TECHNICAL SPECIFICATION

ISO/TS 16976-1

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Respiratory protective devices — Human factors —

Part 1: Metabolic rates and respiratory flow rates

Appareils de protection respiratoire — Facteurs humains —

Partie 1: Régimes métaboliques et régimes des débits respiratoires

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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.

In other circumstances, particularly when there is an urgent market requirement for such documents, a technical committee may decide to publish other types of normative document:

— an ISO Publicly Available Specification (ISO/PAS) represents an agreement between technical experts in an ISO working group and is accepted for publication if it is approved by more than 50 % of the members of the parent committee casting a vote;

— an ISO Technical Specification (ISO/TS) represents an agreement between the members of a technical committee and is accepted for publication if it is approved by 2/3 of the members of the committee casting a vote.

An ISO/PAS or ISO/TS is reviewed after three years in order to decide whether it will be confirmed for a further three years, revised to become an International Standard, or withdrawn. If the ISO/PAS or ISO/TS is confirmed, it is reviewed again after a further three years, at which time it must either be transformed into an International Standard or be withdrawn.

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/TS 16976-1 was prepared by Technical Committee ISO/TC 94, *Personal safety — Protective clothing and equipment*, Subcommittee SC 15, *Respiratory protective devices*.

ISO 16976 consists of the following parts, under the general title *Respiratory protective devices — Human factors*:

— *Part 1: Metabolic rates and respiratory flow rates* [Technical Specification]

The following parts are under preparation:

— *Part 2: Anthropometrics*

— *Part 3: Physiological responses and limitations of oxygen and limitations of carbon dioxide in the breathing environment*

Introduction

For an appropriate design, selection and use of respiratory protective devices, it is important to consider the basic physiological demands of the user. The type and intensity of work affect the metabolic rate (energy expenditure) of the wearer. The weight and weight distribution of the device on the human body also may influence metabolic rate. Metabolic rate is directly correlated with oxygen consumption, which determines the respiratory demands and flow rates. The work of breathing is influenced by the air flow resistances of the device and the lung airways. The work (or energy cost) of a breath is related to the pressure gradient created by the breathing muscles and the volume that is moved in and out of the lung during the breath. Anthropometric and biomechanical data are required for the appropriate design of various components of a respiratory protective device, as well as for the design of relevant test methods.

This Technical Specification is the first part of a series of documents providing basic physiological and anthropometric data on humans. It contains information about metabolic rates and respiratory flow rates for various types of physical activity.

Respiratory protective devices — Human factors —

Part 1:
Metabolic rates and respiratory flow rates

1 Scope

This Technical Specification is part of a series that provides information on factors related to human anthropometry, physiology, ergonomics and performance, for the preparation of standards for performance requirements, testing and use of respiratory protective devices. This Technical Specification contains information related to respiratory and metabolic responses to rest and work at various intensities. Information is provided for:

— metabolic rates associated with various intensities of work;

— oxygen consumption as a function of metabolic rate and minute ventilation for persons representing three body sizes;

— peak inspiratory flow rates during conditions of speech and no speech for persons representing three body sizes as a function of metabolic rates.

The information contained within this Technical Specification represents data for healthy adult men and women of approximately 30 years of age, but is applicable for the age range of the general population.

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 8996:2004, *Ergonomics of the thermal environment — Determination of metabolic rate*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1
aerobic energy production
biochemical process in human cells that delivers energy by combustion of fat, carbohydrates and, to a lesser extent, protein in the presence of oxygen, with water and carbon dioxide as end products

3.2
anaerobic energy production
biochemical process in human cells that delivers energy by combustion of carbohydrates without oxygen, with lactic acid as the end product

3.3
Ambient Temperature Pressure Saturated
ATPS
standard condition for the expression of ventilation parameters related to expired air

NOTE Actual ambient temperature and atmospheric pressure; saturated water vapour pressure.

3.4
Ambient Temperature Pressure Humidity
ATPH
standard condition for the expression of ventilation parameters related to inspired air

NOTE Actual ambient temperature, atmospheric pressure and water vapour pressure.

3.5
breath cycle
respiratory period comprising an inhalation and an exhalation phase

3.6
Body Temperature Pressure Saturated
BTPS
standard condition for the expression of ventilation parameters

NOTE Body temperature (37 °C), atmospheric pressure 101,3 kPa (760 mmHg) and water vapour pressure (6,27 kPa) in saturated air.

3.7
peak inspiratory flow rate
highest instantaneous flow rate during the inhalation phase of a breath cycle, in l/s BTPS

NOTE L/s is the preferred unit as the flow takes place during only a short fraction of the breath cycle.

3.8
minute ventilation
V_E
total volume of air inspired (or expired) in the lungs during one minute, in l/min BTPS

3.9
oxygen consumption
V_{O2}
amount of oxygen consumed by the human tissues for aerobic energy production, in l/min STPD

3.10
physical work capacity
ability of a person to engage in muscular work

3.11
Standard Temperature Pressure Dry
STPD
standard conditions for expression of oxygen consumption

NOTE Standard temperature (0 °C) and pressure (101,3 kPa, 760 mmHg), dry air (0 % relative humidity).

4 Activity and metabolic rate

Users of respiratory protective devices (RPD) perform physical work at various intensities. Physical work, in particular when associated with large muscle groups as is the case with fire fighting, requires high levels of metabolic energy production (metabolic rate). The energy is produced in human cells by aerobic or anaerobic processes.

Aerobic energy production is by far the most common form of energy yield for all types of human cells. It is also the normal form of energy production for the muscles. Depending on physical fitness and other factors, humans can sustain high levels of aerobic energy production for long periods of time. Very high activity levels, however, can only be sustained for short periods of time (minutes) and they also engage the anaerobic energy yielding processes. The associated production of lactic acid is one reason for the early development of fatigue and exhaustion.

Aerobic energy production is strictly dependent on the constant delivery of oxygen to the active cells. Oxygen is extracted from inspired air, bound to haemoglobin in red blood cells in the alveolar capillaries and transported to the target tissues via the circulation. Consequently, there is a direct, linear relationship between the rate of oxygen consumption and the metabolic rate. The relationship is described in ISO 8996.

Table 1 in this Technical Specification is derived from ISO 8996:2004, Table A.2, which defines five classes of metabolic rate. This table forms the basis for developing a standard for the assessment of heat stress. The classes represent types of work found in industry. The figures represent average metabolic rates for work periods or full work shifts, generally including breaks. Metabolic rate shall not be confused with external work rates, such as those defined on a bicycle ergometer.

Rescue work and fire fighting are by nature temporary and often unpredictable. Activities may become very demanding and high levels of metabolic rate have been reported in references [1], [8], [9], [10], [11], [15], [16] and [17]. According to reference [15], mean values for oxygen uptake of between 40 ml/(kg × min) and 45 ml/(kg × min) are reported for the most demanding tasks in fire fighting drills (see references [2], [4] and [8]). Assuming an average body weight of 80 kg, the absolute oxygen uptake is between about 3,2 l/min and 3,6 l/min. In reference [15], mean values of (2,4 ± 0,5) l/min for a 17 min test drill exercise were reported; reference [10] reported a mean value of (2,75 ± 0,3) l/min for a 22 min test drill. The average value for the most demanding task (ascending a tower) was (3,55 ± 0,27) l/min. The range of values for this task was between 3,24 l/min and 4,13 l/min. This corresponded to average metabolic rates of 474 W/m^2 and 612 W/m^2, respectively.

Table 1 — Classification of work based on metabolic rate (MR)

Class	Work	Average metabolic rate W/m^2
1	Resting	65
2	Light work	100
3	Moderate work	165
4	Heavy work	230
5	Very heavy work	290
6	Very, very heavy work (2 h)	400
7	Extremely heavy work (15 min)	475
8	Maximal work (5 min)	600

NOTE The first five classes in this table are derived from ISO 8996. These classes are valid for repeated activities during work shifts in everyday occupational exposure. Classes 6 to 8 are added as examples of metabolic rates associated with temporary activities of an escape and rescue nature whilst wearing RPD.

Table 1 in this Technical Specification contains three additional classes compared to ISO 8996:2004, Table A.2, in order to cover work that is, by its nature, limited by time, such as fire fighting and rescue. One class refers to sustained rescue action, as can be found in mining or in wild land fire fighting, with time periods of up to 2 h of work (class 6). The other two classes refer to fire fighting or rescue operations of short duration and very high intensity, i.e. 15 min (class 7) and 5 min (class 8), respectively. Table 1 presents values expected from individuals with a high level of physical fitness. The highest class (class 8) represents maximal or close to maximal work and can only be endured by fit men for durations of 3 min to 5 min. The three new classes are defined by metabolic rates at 400 W/m^2, 475 W/m^2 and 600 W/m^2, respectively. The values represent the average metabolic rate for the specified period of time, excluding any breaks.

For natural reasons, many types of rescue and emergency work are carried out with personal protective equipment. This adds to the physical work load and is one reason for the high values of metabolic rate in classes 6 to 8. The data given for the types of work shown in classes 1 to 5 is carried out without wearing RPD and/or personal protective equipment.

5 Metabolic rate and oxygen consumption

The energetic equivalent (EE) of oxygen as described in ISO 8996:2004, 7.1.2, is determined using Equation (1):

$$\mathrm{EE} = (0{,}23 \times \mathrm{RQ} + 0{,}77) \times 5{,}88 \tag{1}$$

where RQ is the respiratory quotient (the ratio of the amount of carbon dioxide produced to the amount of oxygen consumed (V_{CO_2} / V_{O_2}), and the energetic equivalent of oxygen is 5,88 Wh/l O_2, which corresponds approximately to the value of 5 kcal/l O_2, a value that is commonly found in the physiological literature.

Assuming a value of 5 kcal/l O_2 (equal to 5,815 Wh/l O_2), the following expressions apply for the conversion of metabolic rates (in W/m^2), to V_{O_2} (in l/min):

$$V_{O_2} = \frac{M \times A_{Du}}{\mathrm{EE}} = \frac{M \times A_{Du}}{60 \times 5{,}815} = \frac{M \times A_{Du}}{349} \tag{2}$$

where

V_{O_2} is the oxygen consumption, in l/min;

M is the metabolic rate, in W/m^2;

A_{Du} is the Dubois body surface area, in m^2;

60 is the conversion factor for min/h;

and the energy equivalent of oxygen is 5,815 Wh/l O_2.

For the same metabolic rate, the oxygen consumption will vary dependant on body size. Examples are given in Tables 2, 3 and 4 for persons representing three body sizes. The associated body surface area is 1,69 m^2, 1,84 m^2 and 2,11 m^2, respectively. As defined in ISO 8996, a person's body surface area, A_{Du}, is determined on the basis of values for body weight, W_b, in kg, and body height, H_b, in m, by Equation (3):

$$A_{Du} = 0{,}202 \times W_b^{0{,}425} \times H_b^{0{,}725} \tag{3}$$

Values for V_{O_2} in Tables 2, 3 and 4 are based on Equations (4), (5) and (6).

A small sized person is defined by W_b = 60 kg, H_b = 1,7 m and A_{Du} = 1,69 m^2. The oxygen consumption, V_{O_2}, is calculated as:

$$V_{O_2} = \frac{M}{207} \tag{4}$$

A medium sized person is defined by W_b = 70 kg, H_b = 1,75 m and A_{Du} = 1,84 m^2. The oxygen consumption, V_{O_2}, is calculated as:

$$V_{O_2} = \frac{M}{190} \tag{5}$$

A large sized person is defined by W_b = 85 kg, H_b = 1,88 m and A_{Du} = 2,11 m^2. The oxygen consumption, V_{O_2}, is calculated as:

$$V_{O_2} = \frac{M}{160} \tag{6}$$

6 Oxygen consumption and minute volume

Oxygen transport to tissues requires its extraction from inspired air in the lungs. Concentration of oxygen in inspired air is equivalent to atmospheric concentration: 20,93 % by volume in dry air. Normally only 15 % to 30 % of this fraction is consumed. The expired air still contains approximately 15 % to 18 % O_2 by volume. This means that the minute ventilation of air, V_E, required for most levels of oxygen consumption is about 20 to 25 times higher (see reference [22]). At high activity levels, the value may be even higher, as there is a tendency for hyperventilation.

Reference [5] contains a review of 19 papers published in the relevant literature. The data for 14 non-respirator studies are plotted again in Figure 1, together with data from references [3], [11] and [12]. Each data point represents the mean value of several individual subjects. The linear regression line for the mean values is plotted. A power function regression line differs only marginally from the linear model. The Hagan equation (at the bottom of the graph) provides an exponential regression that overestimates V_E at low and very high V_{O_2} levels and underestimates at medium levels. Exponential relations have also been proposed by others (see references [1] and [7]). All three of the studies mentioned used incremental exercise as a means of increasing the workload. It can be questioned if V_E and V_{O_2} equilibrate in such a short time. In particular, V_{O_2}, should have a time constant of more than a minute. In the Hagan study, workload was increased every minute.

From a physiological point of view, one would not expect an exponential relationship. Indeed, individual curves show that, up to 60 % to 70 % of maximum V_{O_2}, the relation is almost linear. At higher levels of V_{O_2}, hyperventilation increases V_E in a curvilinear manner (see reference [22]). Respiratory adaptation to increased workloads is likely to represent a two component equation: one linear and one power or exponential. The model equation would be described by

$$y = \left(a \times x\right) + e^{b \times x} \tag{7}$$

where

a, b are constants;

y represents V_E;

x represents V_{O_2}.

At low values of x, the first term is determinant. With increasing x, the second component becomes more and more important. The highest correlation coefficient is obtained for a = 27,1 and b = 0,839. The value of R^2 = 0,90.

Applying a linear regression forced through zero provides a value of R^2 = 0,90. For simplicity, the linear regression is selected. The regression equation for the mean values is given by Equation (8). Calculating V_E for two times the standard error (S_E) of the average V_E, representing 95 % of the populations, gives Equation (9). S_E defines the error in the prediction of V_E, based on the regression equation, Equation (7). These equations are subsequently used for estimations of V_E and peak flows (see Tables 2 to 4).

$$V_E = 31{,}85 \times \overline{V_{O_2}} \tag{8}$$

$$V_E = \left(41{,}48 \times \overline{V_{O_2}}\right) + 2S_E \tag{9}$$

