Ergonomics of the thermal environment
Evaluation of metabolic rate

1. Scope

The metabolic rate, as a conversion of chemical into mechanical and thermal energy, measures the energetic cost of muscular load and gives a quantitative estimate of the activity. Metabolic rate is an important determinant of the comfort or the strain resulting from exposure to a thermal environment. In particular, in hot climates, the high levels of metabolic heat production associated with muscular work aggravate heat stress, as large amounts of heat need to be dissipated, mostly by sweat evaporation. On the contrary, in cold environments, they help to compensate for excessive heat losses and therefore reduce the cold strain

This International Standard specifies different methods for the evaluation of metabolic rate in the context of ergonomics of the climatic working environment. It can also be used for other applications — for example, the assessment of working practices, energetic cost of specific jobs or sport activities, the total cost of an activity, etc.

The estimations, tables and other data included in this International Standard concern the general working population. Users should make appropriate corrections when they are dealing with special populations including children, aged persons, people with physical disabilities, etc.

2. 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 it will vary as a function of the weight of the subject (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}.

3. 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 here:

- Level 1, *Screening*: a method simple and easy to use is presented to quickly characterize 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*: Three methods are presented. They require very specific measurements made by experts:
  - in 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 is the so-called doubly labelled water method aiming at characterizing the average metabolic rate over much longer periods (1 to 2 weeks);
  - method 4C is a direct calorimetry method.

Table 1 — Levels for the evaluation of the metabolic rate

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

4. 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.

- The 2 methods at level 1, *Screening*, provide only a rough estimate and there is considerable scope for error. This limits their accuracy considerably. At this level, an inspection of the work place is not necessary.
- The accuracy of the time and activity procedure at level 2, *Observation*, depends strongly of the level of training of the observer and his knowledge of the working conditions: the possibility for errors is high.
- When using 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 (evaluation of gas volume and oxygen fraction).

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;

5. 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.

6. Level 2, *Observation*

6.1. Evaluation of metabolic rate for a given activity

Annex B gives the mean values and formulas for estimating the metabolic rate in watts

- At rest;
- When walking with/without load at < 6 $km \cdot h^{-1}$;
- When running with/without load at > 6 $km \cdot h^{-1}$;
- 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;

6.2. 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 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.

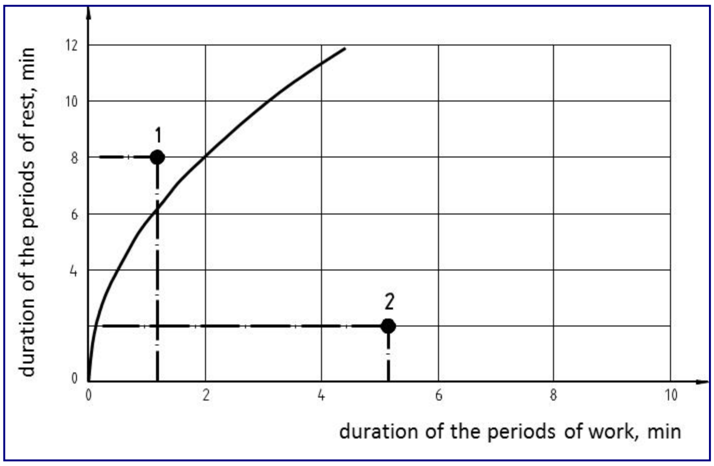
6.3. Influence of the length of rest periods and work periods

The data in Annex B cannot be used for the evaluation of the average metabolic rate for working conditions with a sequence of short periods of activity and long rest periods. In this case, the procedure described in 7.2 would lead to an underestimation of the metabolic rate, known as the Simonson effect. The limit of validity of combinations of work and rest periods is shown by the curve in Figure 1. Case 1 concerns a cycle of 8 min of rest and 1 min (see figure 1) of work. In this case, the technique described in 6.2 would lead to an underestimation of the metabolic rate and the data in Annex B cannot be used. For work-rest cycles such as in case 2, the procedure described in 7.2 can be used with the indicated accuracy.

Figure 1 only applies if there is no physical workload during the rest periods.

An increase in the metabolic rate due to this effect depends on the type of work and the muscle groups used. Further information on this problem is not given here, because of its complexity and because of its low relevancy at this level of evaluation.

Figure 1. Limit of validity of combinations of work and rest periods when estimating metabolic rate



7. Level 3, *Analysis*

7.1. Evaluation of metabolic rate using heart rate

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

$$HR = HR_0 + \Delta HR_M + \Delta HR_S + \Delta HR_T + \Delta HR_N + \Delta HR_\varepsilon \qquad (2)$$

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 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 less complex than the measurement of oxygen consumption.

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 (see ISO 9886).

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.

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.

7.2. Relationship between heart rate and metabolic rate

The relationship between heart rate and metabolic rate can be determined during a cardiac stress test where the heart rate and corresponding oxygen consumption or physical work performed are recorded during dynamic muscular work at increasing load stages. As the type of muscular work (cycle ergometer, step test, treadmill) and the sequence and duration of the load stages have an influence on both parameters, it is necessary to use a standardized procedure.

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

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

where

- M is the metabolic rate, W;
- M_0 is the metabolic rate at rest, W;
- HR is the heart rate measured, beats·min^{-1};
- HR_0 is the heart rate at rest, under neutral thermal conditions, beats·min^{-1};
- RM is the increase in heart rate per unit of metabolic rate, beats·min^{-1}·W^{-1} ;

This relationship is used to derive the metabolic rate from the measured heart rate.

When this expression is derived from HR and M measurements during an experiment, the precision can be estimated at about 10 %.

With a further loss of accuracy, the expression can 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};
- $RM = (HR_{max} - HR_0) / (MWC - M_0)$ (4)

Annex C provides formulas for the prediction of the MWC as a function of age (A, in years) and body mass (W_b, in kg, of HR_{max} as a function of age, as well as for the evaluation of M_0 and HR_0. 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, in that case, is further reduced.

8. Level 4, Expertise

8.1. Evaluation of metabolic rate by measurement of oxygen consumption rate

8.1.1. Partial and integral methods

The metabolic rate can be evaluated by two main methods:

- The partial method, to be used for light and moderately heavy work;
- The integral method, to be used for heavy work of short duration.

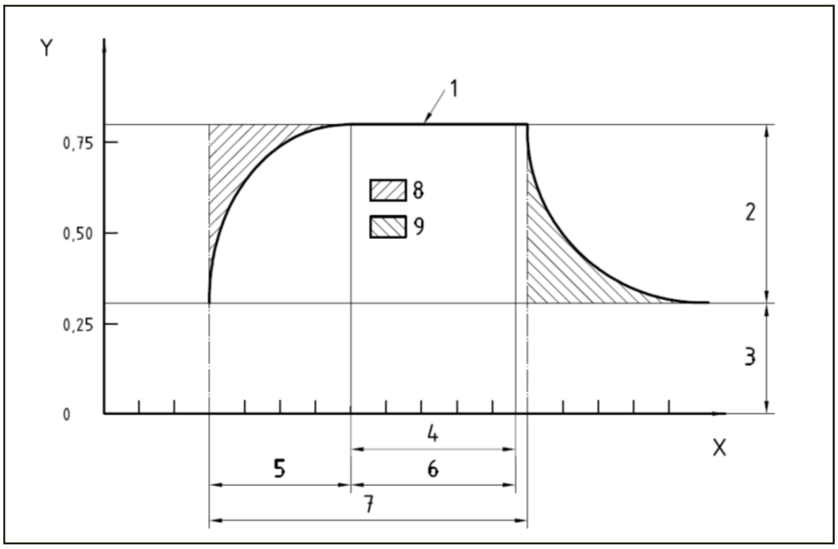
The use of these two methods is justified as follows:

- In the case of light and moderate work, the oxygen uptake reaches a steady state equal to the oxygen requirement after a short period of work.
- In the case of heavy work, the oxygen requirement is above the long term limit of aerobic power and, in the case of very heavy work, above the maximum aerobic power. During heavy work, the oxygen uptake cannot satisfy the oxygen requirement. The oxygen deficit is balanced after work has ceased. Thus, the measurement includes the work period and the subsequent rest period. The integral method shall be used for an oxygen consumption rate of more than 60 litres of oxygen per hour (60 l_{O_2}·h^{-1}), equivalent to 1 l_{O_2}·min^{-1}.

Figure 2 shows the procedure to be followed when using the partial method.

Since the steady state is only reached after 3 min to 5 min, the collection of expired air starts after about 5 min (preliminary period), without interrupting the work. The work continues for 5 min to 10 min (main period). Air collection can be either complete (for example with a Douglas bag) or by regular sampling (for example with a gas meter). It is stopped when work ceases.

Figure 2 — Measurement of metabolic rate using the partial method

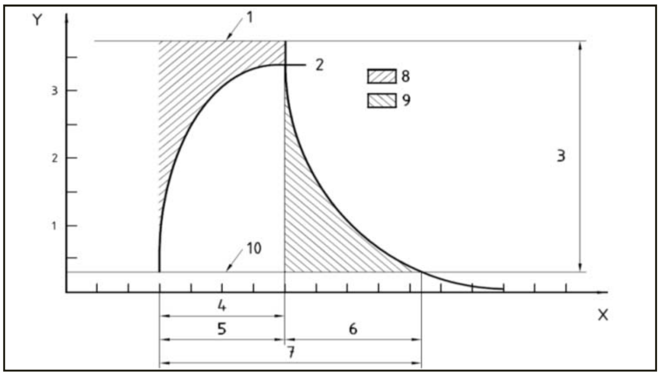


Key

X	time min	5	preliminary period
Y	oxygen uptake, l/min	6	main period
1	O_2 requirement	7	work period
2	increase in metabolic rate due to work	8	O_2 deficit
3	baseline metabolic rate	9	O_2 debt repayment
4	measurement period		

With the integral method (see Figure 3), expired air collection is started immediately at the beginning of the work period and the work is continued for a certain time, usually for not more than 2 min to 3 min (main period). At the end of the work period, the subject is asked to sit down and air collection is continued until the resting value is reached. During this recovery period, the oxygen debt incurred during the work is repaid. Since the measurement includes the working (main period) and sitting (recovery period) activity, the metabolic rate needed for sitting has to be subtracted from the measured value in order to obtain the metabolic rate related to the work alone.

It is necessary to record the course of the work (time and motion study) and the frequency of repeated activities for further evaluation of the results and for comparison of the metabolic rate with data in the literature. Examples of the calculation of metabolic rate are given in Annex D.



Key

X	time, min		
Y	oxygen uptake, l/min		
1	O_2 requirement	6	recovery period
2	maximum aerobic power	7	measurement period
3	increase in metabolic rate due to work	8	O_2 deficit
4	work period	9	O_2 debt repayment
5	main period	10	baseline metabolic rate

Figure 3 — Measurement of metabolic rate using the integral method

8.1.2. Evaluation of metabolic rate from oxygen consumption rate

Since very small amounts of oxygen can be stored in the human body, it must be continuously taken up from the atmosphere by respiration. Muscles can work for a short time without being directly provided with oxygen (anaerobic work) but, for longer periods of work, oxidative metabolism is the major energy source.

The metabolic rate can be evaluated, therefore, by measuring oxygen consumption rate. The energetic equivalent (EE) of oxygen is used to convert oxygen consumption rate into metabolic rate.

The energetic equivalent depends on the type of metabolism that is indicated by the respiratory quotient (RQ). In the evaluation of the metabolic rate, the use of a mean RQ of 0,85 and thereby of an EE of 5,68 $W \cdot h \cdot l_{O_2}^{-1}$ is often sufficient. In that case, measurement of the carbon dioxide production rate is not required. The maximum possible error is ± 3,5 %, but generally the error will not exceed 1 %.

The metabolic rate can be evaluated from the following equations:

$$RQ = \frac{\dot{V}_{CO_2}}{\dot{V}_{O_2}} \quad (5)$$

$$EE = (0{,}23RQ + 0{,}77)5{,}88 \quad (6)$$

$$M = EE \times \dot{V}_{O_2} \quad (7)$$

where

- RQ is the respiratory quotient;
- V_{O_2} is the oxygen consumption rate, $l_{O_2} \cdot h^{-1}$;
- V_{CO_2} is the carbon dioxide production rate, $l_{CO_2} \cdot h^{-1}$;
- EE is the energetic equivalent, in watt hours per litre of oxygen ($W \cdot h \cdot l_{O_2}^{-1}$);
- M is the metabolic rate, W.

8.1.3. Evaluation of oxygen uptake

The procedure for determining the oxygen uptake is described in the following subclauses.

8.1.3.1. Calculation of the STPD reduction factor

The evaluation of the oxygen uptake requires the following data to be measured or recorded:

a. the personal data: sex, weight, height, age;
b. the method of measurement;
c. the duration of the measurement: partial method or integral method as described in 9.1.1;
d. the atmospheric pressure;
e. the volume of air expired;
f. the temperature of the expired air;
g. the fraction of oxygen in the expired air;
h. the fraction of carbon dioxide in the expired air if evaluation of RQ is required.

The gas volume shall be related to $\theta = 0$ °C, $p = 101{,}3$ kPa (normal atmospheric pressure) for a dry gas (i.e. STPD conditions: standard temperature and pressure, dry). As the collected air is saturated with water vapour (the saturation pressure of which is a function of temperature) and its temperature is determined by ambient temperature (ATPS conditions: atmospheric temperature and pressure, saturated), the reduction factor f can be calculated from the following equation using the partial pressure of water vapour (see Table 2).

$$f = \frac{273 \times (p - p_a)}{(273 + \theta) \times 101{,}3} \quad (8)$$

where

f is the STPD reduction factor;

p is the measured atmospheric pressure, kPa;

θ is the temperature of the expired air, °C, measured in the gas meter or assumed the ambient temperature when a Douglas bag is used;

p_a is the water vapour partial pressure, kPa, corresponding to the temperature θ. (Table 2).

Table 2 — Saturated water vapour pressure (in kPa) for temperatures between 10 °C and 37 °C (1 °C steps)

Temperature (°C)	0	1	2	3	4	5	6	7	8	9
10	1,23	1,31	1,40	1,50	1,60	1,70	1,82	1,94	2,06	2,20
20	2,34	2,49	2,64	2,81	2,98	3,17	3,36	3,56	3,78	4,00
30	4,24	4,49	4,75	5,03	5,32	5,62	5,94	6,27	—	—

If the collected expired air is heated up by the environment to a temperature in excess of 37 °C, the saturated water vapour pressure of 6,27 kPa at the temperature of 37 °C shall be used.

8.1.3.2. Calculation of the expired volume at STPD

$$V_{exSTPD} = V_{exATPS} \cdot f \quad (9$$

where

V_{exSTPD} is the expired volume, l, at STPD;

V_{exATPS} is the expired volume, l, at ATPS;

f is as defined in 9.1.3.1

8.1.3.3. Calculation of the volume flow rate

$$\dot{V}_{ex} = \frac{V_{ex\,STPD}}{t} \quad (10)$$

Where:

V_{ex} is the volume flow rate, $l \cdot h^{-1}$;

t is the test duration, h, i.e. the main period for the partial method and the main and recovery periods for the integral method.

8.1.3.4. Calculation of oxygen consumption rate

$$V_{O_2} = V_{ex} \cdot (0{,}209 - F_{O_2}) \quad (11)$$

where

V_{O_2} is the oxygen consumption rate, $l_{O_2} \cdot h^{-1}$;

F_{O_2} is the fraction of oxygen in the expired air.

8.1.3.5. Calculation of carbon dioxide production rate

$$V_{CO_2} = V_{ex} \cdot (F_{CO_2} - 0{,}0003) \quad (12)$$

where

V_{CO_2} is the carbon dioxide production rate, $l_{CO_2} \cdot h^{-1}$;

F_{CO_2} is the fraction of carbon dioxide in the expired air.

8.1.3.6. The effect of contraction of the expired volume

The inspired and expired volumes are not equal if RQ is not equal to 1. Contraction can be taken into account using the following equations:

$$V_{O_2} = V_{ex} [0{,}265(1 - F_{O_2} - F_{CO_2}) - F_{O_2}] \quad (13)$$

$$V_{CO_2} = V_{ex} [F_{CO2} - (1 - F_{O_2} - F_{CO_2}) \, 0{,}380 \cdot 10^{-3}] \quad (14)$$

8.1.4. Calculation of metabolic rate

8.1.4.1. Partial method

The metabolic rate is evaluated from the oxygen uptake and the energetic equivalent using Equation (7).

8.1.4.2. Integral method

The following calculation shall be carried out when using the integral method, as only the difference between the total measured metabolic rate and the known metabolic rate for the activity during the recovery period, i.e. sitting, is related to the work itself.

First, the metabolic rate is derived as in the partial method, and then the following conversion is performed:

$$M = \left(M_{\text{p}} \times \frac{t_{\text{m}} + t_{\text{r}}}{t_{\text{m}}} \right) - \left(M_{\text{s}} \times \frac{t_{\text{r}}}{t_{\text{m}}} \right) \quad (15)$$

where

- M is the metabolic rate, W;
- M_p is the metabolic rate, W, for the partial method;
- M_s is the metabolic rate, W, when seated;
- t_m is the length of the main period, min;
- t_r is the length of the recovery period, min.

8.2. The doubly labelled water method for long term measurements

This subclause describes only the principle of the method.

After collection of a baseline urine sample, the subject drinks an accurately weighed oral loading dose of $^{2}H_2{}^{18}O$.

Deuterium (^{2}H) labels the body water pool and its rate of disappearance from the body (k_2) provides a measure of water turnover (r_{H2O}).

The ^{18}O labels both the water and bicarbonate pools which are in rapid equilibrium through the carbonic anhydrase reaction.

The rate of disappearance of ^{18}O (k_{18}) provides a measure of the combined turnover of water and bicarbonate ($r_{H2O} + r_{CO_2}$).

Therefore, bicarbonate turnover (i.e. the subject's carbon dioxide production rate) can be calculated as the difference between the two rate constants ($k_{18} - k_2$).

Carbon dioxide production rate can be converted to energy expenditure using classical indirect calorimetric calculations. The initial dilution of the isotopes provides a measure of the ^{2}H and ^{18}O spaces, which are useful in calculating body composition.

The method requires the measurements to be made over at least two biological half-lives of the isotopes: in children, the minimum test duration is about 6 days, in normal adults it is about 12 days to 14 days, and in the elderly it may be longer.

The doubly labelled water (DLW) method has been cross-validated against whole-body calorimetry and intake/balance procedures in a number of studies. None of these has recorded a significant discrepancy between DLW and the comparator method in subjects under steady-state conditions. The overall precision of the method is about ± 5 %, depending on circumstances.

Although the DLW technique is simple in concept, there are a number of complex details that must be thoroughly understood by the user.

8.3. Direct calorimetry — Principle

Direct calorimetry measures energy expenditure as the rate at which heat is lost from the body to the environment. This heat is transferred through non evaporative heat loss (radiation, convection, conduction) and through the evaporation of water. Direct calorimetry is usually a whole-body measurement made within the confines of a chamber, but has also been carried out using a heat exchanging body suit. The non-evaporative components of heat exchange are measured passively in terms of the temperature gradient across the walls of a poorly insulated chamber (gradient layer calorimetry), or actively by measuring the rate at which heat must be extracted from a chamber to avoid heat loss through well insulated walls (heat sink calorimetry). Evaporative heat loss affects the moisture content of the environment and requires independent measurement. It is measured either by condensing the water appearing in the chamber and measuring the latent water content of the air (without condensation) or calculating its associated latent heat of evaporation. Total heat loss is estimated as the sum of the evaporative and non-evaporative components.

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

This annex provides the data to classify for 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	Light manual work (writing, typing, drawing, sewing, book keeping); Hand and arm work (small bench tools, inspection, assembly or sorting of light materials); Arm and leg work (driving vehicle in normal conditions, operating foot switch or pedal). Standing drilling (small parts); Milling machine (small parts); Coil winding; Small armature winding; Machining with low power tools; Casual walking (speed up to 2,5 km·h^{-1}).
2 Moderate metabolic rate	235 to 360	Sustained hand and arm work (hammering in nails, filing); Arm and leg work (off-road operation of lorries, tractors or construction equipment); Arm and trunk work (work with pneumatic hammer, tractor assembly, plastering); Intermittent handling of moderately heavy material, Weeding, hoeing, picking fruits or vegetables; Pushing or pulling lightweight carts or wheelbarrows Walking at a speed of 2,5 km·h^{-1} to 5,5 km·h^{-1}, forging).
3 High metabolic rate	360 to 465	Intense arm and trunk work; Carrying heavy material; shovelling; Sledgehammer work; sawing; planning or chiselling hard wood; hand mowing; digging; Walking at a speed of 5,5 km·h^{-1} to 7 km·h^{-1}. Pushing or pulling heavily loaded hand carts or wheelbarrows; Chipping castings; concrete block laying.
4 Very high metabolic rate	>465	Very intense activity at fast to maximum pace; Working with an axe; intense shovelling or digging; Climbing stairs, ramp or ladder; Walking quickly with small steps; running; Walking at a speed greater than 7 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

B1.1.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:

$M_0 = 60 \cdot A_{Du}$ for men

$= 55 \cdot A_{Du}$ 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.

B1.2.Metabolic rate when walking/running with/without load at

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

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, %

B1.3.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 ($1 m \cdot min^{-1} = 5{,}88$ $steps \cdot min^{-1}$);

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

B1.4.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.

B1.5.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

B1.6.Metabolic rate for other specific activities

Table B.4 — Metabolic rate 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 (M – HR) relationship as a function of the characteristics of the subject.

- Maximum Working Capacity MWC, W:
  - Men: $(18{,}0 - 0{,}1 \cdot Age) \cdot W_b$
  - Women: $(15{,}5 - 0{,}1 \cdot Age) \cdot W_b$

  where:

  Age is the age of the subject, years;

  W_b is the body mass, kg.
- 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 weight of the subject (for women and men)

	Weight (kg)						
Age (Years)	50	60	70	80	90	100	110
Women							
20	4,60	5,69	6,77	7,86	8,95	10,04	11,13
25	4,52	5,60	6,68	7,76	8,84	9,92	11,00
30	4,44	5,51	6,58	7,65	8,72	9,79	10,85
35	4,36	5,42	6,48	7,53	8,59	9,65	10,70
40	4,27	5,32	6,36	7,41	8,45	9,50	10,55
45	4,18	5,21	6,24	7,28	8,31	9,34	10,38
50	4,08	5,10	6,12	7,14	8,16	9,17	10,19
55	3,97	4,97	5,98	6,98	7,99	8,99	10,00
60	3,85	4,84	5,83	6,82	7,81	8,80	9,79
65	3,73	4,70	5,68	6,65	7,62	8,59	9,57
Men							
20	5,60	6,90	8,19	9,48	10,77	12,06	13,35
25	5,56	6,85	8,13	9,42	10,71	11,99	13,28
30	5,51	6,79	8,08	9,36	10,64	11,92	13,21
35	5,46	6,74	8,02	9,30	10,57	11,85	13,13
40	5,41	6,68	7,95	9,23	10,50	11,77	13,05
45	5,35	6,62	7,89	9,15	10,42	11,69	12,96
50	5,29	6,55	7,82	9,08	10,34	11,60	12,86
55	5,23	6,48	7,74	8,99	10,25	11,51	12,76
60	5,16	6,41	7,66	8,91	10,16	11,41	12,66
65	5,08	6,32	7,57	8,81	10,05	11,30	12,54

Annex D (informative)

Evaluation of the metabolic rate at level 4, *Expertise* — Examples of the calculation of metabolic rate based on measured data

An example of the calculation of metabolic rate for both the partial and the integral methods is given below. A gas meter was used to collect the expired gases.

D.1 Calculation of metabolic rate by the partial method

D.1.1 Personal data

Sex: male Age: 35 years Height: 1,75 m Weight: 75 kg A_{Du}: 1,90 m^2

D.1.2 Duration of measurement

Preliminary period: 0,05 h (3 min)

Main period: 0,2 h (12 min)

D.1.3 Atmospheric pressure: p = 100,8 kPa

D.1.4 Measured values

D.1.4.1 Gas meter

Correction factor for the gas meter = 0,998

Temperature of the gas meter (i.e. temperature θ of the expired air) = 26,8 °C

Final reading of the gas meter = 7981,2 l

Initial reading of the gas meter = 7 775,0 l

Ventilation = 206,2 l

D.1.4.2 Fraction of oxygen and carbon dioxide in the expired air

Fraction of oxygen F_{O_2} 0,162

Fraction of carbon dioxide F_{CO_2} 0,042

D.1.5 Calculation of the expired volume

The expired volume V_{exATPS} is calculated from the ventilation and the correction factor of the gas meter:

$V_{exATPS} = 206,2 \cdot 0,998 = 205,8$ l

The STPD reduction factor is calculated from Equation (8):

$f = 273 \cdot (100,8 - 3,52) / ((273 + 26,8) \cdot 101,3) = 0,874$

Thus

$V_{exSTPD} = V_{exATPS} \cdot f = 205,8 \cdot 0,874 = 179,9$ l

D.1.6 Calculation of the volume flow rate

$V_{ex} = V_{exSTPD} / t = 179,9 / 0,2 = 899,5\ l \cdot h^{-1}$

D.1.7 Calculation of the oxygen consumption rate

$V_{O_2} = V_{ex} \cdot (0,209 - F_{O_2}) = 899,5(0,209 - 0,162) = 42,3\ l_{O_2} \cdot h^{-1}$

D.1.8 Calculation of the carbon dioxide production rate

$V_{CO_2} = V_{ex} \cdot (F_{CO_2} - 0,0003) = 899,5(0,042 - 0,000\ 3) = 37,5\ l_{CO_2} \cdot h^{-1}$

D.1.9 Consideration of the shrinkage of the expired volume

$V_{O_2} = V_{ex} \cdot [0,265 \cdot (1 - F_{O_2} - F_{CO_2}) - F_{O_2}]$

$= 899,5 \cdot [0,265 \cdot (1 - 0,162 - 0,042) - 0,162] = 44,0\ l_{O_2} \cdot h^{-1}$

$V_{CO_2} = V_{ex} \cdot [F_{CO_2} - 0,00038\ (1 - F_{O_2} - F_{CO_2})]$

$= 899,5 \cdot [0,042 - 0,00038 \cdot (1 - 0,162 - 0,042)] = 37,5\ l_{CO_2} \cdot h^{-1}$

D.1.10 Calculation of the metabolic rate

$RQ = V_{CO_2} / V_{O_2} = 37{,}5/44{,}0 = 0{,}852$

$EE = (0{,}23 \cdot RQ + 0{,}77) \cdot 5{,}88 = 5{,}68\ W \cdot h \cdot l_{O_2}^{-1}$

$M = EE \cdot V_{O_2} = 5{,}68 \cdot 44{,}0 = 250\ W$

D.2 Calculation of the metabolic rate using the integral method

Contraction of the expired volume and calculation of RQ using CO_2 production are omitted in this example, because these corrections have no significant effect on the final result.

D.2.1 Personal data: same as in D1.1

D.2.2 Duration of measurement

Main period = 0,05 h (3 min)
Recovery period = 0,15 h (9 min)
Test duration = 0,2 h (12 min)

D.2.3 Atmospheric pressure: p = 100,8 kPa

D.2.4 Measured values

D.2.4.1 Gas meter

Correction factor for the gas meter = 0,998
Temperature of the gas meter = 26,8 °C
Final reading of the gas meter = 5877,5 l
Initial reading of the gas meter = 5707,0 l
Ventilation = 170,5 l

D.2.4.2 Fraction of oxygen in the expired air

Fraction of oxygen $F_{O_2} = 0{,}155$

D.2.5 Calculation of the expired volume

The expired volume V_{exATPS} is calculated from the ventilation and the correction factor of the gas meter:

$V_{exATPS} = 170{,}5 \cdot 0{,}998 = 170{,}2\ l$

The V_{exSTPD} reduction factor has the same value as in D.1.5. Thus

$V_{exSTPD} = V_{exATPS} \cdot f = 170{,}2 \cdot 0{,}874 = 148{,}8\ l$

D.2.6 Calculation of the volume flow rate

$V_{ex} = V_{exSTPD} / t = 148{,}8/0{,}2 = 744{,}0\ l \cdot h^{-1}$

D.2.7 Calculation of the oxygen consumption rate

$V_{O_2} = V_{ex} \cdot (0{,}209 - F_{O_2}) = 40{,}2\ l_{O_2} \cdot h^{-1}$

D.2.8 Calculation of the metabolic rate

Using a mean RQ of 0,85 and thereby an energetic equivalent of 5,68 $W \cdot h / l_{O_2}$, the following result is obtained:

$M = EE \cdot V_{ex} = 5{,}68 \cdot 40{,}2 = 228\ W$

In order to relate the metabolic rate to the main period, the conversion according to Equation (15) is performed.

The metabolic rate for sitting being $60 \cdot 1{,}9 = 114\ W$

$M = 228 \cdot 0{,}2 / 0{,}05 - 114 \cdot 0{,}15 / 0{,}05 = 570\ W$

Annex E (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.

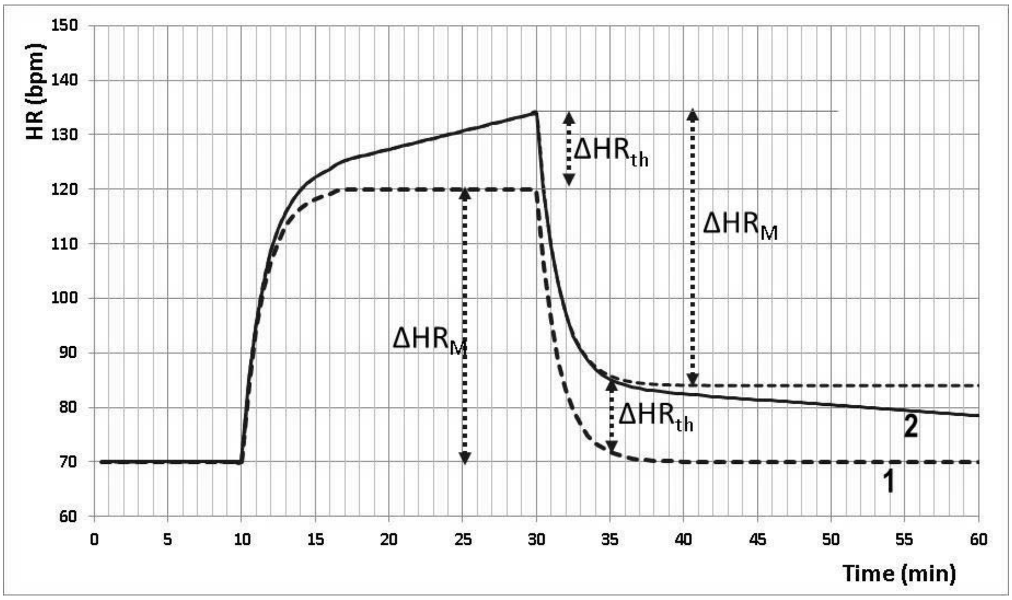

Figure E1: Correction of the heart rate measurement for thermal effects

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.