
**Ergonomics of the thermal
environment — Determination of
metabolic rate**

*Ergonomie de l'environnement thermique — Détermination du
métabolisme énergétique*

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 159, *Ergonomics*, Subcommittee SC 5, *Ergonomics of the physical environment*, in collaboration with the European Committee for Standardization (CEN) Technical Committee CEN/TC 122, *Ergonomics*, in accordance with the Agreement on technical cooperation between ISO and CEN (Vienna Agreement).

This third edition cancels and replaces the second edition (ISO 8996:2004), which has been technically revised.

The main changes to the previous edition are as follows:

- The metabolic rate associated with a given task and estimated using the methods described in this document is expressed in watts.
- At level 1, Screening, the method classifying metabolic rate according to occupation has been removed, and revised procedures are provided for the evaluation of metabolic rate for given activities (level 2, Observation) and when using heart rate (level 3, Analysis).
- The accuracy of the methods for estimating the metabolic rate has been reevaluated in light of the recent literature and consequently the integral method is no longer recommended at level 4, Expertise.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

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, high levels of metabolic heat production help to compensate for excessive heat losses through the skin and therefore reduce the cold strain.

The estimations, tables and other data included in this document concern the general working population. Corrections can be needed when dealing with special populations, including children, aged persons or people with physical disabilities. Personal characteristics, such as body mass, may be used if the body is moved due to walking or climbing ([Annex B](#)). Gender, age and body mass are considered in [Annex C](#) for the evaluation of the metabolic rate from heart rate.

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Ergonomics of the thermal environment — Determination of metabolic rate

1 Scope

This document specifies different methods for the determination of metabolic rate in the context of ergonomics of the thermal working environment. It can also be used for other applications, e.g. the assessment of working practices, the energetic cost of specific jobs or sport activities and the total energy cost of an activity. The methods are classified in four levels of increasing accuracy: level 1, Screening, with a table giving examples of activities with low, moderate and high metabolic rates; level 2, Observation, where the metabolic rate is estimated by a time and motion study; level 3, Analysis, where the metabolic rate is estimated from heart rate recordings or accelerometers measurements; and level 4, Expertise, where more sophisticated techniques are described. The procedure to put into practice these methods is presented and the uncertainties are discussed.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

No terms and definitions are listed in this document.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at <https://www.iso.org/obp>
- IEC Electropedia: available at <https://www.electropedia.org/>

4 The units

The metabolic rate associated with a given task and estimated using the methods described in this document shall be expressed in watts.

If the task does not involve displacements, the metabolic rate will not vary as a function of the size and the weight of the subject. If it involves displacements, then the weight of the person shall be taken into account (see [Annex B](#)).

As the heat associated to this metabolic rate and produced inside the body leaves it essentially through the skin, thermophysicologists usually express the metabolic rate per unit of body surface area in $W \cdot m^{-2}$ and the estimations of thermal comfort and thermal constraints described in ISO 7243, ISO 7730, ISO 7933 and ISO 11079 are done using metabolic rates in $W \cdot m^{-2}$.

5 The four 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 per cent) that it is assumed to be nil. This means that the energy spent while working is assumed to be completely transformed into heat. For the purposes of this document, the metabolic rate is assumed to be equal to the rate of heat production.

[Table 1](#) lists the different approaches presented in this document 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 formulae 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 its relationship with heart rate under defined conditions. Another method at this level is based on the use of accelerometry to record body movement.
- Level 4, Expertise: three methods are presented. They require very specific measurements made by experts:
 - Method 4A: the oxygen consumption measured over short periods (10 min to 20 min);
 - Method 4B: the so-called doubly labelled water method aiming at characterizing the average metabolic rate over much longer periods (1 week to 2 weeks);
 - Method 4C: a direct calorimetry method.

Table 1 — Levels for the evaluation of the metabolic rate

Level	Method	Uncertainty	Inspection of the work place
1 Screening	Classification according to activity	Rough information Very great risk of error	Not required
2 Observation	Time and motion study	High error risk Uncertainty: ± 20 %	Required
3 Analysis	3A: Heart rate measurement under defined conditions	Medium error risk Uncertainty: ± 10 to 15 %	Study required to determine a representative period
	3B: Accelerometry	High risk of error	
4 Expertise	4A: Measurement of oxygen consumption	Errors within the limits of the accuracy of the measurement or of the time and motion study, if assumptions (9.1.1, 9.1.4) are met Uncertainty: ± 5 %	Time and motion study necessary
	4B: Doubly labelled water method		Inspection of work place not required, but leisure activities shall be evaluated.
	4C: Direct calorimetry	Errors within the limits of the accuracy of the measurement or of the time and motion study Uncertainty: ± 5 %	Inspection of work place not required.

The uncertainty of each method is provided in [Table 1](#) as coefficient of variation (CV), i.e. the percentage ratio of the standard deviation to the mean, and should be understood as indicative values, which can increase due to non-controlled influences discussed as follows. The accuracy at each level is discussed in describing the methods in [Clauses 6 to 9](#). It increases from level 1 to level 4 and, as far as possible, the most accurate method should be used.

Attention should be drawn to various sources of variations:

- 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 cold conditions, an increase of up to 400 W can be observed when shivering occurs.
- Heavy clothing can also increase the metabolic rate by 20 % or more, by increasing the weight carried by the subject and decreasing the subject's ease of movement.

The accuracy depends also upon the following:

- 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.
- The number of measurements: repetition is one method to reduce random measurement error. Based on the CV of an unbiased estimate, the formula $(\text{actual CV}/\text{requested CV})^2$ approximates the required number of repetitions (Vogt et al., 1976). This implies that in order to achieve a 10 % uncertainty level, two measurements would be necessary with a method actually providing 14 %, while four repetitions would be needed with 20 % uncertainty, and nine with 30 %. Of course, this improvement will only work if no systematic errors are inherent. It is recommended that the metabolic rate from all the samples is evaluated and the mean value adopted as the metabolic rate of the condition studied.

6 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 and 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.

An inspection of the work place is not necessary.

The examples given in [Table A.1](#) illustrate the classification.

As the method provides only a rough estimate of the metabolic rate with considerable possibilities for error, it should only be used for classification purposes without interpolation between the four categories.

7 Level 2, Observation

7.1 Evaluation of metabolic rate for a given activity

[Annex B](#) gives mean values or formulae for estimating the metabolic rate in watts in the following cases:

- at rest;
- for activities with displacements:
 - when walking with or without load at $< 6 \text{ km}\cdot\text{h}^{-1}$;
 - when running with or without load at $\geq 6 \text{ km}\cdot\text{h}^{-1}$;

- when going up or down stairs and ladders;
- for activities without displacement
 - when lifting or lowering loads 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;

7.2 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](#), e.g. speed of displacement, heights climbed, weights manipulated, number of actions carried out;
- 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 [Formula \(1\)](#):

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

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 evaluation is further described in [Annex B](#).

The time and duration of the study shall be representative of the activity in all its possible variations: the duration may be rather short if the work cycle is short and repetitive, and very long when the activities change permanently.

7.3 Accuracy

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 observers and their knowledge of the working conditions: the possibility for errors is high.

8 Level 3, Analysis

8.1 Evaluation of metabolic rate using heart rate

8.1.1 Principle of the method

In the case of pure dynamic work using major muscle groups, with no static muscular, thermal 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 in level 4. In that case, the relationship between heart rate and metabolic rate is shown in [Formula \(2\)](#):

$$M = a + b HR \quad (2)$$

where

M is the metabolic rate, W;

HR is the heart rate measured, beats-per min;

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 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 in [Formula \(2\)](#);
- the magnitude of the HR components not linked to the dynamic muscular load.

8.1.2 Determination of the $(HR-M)$ relationship for purely dynamic muscular work

The $(HR-M)$ relation can be determined by different methods of decreasing accuracy:

- a) The most accurate method consists of recording the heart rate and corresponding oxygen consumption at different effort levels during a cardiac stress test, for example on an ergometer or a treadmill in a thermically neutral environment. The $(HR-M)$ relation can be used provided the durations of the efforts at each level are such that stable HR and oxygen consumption values are reached.

Studies showed that when the cardiac test consists of manual crank efforts, instead of cycling on a bicycle or walking on a treadmill the metabolic rate for the same HR value is 23 % to 30 % lower and the validity of $(HR-M)$ will be limited to activities involving only the upper body and limbs. Conversely, the $(HR-M)$ relation derived from tests on an ergometer or treadmill will mainly be valid for activities involving the lower limbs and the entire body.

This method of determination of the $(HR-M)$ relationship is very strenuous and may only be performed in a medical environment.

- b) A simpler procedure consists of recording the stable heart rate during a few dynamic efforts whose metabolic rates are known. The step-test method is an example of such a procedure, as well as the use of the Astrand-Rything nomogram. The accuracy is then reduced as the oxygen consumption is not measured.

When such step test or full cardiac stress tests are used, the $(HR-M)$ relation characterizes the subject at the time of the test and obviously takes into account his or her fitness and health status at this time.

- c) When the methods in a) and b) cannot be used, $(HR-M)$ 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-per min;
- the increase in heart rate per unit of metabolic rate: $RM = (HR_{max} - HR_0)/(MWC - M_0)$.

The $(HR-M)$ relation is then given by [Formula \(3\)](#):

$$M = M_0 + (HR - HR_0)/RM \tag{3}$$

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 formulae for estimating these four parameters as a function of the sex, age, lean weight and height of an “average” person of “average” fitness.

- d) An even simpler method is to use direct evaluations of the $(HR-M)$ relationship such as provided in [Table C.1](#) for women and men with ages ranging from 20 years to 65 years and body masses ranging from 40 kg to 110 kg. The precision is then further reduced.

8.1.3 Evaluation of the metabolic rate as a function of HR in real situations

In any given situation, the heart rate at a given time can be regarded as the sum of several components, as shown in [Formula \(4\)](#):

$$HR = HR_0 + \Delta HR_M + \Delta HR_S + \Delta HR_T + \Delta HR_N + \Delta HR_\epsilon \tag{4}$$

where

HR_0 is the heart rate, in beats per minute, at rest 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.

When these evaluations made using this model are compared with data recorded in the field, differences will usually be observed due to the factors listed in [Clause 5](#) and the following factors.

- The fact that the work is performed in a hot environment that can lead to a significant increase of HR : the error on the evaluation of M can then rise dramatically (Bröde and Kampmann, 2019). To eliminate or at least reduce the resulting error, the HR recordings should be made in a neutral environment, that is, in thermal conditions in which the core temperature does not increase and these thermal HR components do not exist. If it is not possible, the heart rate measurements shall be corrected for thermal effects by the procedure described in [Annex E](#).
- The fact that the work performed by the subject is not purely dynamic and that the HR components due to, for example, static work, stress and mental load can be important. As these components cannot be evaluated and subtracted, the estimated M value will be an overestimation of the true energy expenditure. In a cold environment, this overestimation will result in an underestimation of the risk for the people exposed, while in the case of heat stress (even after the mandatory correction

for the heat component of *HR*) it will lead to a prediction of a greater risk and therefore result in an increased protection of the people.

- The fitness of the subject influences strongly his or her MWC and therefore the (*HR-M*) relation. The MWC can vary from the average roughly by +40 % for fit people (percentile 95 of the working population) to -40 % for unfit people (percentile 5 %) (Kaminsky, 2015).
- The individual determination of MWC during a cardiac stress test helps to maintain the intended level of accuracy in field situations concerning populations different from the average person (Arab et al., 2020).

In any case, it should be noted that the *HR* values, including all the possible components, as well as the metabolic rates estimated from them, reflect the global strain of the person and therefore can be used to estimate the strenuousness of the task or job for that person.

8.2 Evaluation of metabolic rate by accelerometry

The increase of metabolic rate above resting is typically linked to an increased rate of body movement. This increase in movement can be assessed using accelerometers that can be placed on the trunk (e.g. step counters) or on a number of body locations, allowing additional assessment of movement of arm and legs. Due to the increasing focus on physical activity and health, the use of accelerometers for the determination of total daily energy expenditure (TEE) or activity-based energy expenditure (AEE) has grown dramatically over the last 10 years. In part this was stimulated by the incorporation of such devices in small fitness monitoring devices, often linked to mobile phone apps, the widespread use of simple pedometers for personal activity monitoring, and the increased use of research-based systems for tracking activity and metabolic rate.

Due to the proprietary nature of many of these devices, in most cases the underlying calculations to get from accelerometry data to energy expenditure are not publicly available.

Research-based systems are using a range of technologies, with a move from using piezoelectric sensors, that are unable to detect the field of gravity and thus cannot identify the body position, to piezo-resistive and capacitive sensors, which do measure the gravitational field, and thus are able to identify posture (standing, sitting or lying). Some systems use single accelerometers, while others use multiaxial systems or even several sensors placed on different body parts. Systems vary in sampling frequency, mass (8 g to 200 g), sensor location(s) on the body and dynamic range (a range of -6 g to +6 g has been recommended). Several research systems use additional information, either static information on the person (body mass, height, age, gender) and dynamic measurements (heart rate, skin temperature, surface-based core temperature estimate, galvanic skin response, heat flux), though the latter do not necessarily lead to improved predictions of energy expenditure.

A multitude of research systems has been validated against doubly labelled water measurements (see 9.2) over several days (Plasqui et al., 2013; Plasqui and Westerterp, 2007). Correlations of accelerometer outcomes (step counts, activity levels, AEE, TEE) and doubly labelled water measurements obtained showed large variations between studies and equipment types, with correlations ranging from non-significant to 0,91. While mean differences at group level between doubly labelled water and TEE or AEE were often small, variability was quite large. Though some systems can be used effectively for longer-term metabolic rate estimations, less information is available on using such systems for short work periods. In addition, the work type is important as, for example, sitting hand or arm work is not detected as activity by most systems.

The accuracy of the evaluation using accelerometers is highly dependent upon the material used and the method appears to be more appropriate for long-term than short-term evaluation.

9 Level 4, Expertise

9.1 Evaluation of metabolic rate by measurement of oxygen consumption rate

9.1.1 Partial and integral method

The metabolic rate has traditionally been 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 the partial method is justified under the following assumption:

- 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 ([Figure 1](#)).
- This assumption holds as long as body temperature will not change, additional types of muscle fibres are not recruited during work or lactic acidosis will occur.

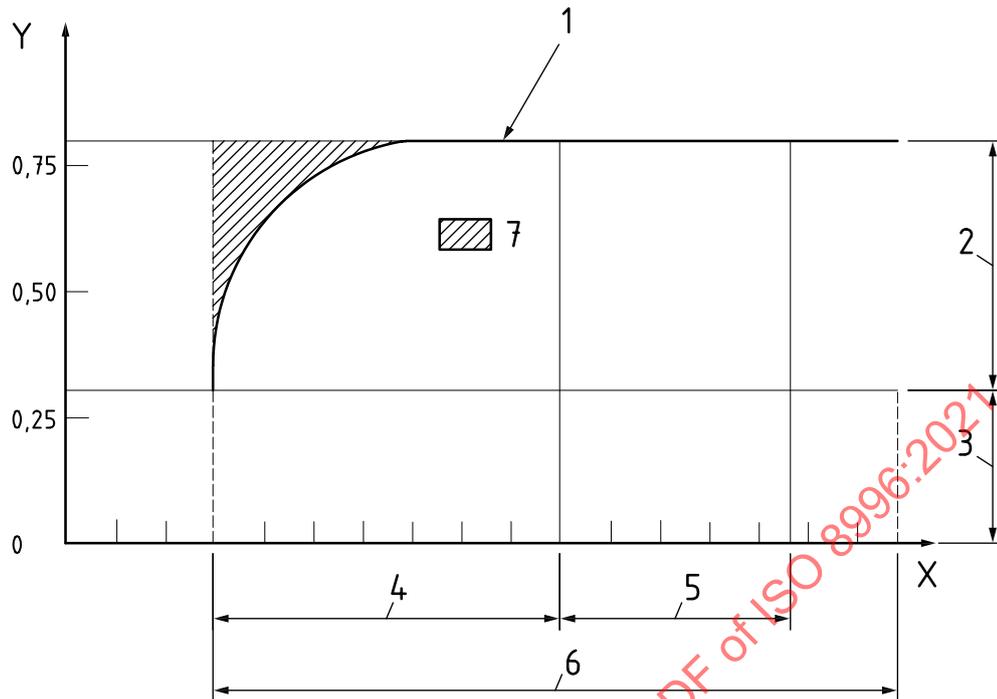
Otherwise, a slow component of oxygen uptake will show up (e.g. Gaesser and Poole, 1996; Barstow and Molé, 1991; see [Figure 2](#)) and by this the value of the energetic equivalent (EE) to be used to estimate metabolic rates (see [9.1.2](#) and [9.1.4](#)) can be dubious, and in total lead to an overestimation of metabolic rates, whereas oxygen uptake rate will be measured correctly.

When a “slow component” is present ([Figure 2](#)), there will be no steady state in the measured oxygen uptake at a constant work rate for some time, and the value therefore can depend on the time of the measurement. Thus, the slow component can lead to an overestimation of metabolic rates as well as oxygen uptake rates for a given workload.

An increase of body temperature can be observed well below an oxygen uptake of $1 \text{ l O}_2 \cdot \text{min}^{-1}$ and will lead to an increased oxygen uptake due to the Q_{10} -effect. Q_{10} is defined as “ratio of the rate of a physiological process at a particular temperature to the rate at a temperature 10 °C lower” and increases oxygen uptake by 7 % per degree rise in core temperature with typical $Q_{10} = 2$.

[Figure 1](#) 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 (measurement period). Air collection can be either complete (e.g. with a Douglas bag) or by regular sampling (e.g. with a gas meter). It is stopped when sufficient expired air has been sampled or, for example, when workload changes.

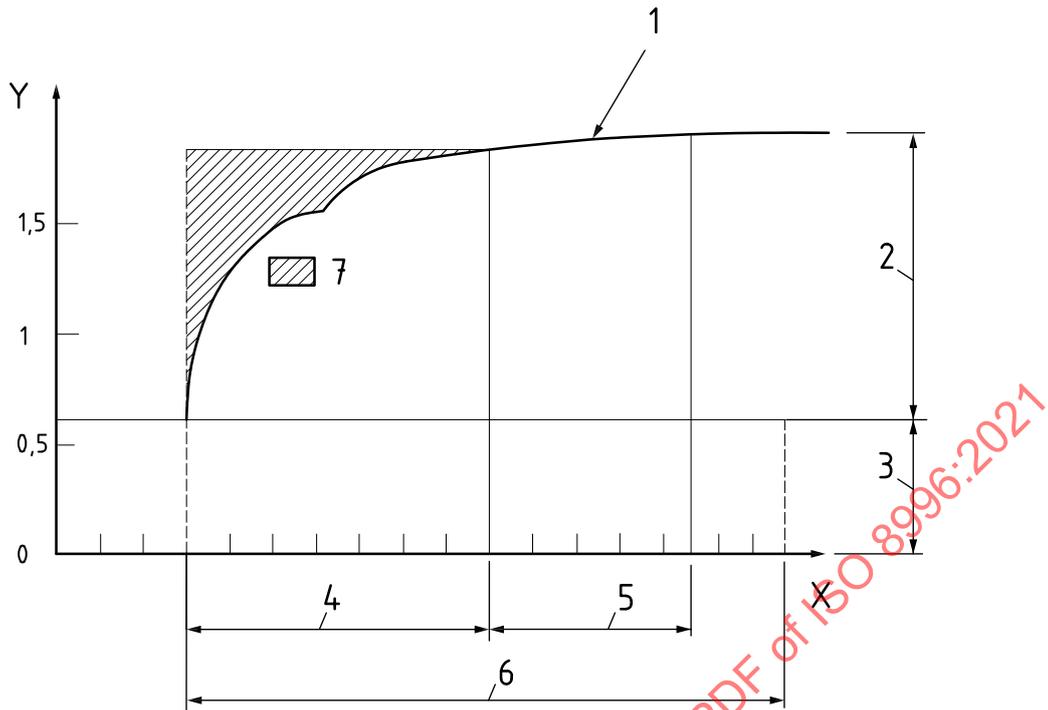


Key

- | | | | |
|---|--|---|--------------------|
| X | time, min | 4 | preliminary period |
| Y | oxygen uptake rate, l/min | 5 | measurement period |
| 1 | oxygen uptake rate required | 6 | work period |
| 2 | increase in oxygen uptake rate due to work | 7 | oxygen deficit |
| 3 | resting rate of oxygen uptake | | |

Figure 1 — Measurement of metabolic rate using the partial method

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Key

X	time, min	4	preliminary period
Y	oxygen uptake rate, l/min	5	measurement period
1	oxygen uptake rate required	6	work period
2	increase in oxygen uptake rate due to work	7	oxygen deficit until start of measurement
3	resting rate of oxygen uptake		

Figure 2 — Measurement of metabolic rate using the partial method for high oxygen uptake rates: slow component at a constant workload

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](#).

For oxygen uptake rates above 1 l O₂·min⁻¹, the integral method was recommended. In the case of heavy work, the oxygen requirement is above the long-term limit of aerobic power; in the case of very heavy work it can be 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 with the oxygen uptake rate slowly returning to the resting value. The total excess above resting rate is called excess post-exercise oxygen consumption (EPOC) (Gaesser and Brooks, 1984), formerly O₂ debt or afterburn. The integral method was based on the assumption that the O₂-deficit is balanced by EPOC, but there is evidence that the O₂ deficit is usually exceeded by the EPOC. So EPOC can amount for 10 l O₂ to 20 l O₂ and the duration of EPOC can last from 30 min to 40 min (Smith and McNaughton, 1993). The ratio of EPOC to O₂-deficit can reach a value of 4 for hard work (Gore and Withers, 1990).

Given the considerations above, the application of the integral method is no longer recommended.

9.1.2 Evaluation of metabolic rate from oxygen consumption rate

Since very small amounts of oxygen can be stored in the human body, it is 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 EE of oxygen is used to convert oxygen consumption rate into metabolic rate.

The EE 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·h·l O₂⁻¹ 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 [Formulae \(5\)](#) to [\(7\)](#):

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

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

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

where

RQ is the respiratory quotient;

\dot{V}_{O_2} is the oxygen consumption rate, l O₂·h⁻¹;

\dot{V}_{CO_2} is the carbon dioxide production rate, l CO₂·h⁻¹;

EE is the energetic equivalent, in watt hours per litre of oxygen (W·h·l O₂⁻¹);

M is the metabolic rate, W.

9.1.3 Evaluation of oxygen uptake

9.1.3.1 General

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

9.1.3.2 Calculation of the STPD reduction factor

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

- a) the method of measurement;
- b) the duration of the measurement: partial method or integral method as described in [9.1.1](#);
- c) the atmospheric pressure;
- d) the volume of air expired;
- e) the temperature of the expired air;
- f) the fraction of oxygen in the expired air;
- g) 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 [Formula \(8\)](#) using the partial pressure of water vapour (see [Table 2](#)).

$$f = \frac{273 \times (p - p_{a,ex})}{(273 + \theta) \times 101,3} \tag{8}$$

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;
- $p_{a,ex}$ is the water vapour partial pressure of the expired air, kPa, estimated as saturated water vapour pressure corresponding to the temperature θ (see [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.

9.1.3.3 Calculation of the expired volume at STPD

Calculation of the expired volume at STPD is made using [Formula \(9\)](#).

$$V_{exSTPD} = V_{exATPS} \cdot f \tag{9}$$

where

- V_{exSTPD} is the expired volume, l, at STPD;
- V_{exATPS} is the expired volume, l, at ATPS;
- f is as defined in [9.1.3.2](#).

9.1.3.4 Calculation of the volume flow rate

Calculation of the volume flow rate is made using [Formula \(10\)](#).

$$\dot{V}_{ex} = \frac{V_{exSTPD}}{t} \tag{10}$$

where

- \dot{V}_{ex} is the volume flow rate, l·h⁻¹;
- t is the test duration, h, i.e. the main period for the partial method.

9.1.3.5 Calculation of oxygen consumption rate

Calculation of the oxygen consumption rate is made using [Formula \(11\)](#).

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

where

\dot{V}_{O_2} is the oxygen consumption rate, l O₂·h⁻¹;

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

9.1.3.6 Calculation of carbon dioxide production rate

Calculation of the carbon dioxide production rate is made using [Formula \(12\)](#).

$$\dot{V}_{CO_2} = \dot{V}_{ex} \cdot (F_{CO_2} - 0,0004) \quad (12)$$

where

\dot{V}_{CO_2} is the carbon dioxide production rate, l CO₂·h⁻¹;

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

9.1.3.7 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 [Formulae \(13\)](#) and [\(14\)](#):

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

$$\dot{V}_{CO_2} = \dot{V}_{ex} [F_{CO_2} - (1 - F_{O_2} - F_{CO_2}) 0,380 \times 10^{-3}] \quad (14)$$

9.1.4 Calculation of metabolic rate

The metabolic rate is evaluated with the partial method from the oxygen uptake and the EE using [Formula \(7\)](#).

If a slow component shows up, the exact value of the EE can be unknown due to the effects listed in [9.1.1](#) and the application of [Formula \(7\)](#), and subsequently the calculation of metabolic rate is not recommended.

9.2 Evaluation of metabolic rate by the doubly labelled water method for long term measurements

This subclause describes only the principle of the method and refers to the literature (Black et al., 1996) for detailed descriptions.

After collection of a baseline urine sample, the subject drinks an accurately weighed oral loading dose of ²H₂ ¹⁸O.

Deuterium (²H) labels the body water pool and its rate of disappearance from the body (k_2) provides a measure of water turnover (r_{H_2O}).

The ¹⁸O 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 ($r_{\text{H}_2\text{O}} + r_{\text{CO}_2}$). 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 ^2H 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 can be longer.

The doubly labelled water 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 doubly labelled water and the comparator method in subjects under steady-state conditions. The overall precision of the method is about $\pm 5\%$, depending on circumstances.

Although the doubly labelled water technique is simple in concept, there are a number of complex details that should be thoroughly understood by the user.

9.3 Evaluation of metabolic rate by 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 should 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.

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 ^a	Range of metabolic rates W	Examples
0 Resting	100 to 125	Resting, sitting at ease
1 Low metabolic rate	125 to 235	<p>Sedentary activity (office, dwelling, school, laboratory: writing, typing, drawing, sewing, book keeping).</p> <p>Standing, light activity (shopping, laboratory, light industry).</p> <p>Hand and arm work (small bench tools, inspection, assembly or sorting of light materials).</p> <p>Light arm and leg work (driving vehicle in normal conditions, operating foot switch or pedal).</p> <p>Machining with low power tools [drilling (small parts), milling (small parts), coil winding, sawing].</p> <p>Casual walking (2 km·h⁻¹) on a level, even path, solid with load ≤ 30 kg.</p>
2 Moderate metabolic rate	235 to 360	<p>Sustained hand and arm work (hammering in nails, filing, loading, polishing).</p> <p>Arm and leg work (off-road operation of lorries, tractors or construction equipment).</p> <p>Arm and trunk work (work with pneumatic hammer, tractor assembly, plastering).</p> <p>Weeding, hoeing, picking fruits or vegetables.</p> <p>Pushing or pulling lightweight carts or wheelbarrows.</p> <p>Bricklaying, 5 bricks/min.</p> <p>Intermittent handling of moderately heavy material.</p> <p>Walking (2,5 to 5 km·h⁻¹) on a level, even path, solid with load ≤ 20 kg.</p> <p>Walking (2,5 to 3 km·h⁻¹) on levelled but irregular to unstable ground with load ≤ 20 kg.</p> <p>Walking (≤2,5 km·h⁻¹) on stable ground uphill (≤5 %) with load ≤ 20 kg.</p>

Table A.1 (continued)

Class ^a	Range of metabolic rates W	Examples
3 High metabolic rate	360 to 465	Intense arm and trunk work with hand tools or machines. Carrying heavy material, shovelling. Sledgehammer work, sawing, planing or chiselling hard wood, hand mowing, digging. Walking (5,5 to 7 km·h ⁻¹) on a level, even path, solid with load ≤ 20 kg. Walking (3,5 to 5 km·h ⁻¹) on levelled but irregular to 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 a level, even path, solid, with or without load. Walking (>5 km·h ⁻¹) on levelled but irregular to 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).

^a The qualitative terms low, moderate and high refer to a whole work shift.

Annex B (informative)

Evaluation of the metabolic rate at level 2, Observation

B.1 General

This annex builds on data (American College of Sports Medicine, 2000; Bernard, 2006; Garg et al., 1978; Hall et al., 2004; FAO/WHO/UNU, 2001; Mufflin et al., 1990, Spitzer et al., 1982) 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.

B.2 Evaluation of the metabolic rate of a specific activity

B.2.1 General

Data and formulae are presented for the evaluation of the metabolic rate at rest and for activities with and without displacement.

B.2.2 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:

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

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

where

M_0 is the metabolic rate, W;

A_{Du} is the body surface area, m² given by $A_{Du} = 0,007\,184 \cdot W_b^{0,425} \cdot H_b^{0,725}$;

W_b is the body mass, kg;

H_b is the body height, cm.

B.2.3 Metabolic rate for activities with displacements

For walking at velocities:

$$< 6 \text{ km} \cdot \text{h}^{-1}: M = (0,5 + 0,37 \cdot v_w + 0,2 \cdot v_w \cdot G) \cdot (W_b + L)$$

For running at velocities:

$$\geq 6 \text{ km} \cdot \text{h}^{-1}: M = (0,5 + 0,75 \cdot v_w + 0,1 \cdot v_w \cdot G) \cdot (W_b + L)$$

where

M is the metabolic rate, W;

- L is the load carried by the person, kg;
- v_w is the walking or running speed, km·h⁻¹;
- G is the ground slope, %.

For going up stairs:

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

For going down stairs:

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

For going up ladders

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

For going down ladders:

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

where

- V_v is the vertical speed in m·min⁻¹;
- N_{steps} is the number of steps of stairs of height = 17 cm per min (1m·min⁻¹ = 5,88 steps·min⁻¹);
- N_{rungs} is the number of rungs of ladders of height = 25 cm per min (1m·min⁻¹ = 4 rungs·min⁻¹).

B.2.4 Metabolic rate for activities without displacements

[Table B.1](#) gives the formulae for the evaluation of the metabolic rate ΔM (in W) when lifting or lowering loads.

[Table B.2](#) provides the metabolic rate (W) for a seated subject as a function of work intensity and body segment involved.

[Table B.3](#) gives the increase ΔM (W) of the metabolic rates estimated from [Table B.2](#) due to body postures.

Table B.1 — Formulae for the evaluation of the metabolic rate M (in W) when lifting or lowering loads

Task	Metabolic rate
	M W
Idle (sit/stand) and hold	$M_0 + 4,12 \cdot L$
Lifting (stoop)	$M_0 + (0,09 \cdot W_b + L \cdot H) \cdot F$
Lifting (arm)	$M_0 + (0,02 \cdot W_b + 1,45 \cdot L \cdot H) \cdot F$
Lifting (squat)	$M_0 + (0,14 \cdot W_b + 1,75 \cdot L \cdot H) \cdot F$
Key	
M Metabolic rate, W	
F Average rate of moves, move·min ⁻¹	
H Height of lift, m	

Table B.1 (continued)

Task	Metabolic rate
	M W
Lowering (stoop)	$M_0 + (0,08 \cdot W_b + 0,47 \cdot L \cdot H + 0,726) \cdot F$
Lowering (arm)	$M_0 + (0,03 \cdot W_b + 0,84 \cdot L \cdot H) \cdot F$
Lowering (squat)	$M_0 + (0,14 \cdot W_b + 0,49 \cdot L \cdot H) \cdot F$
Key	
M Metabolic rate, W	
F Average rate of moves, move·min ⁻¹	
H Height of lift, m	

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

Body segment	Metabolic rate		
	M 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 ΔM (W) of the metabolic rate estimated from Table B.2 due to body postures

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

B.2.5 Metabolic rate for other specific activities

Table B.4 gives the metabolic rate (W) for several 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

Table B.4 (continued)

Activity	Metabolic rate W
Work with a hammer, two 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	$4,5 \cdot M_0$

B.3 Evaluation of the average metabolic rate (W) during a period of time

The procedure is as follows:

- a) Before the observation period:
 - Fill in the 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 or the formulae in [B.2](#) or both.
- b) During the observation period:
 - 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:
 - Calculate the total length of time spent on each activity.
 - Multiply the length of time spent on the 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 formulae (Malchaire et al., 2017) make it possible to predict the ($HR-M$) relationship as a function of the characteristics of the subject.

MWC, W:

- men: $(19,45 - 0,133 \cdot \text{Age}) \cdot W_{bl}$
- women: $(17,51 - 0,150 \cdot \text{Age}) \cdot W_{bl}$

where

Age is the age of the subject, years;

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

The lean body mass (Janmahasatian et al., 2005) is estimated using the following formulae:

- 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): $208 - 0,7 \cdot \text{Age}$.

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 for at least 5 min during the recording.

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

$$M_m = M_0 + (HR_m - HR_0)/RM$$

where

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

Assuming that $HR_0 = 70$ beats·min⁻¹ and $M_0 = 100$ W, [Table C.1](#) provides the increase in heart rate per unit of metabolic rate RM of the relation $M = (HR - 70)/RM + 100$ predicted as a function of the age and

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 (W) and heart rate (beats per min), predicted as a function of the age and the lean body mass of the subject (for women and men)

Age years	Lean body mass kg							
	40	50	60	70	80	90	100	110
Women								
20	3,87	5,04	6,21	7,38	8,55	9,73	10,90	12,07
25	3,74	4,88	6,02	7,16	8,31	9,45	10,59	11,73
30	3,60	4,71	5,82	6,93	8,04	9,15	10,26	11,38
35	3,44	4,52	5,60	6,68	7,76	8,84	9,92	11,00
40	3,28	4,32	5,37	6,42	7,46	8,51	9,55	10,60
45	3,10	4,11	5,12	6,13	7,14	8,15	9,16	10,17
50	2,92	3,89	4,86	5,83	6,80	7,78	8,75	9,72
55	2,68	3,65	4,58	5,51	6,44	7,37	8,30	9,23
60	2,50	3,39	4,28	5,16	6,05	6,94	7,82	8,71
65	2,27	3,11	3,95	4,79	5,63	6,47	7,31	8,15
Men								
20	4,61	5,96	7,32	8,67	10,03	11,38	12,73	14,09
25	4,53	5,86	7,20	8,54	9,88	11,21	12,55	13,89
30	4,43	5,75	7,07	8,39	9,72	11,04	12,36	13,68
35	4,33	5,64	6,94	8,24	9,55	10,85	12,15	13,46
40	4,23	5,51	6,80	8,08	9,37	10,65	11,94	13,22
45	4,12	5,38	6,65	7,91	9,18	10,44	11,70	12,97
50	4,00	5,24	6,49	7,73	8,97	10,21	11,46	12,70
55	3,87	5,09	6,31	7,53	8,75	9,97	11,19	12,41
60	3,74	4,93	6,13	7,32	8,52	9,71	10,91	12,10
65	3,59	4,76	5,93	7,10	8,26	9,43	10,60	11,77