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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 main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

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ISO 8996 was prepared by Technical Committee ISO/TC 159, *Ergonomics*, Subcommittee SC 5, *Ergonomics of the physical environment*.

This second edition cancels and replaces the first edition (ISO 8996:1990), which has been technically revised.

Ergonomics of the thermal environment — Determination 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 numerical index of 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.

This International Standard specifies different methods for the determination 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, the 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 an "average" individual:

— a man 30 years old weighing 70 kg and 1,75 m tall (body surface area 1,8 m^2);

— a woman 30 years old weighing 60 kg and 1,70 m tall (body surface area 1,6 m^2).

Users should make appropriate corrections when they are dealing with special populations including children, aged persons, people with physical disabilities, etc.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 9886, *Ergonomics — Evaluation of thermal strain by physiological measurements*

ISO 15265, *Ergonomics of the thermal environment — Risk assessment strategy for the prevention of stress or discomfort in thermal working conditions*

3 Principle and accuracy

The mechanical efficiency of muscular work — called the "useful work", W — 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 total energy consumption while working is assumed equal to the heat production. 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: Two methods simple and easy to use are presented to quickly characterize the mean workload for a given occupation or for a given activity:

— method 1A is a classification according to occupation;

— method 1B is a classification according to the kind of activity.

Both methods 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.

Level 2, observation: Two methods are 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:

— in method 2A, the metabolic rate is determined by adding to the baseline metabolic rate the metabolic rate for body posture, the metabolic rate for the type of work and the metabolic rate for body motion related to work speed (using group assessment tables);

— in method 2B, the metabolic rate is determined by means of the tabulated values for various activities.

A procedure is described to record the activities with time and compute the time-weighted average metabolic rate, using the data from the two methods above.

The possibility for errors is high. A time and motion study is necessary to determine the metabolic rate in work situations that involve a cycle of different activities.

Level 3, analysis: One method is addressed to people trained in occupational health and ergonomics of the thermal environment. The metabolic rate is determined from heart rate recordings over a representative period. This method for the indirect determination 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 representativity 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.

The main factors affecting the accuracy of the estimations are the following:

— individual variability;

— differences in the work equipment;

— differences in work speed;

— differences in work technique and skill;

— gender differences and anthropometric characteristics;

— cultural differences;

— when using the tables, differences between observers and their level of training;

— when using level 3, the accuracy of the relationship between heart rate and oxygen uptake, as other stress factors also influence the heart rate;

— at level 4, the measurement accuracy (determination of gas volume and oxygen fraction).

The accuracy of the results, but also the costs of the study, increase from level 1 to level 4. Measurement at level 4 gives the most accurate values. As far as possible, the most accurate method should be used.

Table 1 — Levels for the determination of the metabolic rate

Level	Method	Accuracy	Inspection of the work place
1 **Screening**	1A: Classification according to occupation	Rough information Very great risk of error	Not necessary, but information needed on technical equipment, work organization
	1B: Classification according to activity		
2 **Observation**	2A: Group assessment tables	High error risk Accuracy: ± 20 %	Time and motion study necessary
	2B: Tables for specific activities		
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 Level 1, screening

4.1 Table for the estimation of metabolic rate by occupation

Table A.1 in Annex A shows the metabolic rate for different occupations. The values are mean values for the whole working time, but without considering longer rest pauses, for example lunchtime. Significant variation may arise due to differences in technology, work elements, work organization, etc.

4.2 Classification of metabolic rate by categories

The metabolic rate can be estimated approximately using the classification given in Annex A. Table A.2 defines five classes of metabolic rate: resting, low, moderate, high, very high. For each class, an average and a range of metabolic rate values are given as well as a number of examples. These activities are supposed to include short rest pauses. The examples given in Table A.2 illustrate the classification.

5 Level 2, observation

5.1 Estimation of metabolic rate by task requirements

Here, the metabolic rate is estimated from the following observations:

— the body segment involved in the work: both hands, one arm, two arms, the entire body;

— the workload for that body segment: light, medium, heavy, as judged subjectively by the observer;

— the body posture: sitting, kneeling, crouching, standing, standing stooped;

— the work speed.

Table B.1 in Annex B gives the mean value and the range of metabolic rates for a standard person, seated, as a function of the body segment involved and the workload. Table B.2 gives the corrections to be added when the posture is different from seated.

5.2 Metabolic rate for typical activities

Table B.3 in Annex B provides values of metabolic rate for typical activities. These values are based on measurements performed in the past in many different laboratories.

5.3 Metabolic rate for a work cycle

To determine the overall metabolic rate for a work cycle, it is necessary to carry out a time and motion study that includes a detailed description of the work. This involves classifying each activity and taking account of factors such as the duration of each activity, the distances walked, the heights climbed, the weights manipulated, the number of actions carried out, etc.

The time-weighted average metabolic rate for a work cycle can be determined from the metabolic rate of the respective activity and the respective duration 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, in watts per square metre;

M_i is the metabolic rate for activity i, in watts per square metre;

t_i is the duration of activity i, in minutes;

T is the duration, in minutes, of the work cycle considered, and is equal to the sum of the partial durations t_i.

The recording of occupational activities and the duration of the activities for a working day or for a particular period may be simplified by using the diary described in Table B.4 and Table B.5. Activities are recorded when they are changed, using a classification code derived from the tables for the estimation of metabolic rate by task components. The number of components to be considered will vary depending upon the complexity of the activity.

The procedure is as follows:

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

b) Observe the work of the person under study (at least 2 h to 3 h).

c) Determine each individual task component and the corresponding metabolic rate estimated from Table B.1, B.2 or B.3.

d) Always fill in the diary when the task component is changed.

e) Calculate the total length of time spent on each task component.

f) Multiply the length of time spent on each task component by the corresponding metabolic rate.

g) Add the values.

h) Divide the sum by the total length of the observation period.

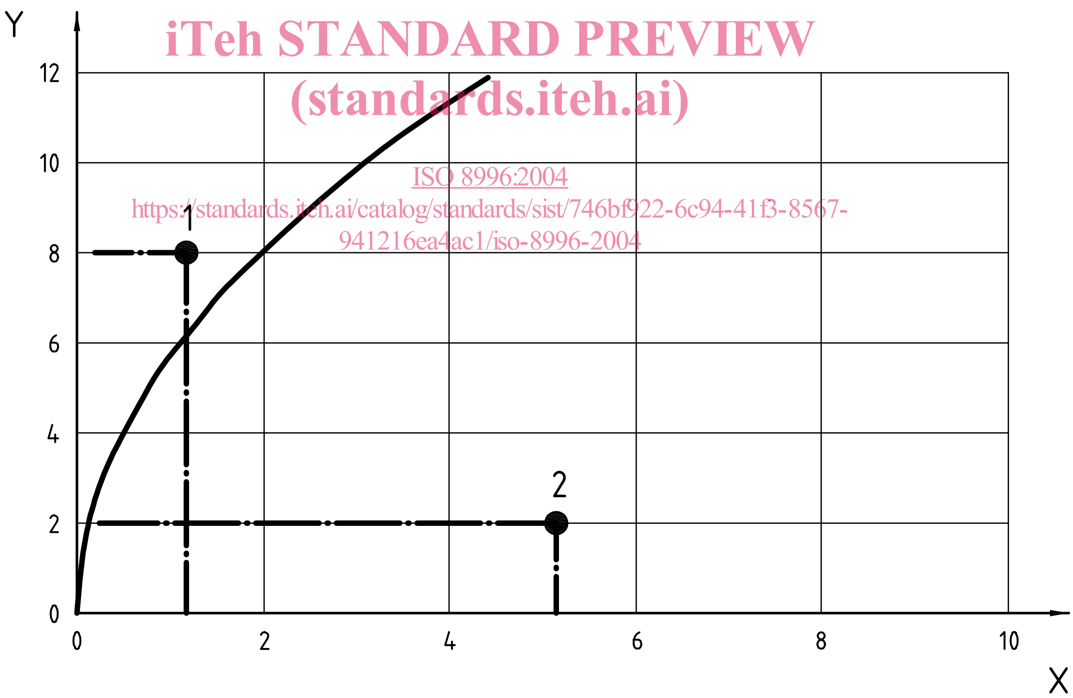
Forms for the evaluation are given in Tables B.4 and B.5.

5.4 Influence of the length of rest periods and work periods

The tables in Annex B cannot be used for the evaluation of the average metabolic rate for working conditions with an intermittent sequence of short periods of activity and long rest periods. In this case, the technique described in 5.3. 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. Example 1 concerns a cycle of 8 min of rest and 1 min of work. In this case, the technique described in 5.3 would lead to an underestimation of the metabolic rate and the tables in Annex B cannot be used. For work-rest cycles such as in Example 2, the tables 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.



Key

X length of work period, min

Y length of rest pause, min

1 Example 1

2 Example 2

Figure 1 — Curve showing limit of validity of combinations of work and rest periods when estimating metabolic rate

5.5 Obtaining values by interpolation

It is possible to obtain metabolic-rate values by interpolation. When working speeds differ from those given in the tables in Annex B, conversion is only possible within a range of ± 25 % of the indicated speed, however.

5.6 Requirements for the application of metabolic-rate tables

To allow comparison of values from different sources, values reported in the tables in Annexes A and B have been standardized with respect to the standard person working in a comfortable thermal environment.

The metabolic rate for a given person performing a given task may vary within certain limits around the mean values given in the tables, due to the influence of the factors mentioned in Clause 3.

However, 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.

Considering this risk of error, it is normally not justified, at this level of evaluation, to take into consideration differences in height or gender.

The consideration of the weight of the subject might be warranted only for activities involving movements of the whole body, such as walking, climbing, lifting weights.

In hot conditions, a maximum increase of 5 W·m^{-2} to 10 W·m^{-2} may be expected due to increased heart rate and sweating. Such a correction is not justified.

On the other hand, in cold conditions, an increase of up to 200 W·m^{-2} may be observed when shivering occurs. The wearing of heavy clothing will also increase metabolic rate, by increasing the weight of the subject and decreasing the subject's ease of movement.

6 Level 3, analysis

6.1 Estimation of metabolic rate using heart rate

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

$$HR = HR_0 + \Delta HR_M + \Delta HR_S + \Delta HR_T + \Delta HR_N + \Delta HR_E \quad (2)$$

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_E 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 load and in the absence of thermal strain 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 estimation (see Table 1) and is less complex than the measurement of oxygen consumption, which provides the most accurate results.

The heart rate may be recorded continuously, for example by the use of telemetric equipment, or, with a further 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 different working cycles or over the whole shift time.

In the presence of considerable thermal load, static muscular work, dynamic work with small muscle groups and/or mental loads, the slope and form of the heart rate to metabolic rate relationship can change drastically. The procedure used to correct the heart rate measurements for thermal effects is described in ISO 9886.

6.2 Relationship between heart rate and metabolic rate

The relationship between heart rate and metabolic rate can be measured by recording the heart rate at different stages of defined muscular load during an experiment in a neutral climatic environment. Heart rate and corresponding oxygen consumption or physical work performed is measured during dynamic muscular work at different load stages. As the type of 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.

In general, linearity holds true for the range extending

— from a lower limit of 120 beats per minute (bpm), because the mental component can then be neglected;

— up to 20 beats below the maximum heart rate of the subject, because the heart rate tends to level off above this value.

Within this range, the relationship between heart rate and metabolic rate can be written as:

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

where

M is the metabolic rate, in watts per square metre;

M_0 is the metabolic rate at rest, in watts per square metre;

RM is the increase in heart rate per unit of metabolic rate;

HR_0 is the heart rate at rest, under neutral thermal conditions.

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 estimations of:

- the heart rate at rest under neutral thermal conditions HR_0;
- the metabolic rate at rest M_0 (= 55 watts per square metre);
- the maximum working capacity MWC, estimated using the following formulae as a function of age (A, in years) and weight (P, in kg):

Men: $$\text{MWC} = (41{,}7 - 0{,}22A)P^{0{,}666}\ \text{W·m}^{-2} \quad (4)$$

Women: $$\text{MWC} = (35{,}0 - 0{,}22A)P^{0{,}666}\ \text{W·m}^{-2} \quad (5)$$

- the maximum heart rate HR_{max}, estimated by the following formula:

$$HR_{max} = 205 - 0{,}62A \quad (6)$$

- $$RM = (HR_{max} - HR_0)/(MWC - M_0) \quad (7)$$

Table C.1 in Annex C provides directly estimations of the HR-M relationship for ages ranging from 20 years to 60 years and weights ranging from 50 kg to 90 kg. The precision, in that case, is further reduced.

7 Level 4, expertise

7.1 Determination of metabolic rate by measurement of oxygen consumption rate

7.1.1 Partial and integral methods

The metabolic rate can be determined 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), equivalent to 1 litre of oxygen per minute.

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.