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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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International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

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.

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.

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.

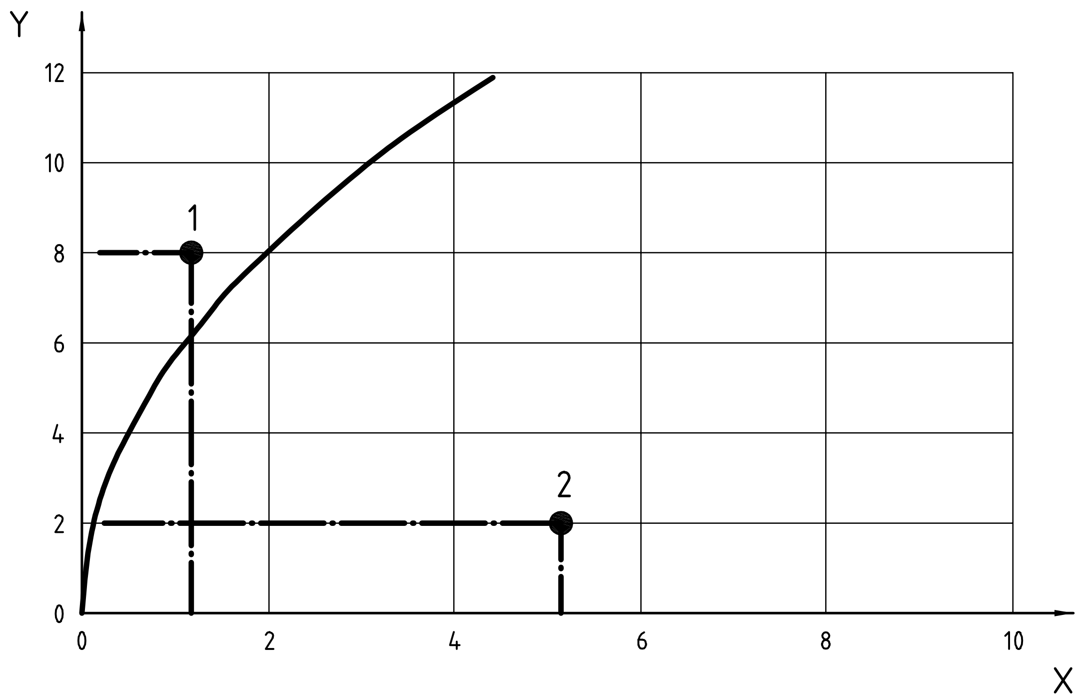
Forms for the evaluation are given in Tables B.4 and B.5.

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 $5\ W{\cdot}m^{-2}$ to $10\ W{\cdot}m^{-2}$ 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 $200\ W{\cdot}m^{-2}$ 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: $\text{MWC} = (41{,}7 - 0{,}22A)P^{0{,}666}\ \text{W·m}^{-2}$ (4)

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

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

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

— $RM = (HR_{max} - HR_0)/(\text{MWC} - M_0)$ (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.

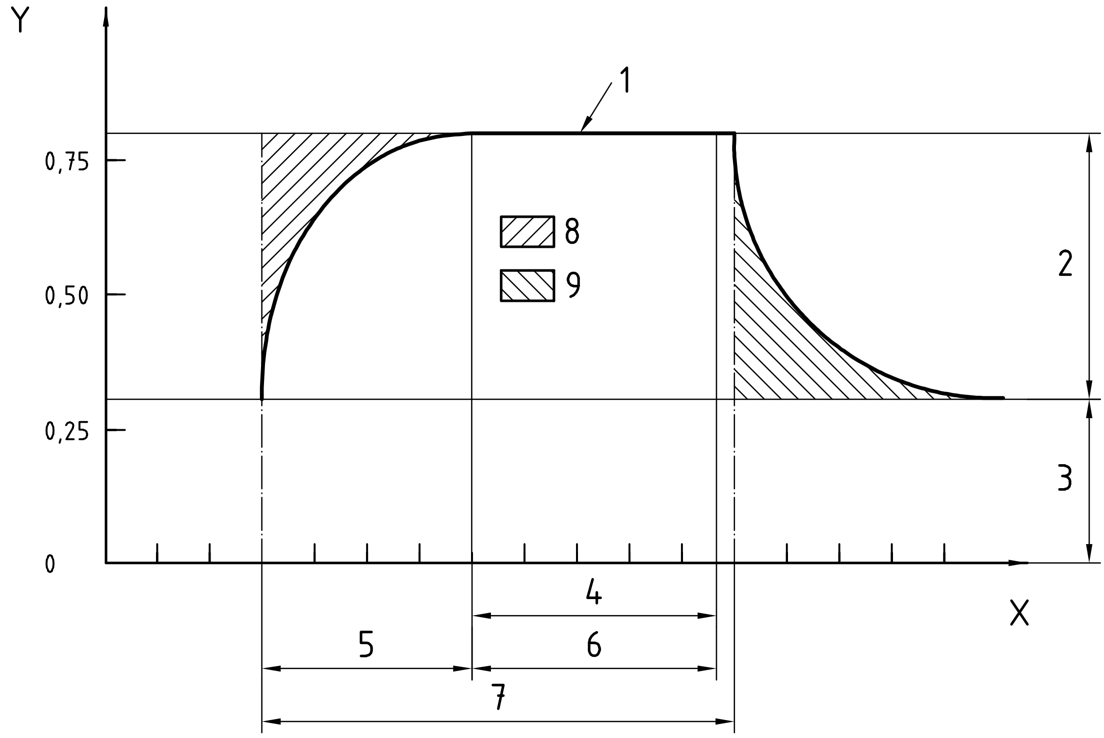
The use of these two methods is justified as follows:

— 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.



Key

X time, min

Y oxygen uptake, l·min^{-1}

1 O_2 requirement

2 increase in metabolic rate due to work

3 baseline metabolic rate

4 measurement period

5 preliminary period

6 main period

7 work period

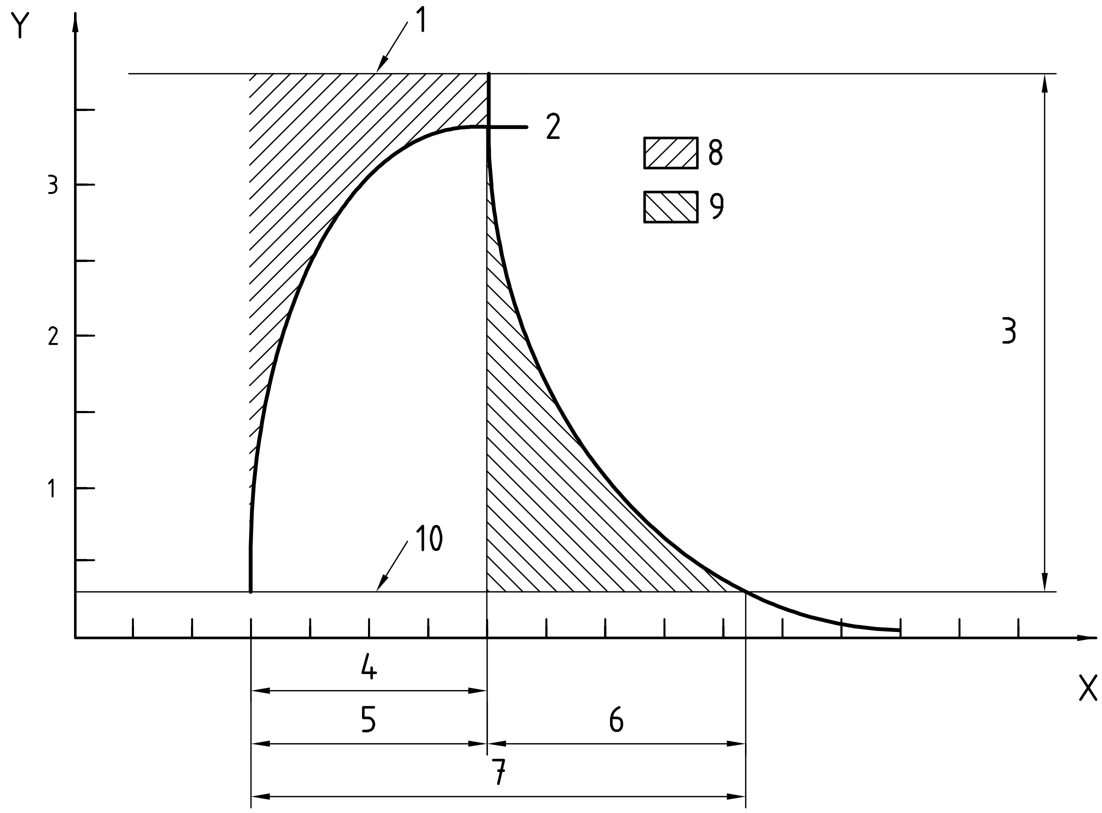
8 O_2 deficit

9 O_2 debt repayment

Figure 2 — Measurement of metabolic rate using the partial method

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

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



Key

X time, min

Y oxygen uptake, $l \cdot min^{-1}$

1 O_2 requirement

2 maximum aerobic power

3 increase in metabolic rate due to work

4 work period

5 main period

6 recovery period

7 measurement period

8 O_2 deficit

9 O_2 debt repayment

10 baseline metabolic rate

Figure 3 — Measurement of metabolic rate using the integral method

7.1.2 Determination of metabolic rate from oxygen consumption rate

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

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

The energetic equivalent depends on the type of metabolism that is indicated by the respiratory quotient (RQ). In the determination of the metabolic rate, the use of a mean RQ of 0,85 and thereby of an EE of 5,68 W·h/l O_2 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 determined from the following equations:

$$\mathrm{RQ} = \frac{\dot{V}_{\mathrm{CO_2}}}{\dot{V}_{\mathrm{O_2}}} \qquad (8)$$

$$EE = (0{,}23RQ + 0{,}77)5{,}88 \quad (9)$$

$$M = EE \times \dot{V}_{O_2} \times \frac{1}{A_{Du}} \quad (10)$$

where

RQ is the respiratory quotient;

$\dot{V}_{O_2}$ is the oxygen consumption rate, in litres of oxygen per hour;

$\dot{V}_{CO_2}$ is the carbon dioxide production rate, in litres of carbon dioxide per hour;

EE is the energetic equivalent, in watt hours per litre of oxygen (W·h/l O_2);

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

A_{Du} is the body surface area, in square metres, given by the Du Bois formula:

$$A_{Du} = 0{,}202 \times W_b^{0{,}425} \times H_b^{0{,}725} \quad (11)$$

in which

W_b is the body weight, in kilograms;

H_b is the body height, in metres.

7.1.3 Determination of oxygen uptake

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

7.1.3.1 Calculation of the STPD reduction factor

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

a) the personal data: sex, weight, height, age;

b) the method of measurement;

c) the duration of the measurement: partial method or integral method as described in 7.1.1;

d) the atmospheric pressure;

e) the volume of air expired;

f) the temperature of the expired air;

g) the fraction of oxygen in the expired air;

h) the fraction of carbon dioxide in the expired air if determination of RQ is required.

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

$$f = \frac{273 \times (p - p_{H_2O})}{(273 + \theta) \times 101{,}3} \quad (12)$$

where

f is the STPD reduction factor;

p is the measured atmospheric pressure, in kilopascals;

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

p_{H_2O} is the partial pressure of the saturated water vapour, in kilopascals, 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.

7.1.3.2 Calculation of the expired volume at STPD

$$V_{ex}\text{STPD} = V_{ex}\text{ATPS} \times f \quad (13)$$

where

V_{ex}STPD is the expired volume, in litres, at STPD;

V_{ex}ATPS is the expired volume, in litres, at ATPS;

f is as defined in 7.1.3.1.

7.1.3.3 Calculation of the volume flow rate

$$\dot{V}_{ex} = \frac{V_{ex}\text{STPD}}{t} \quad (14)$$

where

$\dot{V}_{ex}$ is the volume flow rate, in litres per hour;

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

7.1.3.4 Calculation of oxygen consumption rate

$$\dot{V}_{O_2} = \dot{V}_{ex} \times (0{,}209 - F_{O_2}) \quad (15)$$

where

$\dot{V}_{O_2}$ is the oxygen consumption rate, in litres of oxygen per hour;

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

7.1.3.5 Calculation of carbon dioxide production rate

$$\dot{V}_{CO_2} = \dot{V}_{ex} \times (F_{CO_2} - 0{,}000\,3) \tag{16}$$

where

$\dot{V}_{CO_2}$ is the carbon dioxide production rate, in litres of carbon dioxide per hour;

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

7.1.3.6 The effect of contraction of the expired volume

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

$$\dot{V}_{O_2} = \dot{V}_{ex}[0{,}265(1 - F_{O_2} - F_{CO_2}) - F_{O_2}] \tag{17}$$

$$\dot{V}_{CO_2} = \dot{V}_{ex}[F_{CO_2} - (1 - F_{O_2} - F_{CO_2})\,0{,}380 \times 10^{-3}] \tag{18}$$

7.1.4 Calculation of metabolic rate

7.1.4.1 Partial method

The metabolic rate is determined from the oxygen uptake and the energetic equivalent using Equation (10).

7.1.4.2 Integral method

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

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

$$M = \left(M_p \times \frac{t_m + t_r}{t_m} \right) - \left(M_s \times \frac{t_r}{t_m} \right) \tag{19}$$

where

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

M_p is the metabolic rate, in watts per square metre, for the partial method;

M_s is the metabolic rate, in watts per square metre, when seated;

t_m is the length of the main period, in minutes;

t_r is the length of the recovery period, in minutes.

7.2 The doubly labelled water method for long-term measurements

This subclause describes only the principle of the method.

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

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

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

The rate of disappearance of ^{18}O (k_{18}) provides a measure of the combined turnover of water and bicarbonate $(r_{H_2O} + r_{CO_2})$. Therefore, bicarbonate turnover (i.e. the subject's carbon dioxide production rate) can be calculated as the difference between the two rate constants ($k_{18} - k_2$).

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

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

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

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

7.3 Direct calorimetry — Principle

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

Annex A
(informative)

Evaluation of the metabolic rate at level 1, screening

This annex provides the data to use for simply and easily characterizing the mean workload for a given occupation or for a given activity in accordance with the two methods given for level 1, screening:

Method 1A: Classification according to occupation

Table A.1 — Metabolic rate for various occupations

Occupation		**Metabolic rate** ($W \cdot m^{-2}$)
Office work	Sedentary work	55 to 70
	Clerical work	70 to 100
	Janitor	80 to 115
Craftsmen	Bricklayer	110 to 160
	Carpenter	110 to 175
	Glazier	90 to 125
	Painter	100 to 130
	Baker	110 to 140
	Butcher	105 to 140
	Clock and watch repairer	55 to 70
Mining industry	Haulage operator	70 to 85
	Coal hewer	110
	Cokeoven worker	115 to 175
Iron and steel industry	Blast furnace worker	170 to 220
	Electric furnace worker	125 to 145
	Hand moulder	140 to 240
	Machine moulder	105 to 165
	Foundry man	140 to 240
Iron and metal-working industry	Smith	90 to 200
	Welder	75 to 125
	Turner	75 to 125
	Drilling machine operator	80 to 140
	Precision mechanic	70 to 110
Graphic occupations	Hand compositor	70 to 95
	Book-binder	75 to 100
Agriculture	Gardener	115 to 190
	Tractor driver	85 to 110
Traffic	Car driver	70 to 100
	Bus driver	75 to 125
	Tramway driver	80 to 115
	Crane operator	65 to 145
Various occupations	Laboratory assistant	85 to 100
	Teacher	85 to 100
	Shop assistant	100 to 120
	Secretary	70 to 85

Method 1B: Classification according to the kind of activity

Table A.2 — Classification of metabolic rate by category

Class	Average metabolic rate (with range in brackets) $W \cdot m^{-2}$	Average metabolic rate (with range in brackets) W	Examples
0 Resting	65 (55 to 70)	115 (100 to 125)	Resting, sitting at ease
1 Low metabolic rate	100 (70 to 130)	180 (125 to 235)	Light manual work (writing, typing. drawing. sewing, book-keeping); hand and arm work (small bench tools, inspection, assembly or sorting of light materials); arm and leg work (driving vehicle in normal conditions, operating foot switch or pedal). Standing drilling (small parts); milling machine (small parts); coil winding; small armature winding; machining with low power tools; casual walking (speed up to 2,5 $km \cdot h^{-1}$).
2 Moderate metabolic rate	165 (130 to 200)	295 (235 to 360)	Sustained hand and arm work (hammering in nails, filing); arm and leg work (off-road operation of lorries, tractors or construction equipment); arm and trunk work (work with pneumatic hammer, tractor assembly, plastering, intermittent handling of moderately heavy material, weeding, hoeing, picking fruits or vegetables, pushing or pulling lightweight carts or wheelbarrows, walking at a speed of 2,5 $km \cdot h^{-1}$ to 5,5 $km \cdot h^{-1}$, forging).
3 High metabolic rate	230 (200 to 260)	415 (360 to 465)	Intense arm and trunk work; carrying heavy material; shovelling; sledgehammer work; sawing; planning or chiselling hard wood; hand mowing; digging; walking at a speed of 5,5 $km \cdot h^{-1}$ to 7 $km \cdot h^{-1}$. Pushing or pulling heavily loaded hand carts or wheelbarrows; chipping castings; concrete block laying.
4 Very high metabolic rate	290 (>260)	520 (>465)	Very intense activity at fast to maximum pace; working with an axe; intense shovelling or digging; climbing stairs, ramp or ladder; walking quickly with small steps; running; walking at a speed greater than 7 $km \cdot h^{-1}$.

Annex B
(informative)

Evaluation of the metabolic rate at level 2, observation

This annex provides the data to use for characterizing on average a working situation at a specific time in accordance with the two methods given for level 2, observation:

— Method A: 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 the body motion related to work speed (using group assessment tables).

— Method B: the metabolic rate is determined by means of the tabulated values for various activities.

Table B.1 — Metabolic rate (in $W \cdot m^{-2}$) for a seated subject as a function of workload and body segment involved

Body segment		Workload		
		Light	Medium	Heavy
Both hands	Mean	70	85	95
	Range	<75	75 to 90	>90
One arm	Mean	90	110	130
	Range	<100	100 to 120	>120
Both arms	Mean	120	140	160
	Range	<130	130 to 150	>150
The body	Mean	180	245	335
	Range	<210	210 to 285	>285

Table B.2 — Supplement to metabolic rate (in $W \cdot m^{-2}$) for body postures

Body posture	Metabolic rate ($W \cdot m^{-2}$)
Sitting	0
Kneeling	10
Crouching	10
Standing	15
Standing stooped	20

Table B.3 — Metabolic rate for specific activities

Activity		$W \cdot m^{-2}$
Sleeping		40
Reclining		45
At rest, sitting		55
At rest, standing		70
Walking on the level, even path, solid		
1. without load	at 2 $km \cdot h^{-1}$	110
	at 3 $km \cdot h^{-1}$	140
	at 4 $km \cdot h^{-1}$	165
	at 5 $km \cdot h^{-1}$	200
2. with load	10 kg, 4 $km \cdot h^{-1}$	185
	30 kg, 4 $km \cdot h^{-1}$	250
Walking uphill, even path, solid		
1. without load	5° inclination, 4 $km \cdot h^{-1}$	180
	15° inclination, 3 $km \cdot h^{-1}$	210
	25° inclination, 3 $km \cdot h^{-1}$	300
2. with load of 20 kg	15° inclination, 4 $km \cdot h^{-1}$	270
	25° inclination, 4 $km \cdot h^{-1}$	410
Walking downhill at 5 $km \cdot h^{-1}$, without load	5° inclination	135
	15° inclination	140
	25° inclination	180
Ladder at 70°, climbing at a rate of 11,2 $m \cdot min^{-1}$		
without load		290
with a 20 kg load		360
Pushing or pulling a tip-wagon, 3,6 $km \cdot h^{-1}$, even path, solid		
pushing force: 12 kg		290
pulling force: 16 kg		375
Pushing a wheelbarrow, even path, 4,5 $km \cdot h^{-1}$, rubber tyres, 100 kg load		230
Filing iron	42 file strokes/min	100
	60 file strokes/min	190
Work with a hammer, 2 hands, mass of the hammer 4,4 kg, 15 strokes/min		290
Carpentry work	hand sawing	220
	machine sawing	100
	hand planing	300
Brick-laying, 5 bricks/min		170
Screw driving		100
Digging a trench		290
Sedentary activity (office, dwelling, school, laboratory)		70
Standing, light activity (shopping, laboratory, light industry)		95
Standing, medium activity (shop assistant, domestic work, machine work)		115
Work on a machine tool		
Light (adjusting, assembling)		100
Medium (loading		140
Heavy		210
Work with a hand tool		
Light (light polishing)		100
Medium (polishing)		160
Heavy (heavy drilling)		230

Table B.4 — Diary-form for recording activities

Date	
Subject	
Workplace	
Air temperature, °C	
Black-globe temperature, °C	
Air humidity, RH %	
Air velocity, m/s	
Clothing	

Table B.5 — Table summarizing the diary results

Occupation/work task . . . . Date:						
Category		M		**Time**		**Total**
		W·m^{-2}		min		
1	Task 1	M_1	×		=	
2	Task 2	M_2	×		=	
…	…	…	×		=	
i	Task i	M_i	×		=	
…	…	…	×		=	
n	Task n	M_n	×		=	
	Total			……		……
	Time-weighted average metabolic rate					**……**

Annex C
(informative)

Evaluation of the metabolic rate at level 3, analysis

This annex provides the data to use 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 — Relationship between metabolic rate (in W·m^{-2}) and heart rate (in beats per min), predicted as a function of the age and the weight of the subject (for women and men)
(to obtain the metabolic rate, multiply the heart rate HR by the figure on the left in each case and then subtract the figure on the right)

Age (years)	**Weight** (kg)				
	50 kg	**60 kg**	**70 kg**	**80 kg**	**90 kg**
Women					
20	2,9 × HR – 150	3,4 × HR – 181	3,8 × HR – 210	4,2 × HR – 237	4,5 × HR – 263
30	2,8 × HR – 143	3,3 × HR – 173	3,7 × HR – 201	4,0 × HR – 228	4,4 × HR – 254
40	2,7 × HR – 136	3,1 × HR – 165	3,5 × HR – 192	3,9 × HR – 218	4,3 × HR – 244
50	2,6 × HR – 127	3,0 × HR – 155	3,4 × HR – 182	3,7 × HR – 207	4,1 × HR – 232
60	2,5 × HR – 117	2,9 × HR – 145	3,2 × HR – 170	3,6 × HR – 195	3,9 × HR – 219
Men					
20	3,7 × HR – 201	4,2 × HR – 238	4,7 × HR – 273	5,2 × HR – 307	5,6 × HR – 339
30	3,6 × HR – 197	4,1 × HR – 233	4,6 × HR – 268	5,1 × HR – 301	5,5 × HR – 333
40	3,5 × HR – 192	4,0 × HR – 228	4,5 × HR – 262	5,0 × HR – 295	5,4 × HR – 326
50	3,4 × HR – 186	4,0 × HR – 222	4,4 × HR – 256	4,9 × HR – 288	5,3 × HR – 319
60	3,4 × HR – 180	3,9 × HR – 215	4,5 × HR – 249	4,8 × HR – 280	5,2 × HR – 311

Annex D
(informative)

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

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

D.1 Calculation of metabolic rate by the partial method

D.1.1 Personal data

Sex: male

Age: 35 years

Height: 1,75 m

Weight: 75 kg

A_{Du}: 1,90 m^2

D.1.2 Duration of measurement

Preliminary period: 0,05 h (3 min)

Main period: 0,2 h (12 min)

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

D.1.4 Measured values

D.1.4.1 Gas-meter

Correction factor for the gas-meter = 0,998

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

Final reading of the gas-meter = 7 981,2 litres

Initial reading of the gas-meter = 7 775,0 litres

Ventilation = 206,2 litres

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

Fraction of oxygen F_{O_2} 0,162

Fraction of carbon dioxide F_{CO_2} 0,042

D.1.5 Calculation of the expired volume

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

V_{ex}ATPS = 206,2 × 0,998 = 205,8 litres

The STPD reduction factor is calculated from Equation (12):

$$f = \frac{273 \times (100,8 - 3,52)}{(273 + 26,8) \times 101,3} = 0,874$$

Thus

V_{ex}STPD = V_{ex}ATPS × f = 205,8 × 0,874 = 179,9 litres

D.1.6 Calculation of the volume flow rate

$\dot{V}_{ex} = V_{ex}$STPD/t = 179,9/0,2 = 899,5 l/h

D.1.7 Calculation of the oxygen consumption rate

$\dot{V}_{O_2} = \dot{V}_{ex} \times (0,209 - F_{O_2})$ = 899,5(0,209 – 0,162) = 42,3 l O_2/h

D.1.8 Calculation of the carbon dioxide production rate

$\dot{V}_{CO_2} = \dot{V}_{ex} \times (F_{CO_2}$ – 0,000 3) = 899,5(0,042 – 0,000 3) = 37,5 l CO_2/h

D.1.9 Consideration of the shrinkage of the expired volume

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

= 899,5[0,265(1 – 0,162 – 0,042) – 0,162] = 44,0 l O_2/h

$\dot{V}_{CO_2} = \dot{V}_{ex}[F_{CO_2} - 0,000\,38\,(1 - F_{O_2} - F_{CO_2})]$

= 899,5[0,042 – 0,000 38 (1 – 0,162 – 0,042)] = 37,5 l CO_2/h

D.1.10 Calculation of the metabolic rate

$$\mathrm{RQ} = \frac{\dot{V}_{CO_2}}{\dot{V}_{O_2}} = 37,5/44,0 = 0,852$$

EE = (0,23RQ + 0,77) × 5,88 = 5,68 W·h/l O_2

$$M = \mathrm{EE} \times \dot{V}_{O_2} \times \frac{1}{A_{Du}} = 5,68 \times 44,0/1,9 = 131,5\ \mathrm{W \cdot m^{-2}}$$

Due to the limits of accuracy attainable, the result may be rounded to 132 W·m^{-2}.

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

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

D.2.1 Personal data: same as in D.1.1

D.2.2 Duration of measurement

Main period = 0,05 h (3 min)

Recovery period = 0,15 h (9 min)

Test duration = 0,2 h (12 min)

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

D.2.4 Measured values

D.2.4.1 Gas-meter

Correction factor for the gas-meter = 0,998

Temperature of the gas-meter = 26,8 °C

Final reading of the gas-meter = 5 877,5 litres

Initial reading of the gas-meter = 5 707,0 litres

Ventilation = 170,5 litres

D.2.4.2 Fraction of oxygen in the expired air

Fraction of oxygen F_{O_2} = 0,155

D.2.5 Calculation of the expired volume

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

V_{ex}ATPS = 170,5 × 0,998 = 170,2 litres

The STPD reduction factor has the same value as in D.1.5. Thus

V_{ex}STPD = V_{ex}ATPS $\times f$ = 170,2 × 0,874 = 148,8 litres

D.2.6 Calculation of the volume flow rate

$\dot{V}_{ex} = V_{ex}$STPD/t = 148,8/0,2 = 744,0 l/h

D.2.7 Calculation of the oxygen consumption rate

$\dot{V}_{O_2} = \dot{V}_{ex} \times (0{,}209 - F_{O_2})$ = 40,2 l O_2/h

D.2.8 Calculation of the metabolic rate

Using a mean RQ of 0,85 and thereby an energetic equivalent of 5,68 W·h/l O_2, the following result is obtained:

$$M = \text{EE} \times \dot{V}_{O_2} \times \frac{1}{A_{Du}} = 5{,}68 \times 40{,}2/1{,}9 = 120{,}2\ \text{W}\cdot\text{m}^{-2}$$

In order to relate the metabolic rate to the main period, the conversion according to Equation (18) is performed.

The metabolic rate for sitting being 55 W·m^{-2}

$$M = 120{,}2 \times 0{,}2/0{,}05 - 55 \times 0{,}15/0{,}05 = 318{,}8\ \text{W}\cdot\text{m}^{-2}$$

Due to the limits of accuracy attainable, the result may be rounded to 320 W·m^{-2}.

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