ergonomics of the thermal environment. The metabolic rate is evaluated from heart rate recordings over a representative period. This method for the indirect evaluation of metabolic rate is based on the relationship between oxygen uptake and heart rate under defined conditions.
- Level 4, *Expertise*: 3 methods are presented. They require very specific measurements made by experts:
  - Method 4A: the oxygen consumption is measured over short periods (10 min to 20 min) (a detailed time and motion study is necessary to show the representativeness of the measurement period);
  - Method 4B: the so-called doubly labelled water method aiming at characterizing the average metabolic rate over much longer periods (1 to 2 weeks);
  - Method 4C: a direct calorimetry method.

Table 1 — Levels for the evaluation of the metabolic rate

<table>
<tr><th>Level</th><th>Method</th><th>Accuracy</th><th>Inspection of the work place</th></tr>
<tr><td>1
Screening</td><td>Classification according to activity</td><td>Rough information
Very great risk of error</td><td>Not necessary,</td></tr>
<tr><td>2
Observation</td><td>Time and motion study</td><td>High error risk
Accuracy: ± 20 %</td><td>Necessary</td></tr>
<tr><td>3
Analysis</td><td>Heart rate measurement under defined conditions</td><td>Medium error risk
Accuracy: ± 10 %</td><td>Study required to determine a representative period</td></tr>
<tr><td rowspan="4">4
Expertise</td><td>4A: Measurement of oxygen consumption</td><td rowspan="4">Errors within the limits of the accuracy of the measurement or of the time and motion study
Accuracy: ± 5 %</td><td>Time and motion study necessary</td></tr>
<tr><td>4B: Doubly labelled water method</td><td rowspan="2">Inspection of work place not necessary, but leisure activities must be evaluated.</td></tr>
<tr><td>4C: Direct calorimetry</td></tr>
<tr><td>4D: Accelerometry</td><td>Inspection of work place not necessary</td></tr>
</table>

3 The accuracy of the estimation of the metabolic rate

The accuracy of the results increases from level 1 to level 4 and, as far as possible, the most accurate method should be used.

- At level 1, *Screening,* the method, provides only a rough estimate and there is considerable scope for error. This limits its accuracy considerably. At this level, an inspection of the work place is not necessary.

- At level 2, *Observation,* the accuracy of the time and activity procedure depends upon the accuracy of the formulas used (see annex B), but mostly upon the level of training of the observer and his/her knowledge of the working conditions: the possibility for errors is high.
- At level 3, *Analysis*, the accuracy of the estimated metabolic rate is influenced by the accuracy of the (HR – M) relationship used, as other stress factors can influence the heart rate;
- At level 4, *Expertise*, the accuracy is the one of the measurement system (accelerations, gas volume and oxygen fraction, accelerometry).

It can be estimated that:

- For the same work and under the same working conditions, the metabolic rate can vary from person to person by about 5 %;
- For a person trained in the activity, the variation is about 5 % under laboratory conditions;
- Under field conditions, i.e. when the activity to be measured is not exactly the same from test to test, a variation of up to 20 % can be expected;
- In hot conditions, a maximum increase of 10 w may be expected due to increased heart rate and sweating. Such a correction is negligible in most cases
- In cold conditions, an increase of up to 400 w may be observed when shivering occurs. The wearing of heavy clothing will also increase metabolic rate, by increasing the weight carried by the subject and decreasing the subject's ease of movement.

In addition, other factors can affect the accuracy of the estimations, such as:

- individual variability;
- differences in work equipment;
- differences in work speed;
- differences in work technique and skill;
- gender differences and anthropometric characteristics.

Attention must be drawn to the fact that the accuracy depends also upon:

- the representativeness of the time period observed
- the possible disturbance of the normal activity by the observer and/or the procedure. In this regard, the method based on heart rate recordings appears to be one that interferes the least with the activity.

4 Level 1, Screening: Classification of metabolic rate by categories

The metabolic rate can be estimated approximately using the classification given in Annex A. Table A.1 defines five classes of metabolic rate: resting, low, moderate, high, very high. For each class, a range of metabolic rate values is given as well as a number of examples. These activities are supposed to include short rest pauses. The examples given in Table A.1 illustrate the classification.

As the accuracy of this method is low, it should only be used classification purposes without interpolation between the 4 levels.

5 Level 2, Observation

5.1 Evaluation of metabolic rate for a given activity

Annex B gives mean values or formulas for estimating the metabolic rate in watts in the following cases:

- At rest;
- When walking with/without load at < 6 km·h^{-1};
- When running with/without load at > 6 km·h^{-1};
- When going up or down stairs and ladders;
- When lifting or lowering loads without displacement;
- For activities without displacement, from the observation of the body segment involved in the work: both

hands, one arm, two arms, the entire body;

- Taking into account the body posture: sitting, kneeling, crouching, standing, standing stooped;

5.2 Evaluation of the mean metabolic rate over a given period of time

To evaluate the average metabolic rate over a given period of time, it is necessary to carry out a detailed study of the work. This involves:

- Determining the list of activities performed during this period of time;
- Estimating the metabolic rate for each of these activities taking account of their characteristics and using the data in Annex B: speed of displacement, heights climbed, weights manipulated, number of actions carried out, etc.;
- Determining the time spent at each activity over the whole period of time considered.

The time weighted average metabolic rate for the time period can then be evaluated using the equation:

$$M = \frac{1}{T}\sum_{i=1}^{n} M_i t_i \qquad (1)$$

where

- M is the average metabolic rate for the work cycle, W;
- M_i is the metabolic rate for activity i, W;
- t_i is the duration of activity i, min;
- T is the total duration, min, of the period of time considered, and is equal to the sum of the partial durations t_i.

The procedure of this time and activity is further described in Annex B.

6 Level 3, Analysis

6.1 Evaluation of metabolic rate using heart rate

In the case of dynamic work using major muscle groups, with only a small amount of static muscular and mental loads, the metabolic rate may be estimated by measuring the heart rate while working. Under such conditions, a linear relationship exists between the metabolic rate and the heart rate. If the above mentioned restrictions are taken into account, this method can be more accurate than the level 1 and level 2 methods of evaluation (see Table 1) and is considerably less complex than the methods listed at level 4.

The relationship between heart rate and metabolic rate can be written as:

$$M = a + b\,HR \qquad (2)$$

where

- M is the metabolic rate, W;
- HR is the heart rate measured, beats·min^{-1};
- *a* and *b* are coefficients

The heart rate may be recorded continuously, for example by the use of telemetric equipment, or, with a reduction in accuracy, measured manually by counting the arterial pulse rate.

The mean heart rate HR may be computed over fixed time intervals, for example 1 min, over a given period of time or over the whole shift time.

The accuracy of this estimation of the metabolic rate depends upon:

- The accuracy and validity of the relation (2)
- The validity of this relation
- The magnitude of the HR components not linked to the dynamic muscular load

6.2 Accuracy of the (HR-M) relationship

The relationship between heart rate and metabolic rate can be determined by different methods of decreasing accuracy:

- The most accurate method consists of recording the heart rate and corresponding oxygen consumption at different effort levels during a cardiac stress test on an ergometer or a treadmill. The (M – HR) can be used provided the durations of the efforts at each level are such that stable HR and oxygen consumption values are reached. Such a procedure is very painful and is usually performed in a medical environment.
- A lighter procedure consists of recording the stable heart rate during a few dynamic efforts whose metabolic rates are known. The accuracy is then reduced as the oxygen consumption is not measured.
- Expression (3) can also be derived from evaluations of:
  - the heart rate at rest under neutral thermal conditions, HR_0, beats·min^{-1};
  - the metabolic rate at rest, M_0, W;
  - the maximum working capacity, MWC, W;
  - the maximum heart rate HR_{max}, beats·min^{-1};
  - $RM = (HR_{max} - HR_0) / (MWC - M_0)$

  The (HR-M)relation is then given by:

  $$M = M_0 + (HR - HR_0) / RM \quad (3)$$

  The accuracy of this relation is a function of the validity of the measurements or estimations of HR_0, M_0, HR_{max} and MWC. Annex C proposes formulas for estimating these 4 parameters
- Table C.1 provides direct evaluations of the (HR-M) relationship for ages ranging from 20 years to 65 years and body masses ranging from 50 kg to 110 kg. The precision is then further reduced.

6.3 Validity of the (HR-M) relationship

The question relates to the relevance of the (HR-M) relation directly or indirectly derived from a cardiac stress test using the great muscular group of the legs, in the event of a work carried out with the upper limbs. Studies showed that the VO_{2max} during manual crank efforts was 23% to 30% lower than that measured for the same HR value during a cardiac stress test on bicycle or treadmill. Using that (HR-M) relation results therefore in an overestimation of the real energy expenditure.

6.4 HR components not linked to the dynamic muscular load

The heart rate at a given time may be regarded as the sum of several components:

$$HR = HR_0 + \Delta HR_M + \Delta HR_S + \Delta HR_T + \Delta HR_N + \Delta HR_\varepsilon \quad (4)$$

where

- HR_0 is the heart rate, in beats per minute, at rest in a prone position under neutral thermal conditions;
- ΔHR_M is the increase in heart rate, in beats per minute, due to dynamic muscular load, under neutral thermal conditions;
- ΔHR_S is the increase in heart rate, in beats per minute, due to static muscular work (this component depends on the relationship between the force used and the maximum voluntary force of the working muscle group);
- ΔHR_T is the increase in heart rate, in beats per minute, due to heat stress (the thermal component is discussed in ISO 9886);
- ΔHR_N is the increase in heart rate, in beats per minute, due to mental load;
- ΔHR_ε is the change in heart rate, in beats per minute, due to other factors, for example respiratory effects, circadian rhythms, dehydration.

In the presence of static muscular work, dynamic work with small muscle groups and/or mental loads, the slope of the heart rate to metabolic rate relationship can change importantly. While the ΔHR_S, ΔHR_N and ΔHR_ε components are linked to the working conditions and cannot be estimated nor removed, the thermal component ΔHR_T can be avoided by making the measurement during a period without heat stress. If this is not the case, the procedure used to correct the heart rate measurements for thermal effects is described in annex E.

If the static muscular and mental components are not negligible, the method leads to an overestimation of the true energy expenditure, which, in case of the evaluation of the strain in hot environments, will result in an increased protection of the people exposed.

Annex A (informative): Evaluation of the metabolic rate at level 1, *Screening*

This annex provides the data to classify simply and easily the mean workload for different activities for level 1, *Screening*:

Table A.1 — Classification of metabolic rate by category

Class	Range of metabolic rates W	Examples
0 Resting	100 to 125	Resting, sitting at ease
1 Low metabolic rate	125 to 235	Sedentary activity (office, dwelling, school, laboratory: writing, typing, drawing, sewing, book keeping); Standing, light activity (shopping, laboratory, light industry); Hand and arm work (small bench tools, inspection, assembly or sorting of light materials); Light arm and leg work (driving vehicle in normal conditions, operating foot switch or pedal); Machining with low power tools(drilling (small parts), milling (small parts), coil winding, sawing); Casual walking (≤ 2 km·h^{-1}) on the level, even path, solid with load ≤ 30 kg.
2 Moderate metabolic rate	235 to 360	Sustained hand and arm work (hammering in nails, filing, loading, polishing); Arm and leg work (off-road operation of lorries, tractors or construction equipment); Arm and trunk work (work with pneumatic hammer, tractor assembly, plastering); Weeding, hoeing, picking fruits or vegetables; Pushing or pulling lightweight carts or wheelbarrows; Brick-laying, 5 bricks/min; Intermittent handling of moderately heavy material; Walking (2,5 to 5 km·h^{-1}) on the level, even path, solid with load ≤ 20kg; Walking (2.5 to 3 km·h^{-1}) on levelled but irregular - unstable ground with load ≤ 20 kg; Walking (≤ 2.5 km·h^{-1}) on stable ground uphill (≤ 5%) with load ≤20 kg.
3 High metabolic rate	360 to 465	Intense arm and trunk work with hand tools or machines; Carrying heavy material, shovelling; Sledgehammer work, sawing; planning or chiselling hard wood, hand mowing, digging; Walking (5,5 to 7 km·h^{-1}) on the level, even path, solid with load ≤ 20kg; Walking (3.5 to 5 km·h^{-1}) on levelled but irregular - unstable ground with load ≤ 20 kg; Walking (2.5 to 3 km·h^{-1}) on stable ground uphill (≤ 5%) with load ≤10 kg; Pushing or pulling heavily loaded hand carts or wheelbarrows; Chipping castings; concrete block laying.
4 Very high metabolic rate	>465	Intense activity at fast to maximum pace; Working with an axe; intense shovelling or digging; Climbing stairs, ramp or ladder; Walking (> 7 km·h^{-1}) on the level, even path, solid, with or without load; Walking (> 5 km·h^{-1}) on levelled but irregular - unstable ground with or without load; Walking (> 3 km·h^{-1}) on stable ground uphill (≥ 5%) with or without load; Running (> 6 km·h^{-1}).

Annex B: (informative): Evaluation of the metabolic rate at level 2, Observation

This annex provides the data to use for estimating the metabolic rate of a specific activity as a function of its characteristics and the mean metabolic rate during a period of time.

B1. Evaluation of the metabolic rate of a specific activity

Data and formulas are presented for the evaluation of the metabolic rate

- At rest
- when walking with/without load
- when going up or down stairs and ladders
- when lifting – lowering loads
- for activities without displacement
- for other specific activities

a) Metabolic rate at rest

The metabolic rate at rest, for a seated subject can be estimated by the following expressions as a function of the body surface:

$$M_0 = 60 \cdot A_{Du} \quad \text{for men}$$
$$= 55 \cdot A_{Du} \quad \text{for women}$$

where M_0 is the metabolic rate, W;

A_{Du} is the body surface area, m² given by $A_{Du} = 0{,}007184 \cdot W_b^{0{,}425} \cdot H_b^{0{,}725}$

where

W_b is the body mass, kg;

H_b is the body height, m².

b) Metabolic rate when walking/running with/without load

- For walking at velocities < 6 km·h⁻¹: $M = (0{,}5 + 0{,}37 \cdot v_w + 0{,}2 \cdot v_w \cdot G) \cdot (W_b + L)$
- For running at velocities ≥ 6 km·h⁻¹: $M = (0{,}5 + 0{,}75 \cdot v_w + 0{,}1 \cdot v_w \cdot G) \cdot (W_b + L)$

where M is the metabolic rate, W;

L is the load carried by the person, kg;

v_w is the walking/running speed, $km \cdot h^{-1}$

G is the ground slope, %

c) Metabolic rate when going up or down stairs and ladders

Stairs – going up $M = (0{,}42 + 0{,}61 \cdot V_v) \cdot (W_b + L) = (0{,}42 + N_{steps} / 10) \cdot (W_b + L)$

– going down $M = (0{,}42 + 0{,}21 \cdot V_v) \cdot (W_b + L) = (0{,}42 + N_{steps} / 28) \cdot (W_b + L)$

Ladder – going up $M = (2{,}78 + 1{,}04 \cdot V_v) \cdot (W_b + L) = (2{,}78 + N_{rungs} / 4) \cdot (W_b + L)$

– going down $M = (1{,}98 + 0{,}17 \cdot V_v) \cdot (W_b + L) = (1{,}98 + N_{rungs} / 23) \cdot (W_b + L)$

where V_v is the vertical speed in $m \cdot min^{-1}$;

N_{steps} is the number of steps of stairs of height = 17 cm per min ($1 m \cdot min^{-1} = 5{,}88$ steps·min⁻¹);

N_{rungs} is the number of rungs of ladders of height = 25 cm per min ($1 m \cdot min^{-1} = 4$ rungs·min⁻¹).

d) Metabolic rate when lifting – lowering loads:

$$M = M_0 + \Delta M$$

Table B.1 — Formulas for the evaluation of the increase of metabolic rate ΔM (in W) when carrying - lifting - lowering loads

Task	ΔM (W)
Idle (Sit/Stand) and Hold:	$4,12 \cdot L$
Lifting (Stoop)	$(0,09 \cdot W_b + L \cdot H) \cdot F$
Lifting (Arm)	$(0,02 \cdot W_b + 1,45 \cdot L \cdot H) \cdot F$
Lifting (Squat)	$(0,14 \cdot W_b + 1,75 \cdot L \cdot H) \cdot F$
Lowering (Stoop)	$(0,08 \cdot W_b + 0,47 \cdot L \cdot H + 0,726) \cdot F$
Lowering (Arm)	$(0,03 \cdot W_b + 0,84 \cdot L \cdot H) \cdot F$
Lowering (Squat)	$(0,14 \cdot W_b + 0,49 \cdot L \cdot H) \cdot F$

where ΔM is the increase of metabolic rate, W;

F is the average rate of moves, move·min^{-1};

H is the height of lift, m.

e) Metabolic rate for activities without displacement

Table B.2 — Metabolic rate (W) for a seated subject as a function of work intensity and body segment involved

Body segment	Metabolic rate (W)		
	Light work intensity	Medium work intensity	Heavy work intensity
Both hands	125	155	170
One arm	160	200	235
Both arms	215	250	290
The body	325	440	605

Table B.3 — Increase of the metabolic rate ΔM (W) for body postures

Body posture	ΔM (W)
Sitting	0
Kneeling	20
Crouching	20
Standing	25
Standing stooped	35

f) Metabolic rate for other specific activities

Table B.4 — Metabolic rate (W) for specific activities

Activity	Metabolic rate (W)
Pushing or pulling a tip-wagon, 3,6 km·h^{-1}, even path, solid	
pushing force: 12 kg	520
pulling force: 16 kg	675
Pushing a wheelbarrow, even path, 4,5 km·h-1, rubber tyres, 100 kg load	415
Filing iron 42 file strokes/min	180
60 file strokes/min	340
Work with a hammer, 2 hands, mass of the hammer 4,4 kg, 15 strokes/min	520
Carpentry work hand sawing	395
machine sawing	180
Hand planing	540
Bricklaying, 5 bricks/min	305
Screw driving	180
Digging a trench	520
Home activities light	$2,5 \cdot M_0$
moderate	$3,5 \cdot M_0$
heavy	$4,5 \cdot M_0$

B2. Evaluation of the average metabolic rate (in watts) during a period of time

The procedure is as follows:

a) Before the observation period:

- Fill in the name and other details of the person under study.

- Identify each individual activity. The number of components to be considered will vary depending upon the complexity of the activity.
- Estimate the corresponding metabolic rate using the data and/or formulas given in section B1 of this annex.

b) During the observation period of time:
   - Fill in the diary by noting the number of the activity and the time each time the activity is changed

c) At the end of the exposure period of time
   - Calculate the total length of time spent on each activity;
   - Multiply the length of time spent on activity by the corresponding metabolic rate.
   - Add the values.
   - Divide the sum by the total length of the observation period.

Annex C (informative): Evaluation of the metabolic rate at level 3, *Analysis*

The following formulas make it possible to predict the (HR – M) relationship as a function of the characteristics of the subject.

- Maximum Working Capacity MWC, W:
  - Men: $(19.45 - 0.133 \cdot Age) \cdot W_{bl}$
  - Women: $(17.51 - 0.150 \cdot Age) \cdot W_{bl}$

  where Age is the age of the subject, years;

  W_{bl} is the lean body mass, kg.

  The lean body mass may be estimated using the following expression:
  - Men: $W_{bl} = (1{,}08 – W_b / (80 \cdot H_b^2) \cdot W_b$
  - Women: $W_{bl} = (0{,}86 – W_b / (107{,}5 \cdot H_b^2) \cdot W_b$

  where W_b is the body mass of the subject, kg

  H_b is the body height, m
- Resting metabolic rate M_0, W:
  - Men: $60 \cdot A_{Du}$
  - Women: $55 \cdot A_{Du}$
- Maximum heart rate $HR_{max,}$ beats·min^{-1}:

  Men and women: $208 - 0{,}7 \cdot Age$
- Heart rate at rest HR_0, beats·min^{-1}:

  The heart rate value exceeded during 99% of the time of the HR recording, provided that the subject was at rest in a neutral environment at least 5 min during the recording.

The mean metabolic rate (M_m) over the recorded period of time may then be derived from the mean heart rate HR_m using the following expression:

$$M = M_0 + (HR_m – HR_0) / RM$$

where:

$$RM = (HR_{max} − HR_0) / (MWC − M_0)$$

Assuming that HR_0 = 70 beats·min^{-1} and M_0 = 105 W, table C.1 provides the increase in heart rate per unit of metabolic rate RM of the relation M = (HR – 70) / RM + 105 predicted as a function of the age and the weight of the worker (women and men) for estimating the metabolic rate from heart rate recordings over a representative period in accordance with the method given for level 3, *Analysis*:

Table C.1 — Value of (1 / RM) in the relation M = (HR – 70) / RM + 100 between metabolic rate (in W) and heart rate (in beats per min), predicted as a function of the age and the lean weight of the subject (for women and men)

	Lean weight (kg)						
Age (Years)	50	60	70	80	90	100	110
Women							
20	5.04	6.21	7.38	8.55	9.73	10.90	12.07
25	4.88	6.02	7.16	8.31	9.45	10.59	11.73
30	4.71	5.82	6.93	8.04	9.15	10.26	11.38
35	4.52	5.60	6.68	7.76	8.84	9.92	11.00
40	4.32	5.37	6.42	7.46	8.51	9.55	10.60
45	4.11	5.12	6.13	7.14	8.15	9.16	10.17
50	3.89	4.86	5.83	6.80	7.78	8.75	9.72
55	3.65	4.58	5.51	6.44	7.37	8.30	9.23
60	3.39	4.28	5.16	6.05	6.94	7.82	8.71

65	3.11	3.95	4.79	5.63	6.47	7.31	8.15
Men							
20	5.96	7.32	8.67	10.03	11.38	12.73	14.09
25	5.86	7.20	8.54	9.88	11.21	12.55	13.89
30	5.75	7.07	8.39	9.72	11.04	12.36	13.68
35	5.64	6.94	8.24	9.55	10.85	12.15	13.46
40	5.51	6.80	8.08	9.37	10.65	11.94	13.22
45	5.38	6.65	7.91	9.18	10.44	11.70	12.97
50	5.24	6.49	7.73	8.97	10.21	11.46	12.70
55	5.09	6.31	7.53	8.75	9.97	11.19	12.41
60	4.93	6.13	7.32	8.52	9.71	10.91	12.10
65	4.76	5.93	7.10	8.26	9.43	10.60	11.77

Annex D (informative): Correction of the heart rate measurements for thermal effects

Figure E1 shows the procedure to be followed for the correction of the heart rate measurements for thermal effects. In this example, an experiment with 10 minutes of rest, followed by 20 minutes of work and 30 minutes of rest is considered.

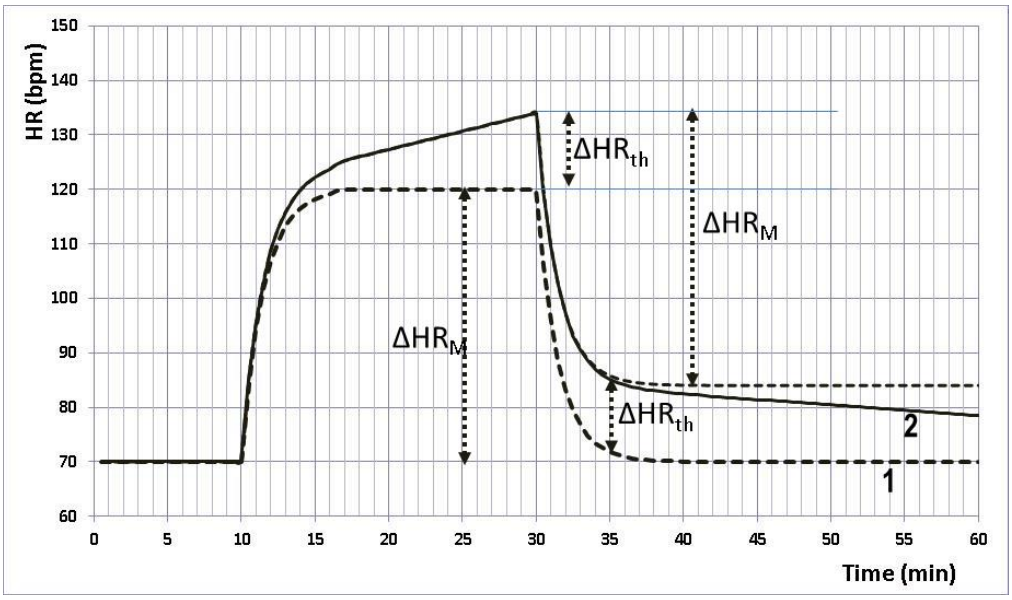

Figure E1: Correction of the heart rate measurement for thermal effects

Curve 1 describes the evolution of heart rate as a function of time when the task is performed in an environment without thermal constraint: the HR at rest of 70bpm increases, as an example, to 120 bpm (ΔHR_M = 50bpm) during the work phase(steady state reached after 5 minutes) and decreases back to 70bpm during the final rest period (steady state again reached after 5 minutes).

Curve 2 describes the evolution of heart rate in the same experiment performed in a hot environment: during the work phase, the heart rate increases this time, for example, to 134 bpm: $\Delta HR = \Delta HR_M + \Delta HR_{th}$

After 5 minutes of rest in an environment without thermal constraint, the elevation of HR of metabolic origin (ΔHR_M = 50bpm) will be recuperated while the increase of thermal origin (14 bpm in this example) will be recuperated very slowly at a rate depending upon the recovery conditions.

The HR recorded after 5 minutes of recovery is therefore equal to $HR_0 + \Delta HR_{th.}$

In the case of constant metabolic rate during the work phase, it can be assumed that the thermal component ΔHR_{th} increases linearly as a function of time (although this is correct only as long as the body temperature increases linearly). The metabolic rate can therefore be estimated from the average heart rate during the work phase minus half of the elevation of HR measured at the 5th minute of recovery.