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Ergonomics of the thermal environment — Determination of metabolic rate

Ergonomie de l'environnement thermique — Détermination du métabolisme énergétique

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Foreword

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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).

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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.

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 terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://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, thermophysiologists 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 accelerometery 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 (actual CV/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 km·h^{-1};

  — when running with or without load at ≥ 6 km·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):

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

where

M is the average metabolic rate for the work cycle, W;

M_i is the metabolic rate for activity i, W;

t_i is the duration of activity i, min;

T is the total duration, min, of the period of time considered, and is equal to the sum of the partial durations t_i.

The procedure of this time and activity 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):

$$M = a + b\,HR \tag{2}$$

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-Rythming nomogram. The accuracy is then reduced as the oxygen consumption is not measured.

   When such step test or full cardias 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 = $(HR_{max} - HR_0)/(\text{MWC} - M_0)$.

The (HR–M) relation is then given by Formula (3):

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

The accuracy of this relation is a function of the validity of the measurements or estimations of HR_0, M_0, HR_{max} and MWC. Annex C proposes 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):

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

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

