TECHNICAL SPECIFICATION

ISO/TS 16976-4

First edition
2012-06-15

Respiratory protective devices — Human factors —

Part 4: Work of breathing and breathing resistance: Physiologically based limits

Appareils de protection respiratoire — Facteurs humains —

Partie 4: Travail de respiration et de résistance à la respiration: Limites physiologiques

Reference number
ISO/TS 16976-4:2012(E)

Contents

Page

Foreword

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

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 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order to decide whether it will be confirmed for a further three years, revised to become an International Standard, or withdrawn.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again after a further three years, at which time it must either be transformed into an International Standard or be withdrawn.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 16976-4 was prepared by Technical Committee ISO/TC 94, *Personal Safety — Protective clothing and equipment*, Subcommittee SC 15, *Respiratory protective devices*.

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

— *Part 1: Metabolic rates and respiratory flow rates*

— *Part 2: Anthropometrics*

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

— *Part 4: Work of breathing and breathing resistance: Physiologically based limits*

The following parts are under preparation:

— *Part 5: Thermal effects*

— *Part 7: Hearing and speech*

— *Part 8: Ergonomic factors*

Introduction

A respiratory protective device (RPD) is designed to offer protection from the inhalation of hazardous substances. However, this protection requires extra effort by the respiratory muscles as they need to generate higher pressures to overcome the associated respiratory loads imposed by the RPD.

Copyrighted material licensed to Dublin Institute of Technology by SAI Global (www.saiglobal.com), downloaded on 12 Jul 12 by Ann McSweeney.
No further reproduction or distribution is permitted. Uncontrolled when printed.

Copyrighted material licensed to Dublin Institute of Technology by SAI Global (www.saiglobal.com), downloaded on 12 Jul 12 by Ann McSweeney.
No further reproduction or distribution is permitted. Uncontrolled when printed.

Respiratory protective devices — Human factors —

Part 4:
Work of breathing and breathing resistance: Physiologically based limits

1 Scope

This Technical Specification describes how to calculate the work performed by a person's respiratory muscles with and without the external respiratory impediments that are imposed by RPD of all kinds, except diving equipment. This Technical Specification describes how much additional impediment people can tolerate and contains values that can be used to judge the acceptability of an RPD.

NOTE These calculations are explained in some textbooks on respiratory physiology (in the absence of an RPD), but most omit them or are incomplete in their explanations.

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 16972, *Respiratory protective devices — Terms, definitions, graphical symbols and units of measurement*

ISO/TS 16976-1, *Respiratory protective devices — Human factors — Part 1: Metabolic rates and respiratory flow rates*

3 Terms and definitions, symbols and abbreviated terms

3.1 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 16972 and the following apply.

3.1.1
body temperature pressure saturated
BTPS
standard condition for the expression of ventilation parameters

NOTE 1 Body temperature (37 °C), ambient pressure and water vapour pressure (6,27 kPa) in saturated air.

NOTE 2 Adapted from ISO 16972.

3.1.2
compliance
change in volume of the human lung that results from a change in pressure, measured in l kPa^{-1}

NOTE This term is the typical term for the elastic behaviour of the lungs and chest. **Compliance** is the inverse of **elastance**.

3.1.3
elastance
change in pressure that results from a given volume change of the human lung, measured in kPa/l

NOTE This term is the typical term for the elastic behaviour of an RPD. **Elastance** is the inverse of **compliance.**

3.1.4
relaxation volume
lung volume when respiratory muscles are relaxed, i.e. the volume at the beginning of an inspiration, also known as functional residual capacity (FRC) and expiratory reserve volume (ERV)

3.1.5
tidal volume
V_T
volume of a breath, measured in litres BTPS

3.1.6
vital capacity
VC
volume of the largest breath a person can take, i.e. the volume difference between a maximum inspiration and a maximum expiration, measured in litres BTPS

3.1.7
work of breathing
WOB
work required for an entire breathing cycle, measured in Joules

NOTE Adapted from ISO 16972.

3.1.8
work of breathing per tidal volume
WOB/V_T
normalized WOB (equivalent to volume-averaged pressure), measured in Joules per litre = kPa

3.2 Symbols and abbreviated terms

BTPS body temperature pressure saturated

ERV expiratory reserve volume

FRC functional residual capacity

RPD respiratory protective device

VC vital capacity

WOB work of breathing

p_{el} pressure required to overcome the elastance

p_{aw} pressure required to overcome the flow resistance of the airways

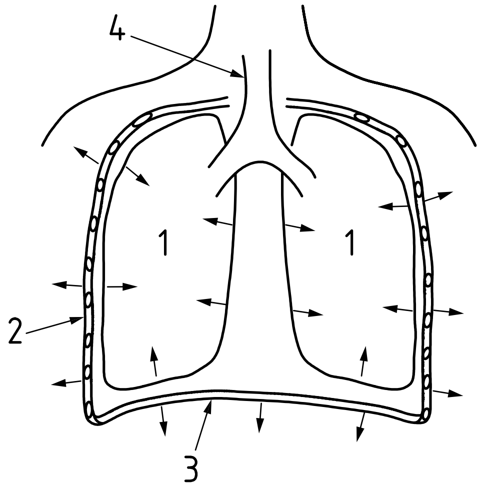
$p_{i,ext}$ pressure required to overcome the inspiratory flow resistance of the RPD

4 Pressure and volume changes during breathing

4.1 Pressure and volume changes in the absence of an RPD

During an inspiration the inspiratory muscles contract which makes the chest expand and the diaphragm flatten. This action causes the lungs to expand to a larger volume. Even in the absence of flow resistance, it takes a certain pressure to expand the chest and lungs. The term used in respiratory physiology for this elastic behaviour is **compliance**. The term **compliance** is also used in laws and regulations; to avoid confusion with this use of the word, the remainder of this Technical Specification will use the term **elastance** instead. By definition, **elastance** is the inverse of **compliance**. **Elastance** describes how much an elastic material changes when a force or a pressure is applied.

Figure 1 shows the lungs (Key 1) inside the chest wall (Key 2) and diaphragm (Key 3). The lungs are connected to the airway (Key 4). The elastance of the lungs tries to act to shrink them (shown by the arrows), similarly to a stretched balloon trying to shrink in volume. The elastance of the chest acts by trying to expand it. Thus, in the absence of muscle effort, the forces on the chest and lungs oppose each other and will, at some volume, be equal and opposite and come to a position of rest. The lung volume at which this happens is referred to as the relaxation volume. During an inhalation the chest wall expands and the diaphragm (Key 3) moves downwards.



Key

1 lungs

2 chest wall

3 diaphragm

4 airway

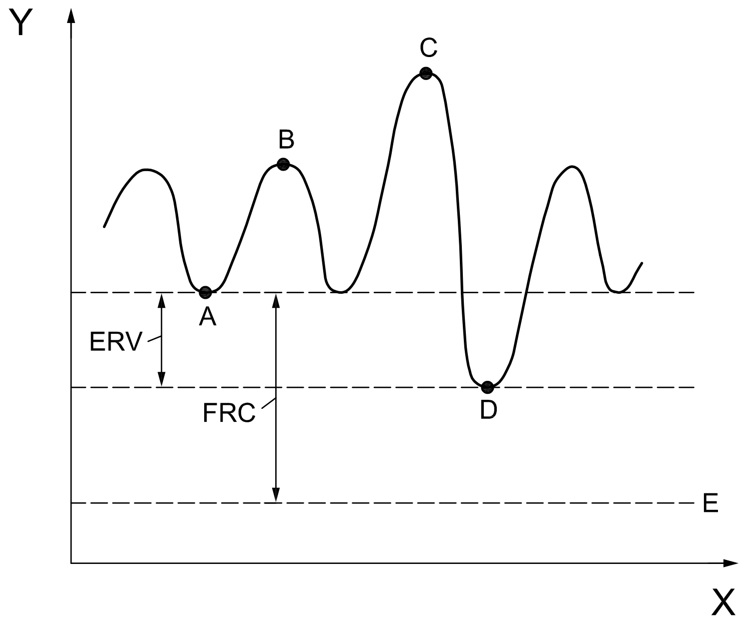
Figure 1 — Schematic cross-section of a person's chest and lungs

Figure 2 illustrates/defines changes in breathing. An inspiration is shown to start at point A and the lung volume increases until it reaches its end, point B, where the following expiration starts. The volume difference between points A and B is the size of the breath, referred to as the tidal volume.

A maximum inspiration is shown at point C and a maximum expiration at point D. The volume difference between these two points is the maximum volume change achievable and is referred to as the vital capacity, VC. The range of VC varies from 3 l to 6 l and depends on a person's age, height and gender. Even with a maximum expiratory effort some volume remains in the lungs. Had the lungs been able to be emptied completely the volume illustrated by line E would have been reached.

Point A is the point where the respiratory muscles are relaxed and that volume is referred to as "relaxation volume". Another term used for this point is "expiratory reserve volume", ERV, which can be calculated as the difference between points A and D. A third term used is "functional residual capacity", FRC, which is the volume difference between points A and E.

Copyrighted material licensed to Dublin Institute of Technology by SAI Global (www.saiglobal.com), downloaded on 12 Jul 12 by Ann McSweeney.
No further reproduction or distribution is permitted. Uncontrolled when printed.



Key

X time

Y lung volume

A start of an inspiration

B end of an inspiration and start of the following expiration

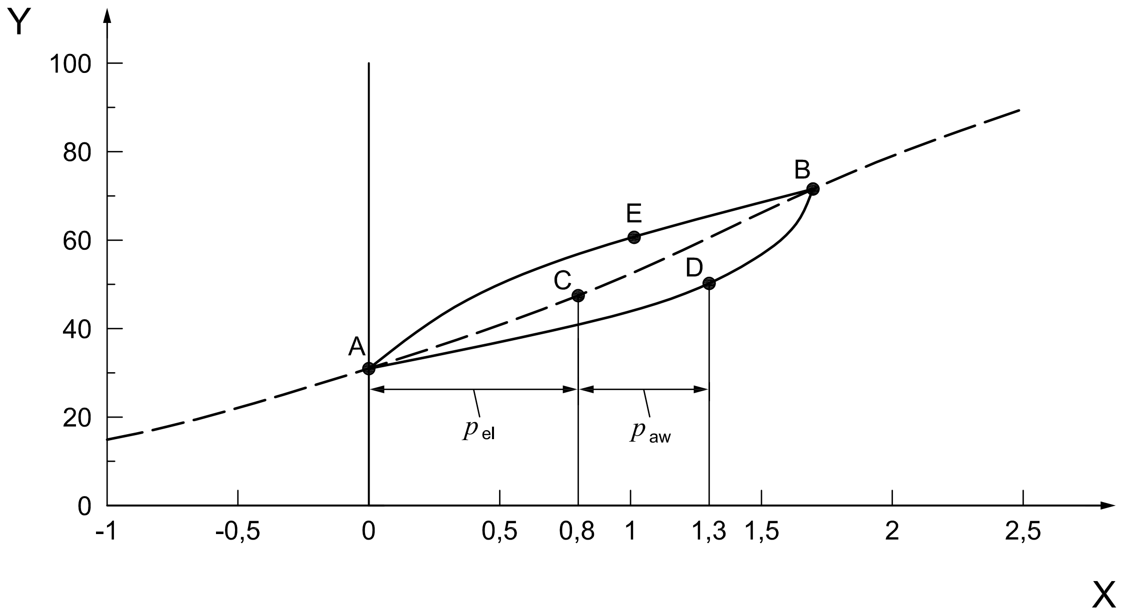
C maximum inspiration

D maximum expiration

E lungs and chest completely empty

Figure 2 — Definitions of volume changes

In order to inhale, effort is required to overcome the combined elastance of the chest and lungs, as well as the flow resistance in the airways. Figure 3 illustrates the pressure generated and the resulting volume changes.



Key

X alveolar pressure, in kPa

Y volume, in percent of VC

A start of an inspiration and end of the following expiration

B end of an inspiration and start of the following expiration

C point on the elastance line partway through an inspiration

D point on the combined elastance and pressure drop line during an inspiration

E point on the combined elastance and pressure drop line during an expiration

NOTE The interrupted line is not a straight line but becomes less steep at low and high volume.

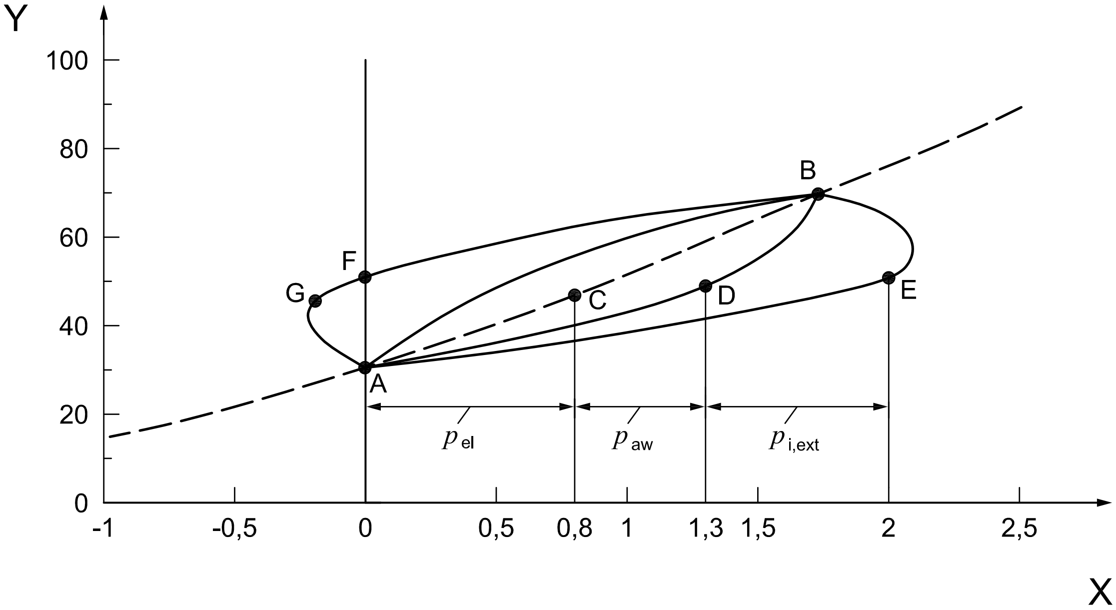
Figure 3 — Lung volume versus pressure in the absence of an RPD (see 4.1 for details)

For a person, the muscles generate the pressure which in turn generates a change in lung volume. Therefore, the pressure is the independent variable and the volume is the dependent one. It is the opposite for an RPD, for which it is the change in volume in the lungs (i.e. gas flow) that generates pressure across a flow resistance. At the beginning of the inspiration (point A in Figure 3) no pressure is generated, i.e. it is the relaxation volume. At the end of the inspiration (point B) the greatest volume has been achieved, called the tidal volume, V_T. The interrupted line shows the interaction of the pressures and volumes from the combined elastance of the chest and lungs. For instance, at point C the elastance requires a pressure of about 0,8 kPa to change the volume to about 50 % of VC; values given are based on a VC of 4 l and a typical textbook value for elastance of 1 kPa/l. The lower solid line ADB shows the total pressure (elastance plus pressure due to flow resistance) generated by the respiratory muscles and the resulting change in volume during the inspiration. The expiration follows the upper solid line BEA. To reach the volume of 50 % VC during inspiration (point D), a total pressure of about 1,3 kPa is required. This is the sum of the pressure of about 0,8 kPa required for the total elastance, p_{el}, and an additional 0,5 kPa (approximately) for the flow resistance of the airway, p_{aw}. Towards the end of the inspiration the flow slows down and the pressure drop due to flow resistance decreases and the inspiration ends at point B where there is no flow. The tidal volume becomes 70 % VC – 30 % VC = 40 % VC. The inspiratory and expiratory curves combine to form a volume-pressure loop.

At the end of the inspiration (point B) pressure is stored due to the total elastance. During low breathing rates this pressure is sufficient to move the gas out during the following expiration. Thus, such an expiration is said to be passive because the expiratory muscles are inactive. However, the inspiratory muscles are active by controlling the flow. When more ventilation is desired, the pressure due to elastance is not sufficient and the expiratory muscles take an active part.

4.2 The effect of RPD flow resistance on pressure and volume changes while using an RPD

An RPD imposes additional flow resistance. This external flow resistance is present both during inspiration and expiration, but does not have to be of the same magnitude. For instance, an unassisted filtering RPD will generally have a larger inspiratory flow resistance. Figure 4 illustrates how the internal and external flow resistances add up. The pressure needed to achieve a volume of 50 % VC is now the pressure at point E. At this point, the external, inspiratory flow resistance requires an additional pressure increase by about 0,7 kPa $p_{\text{i,ext}}$ for a total pressure of about 2 kPa ($p_{\text{el}} + p_{\text{aw}} + p_{\text{i,ext}}$).



Key

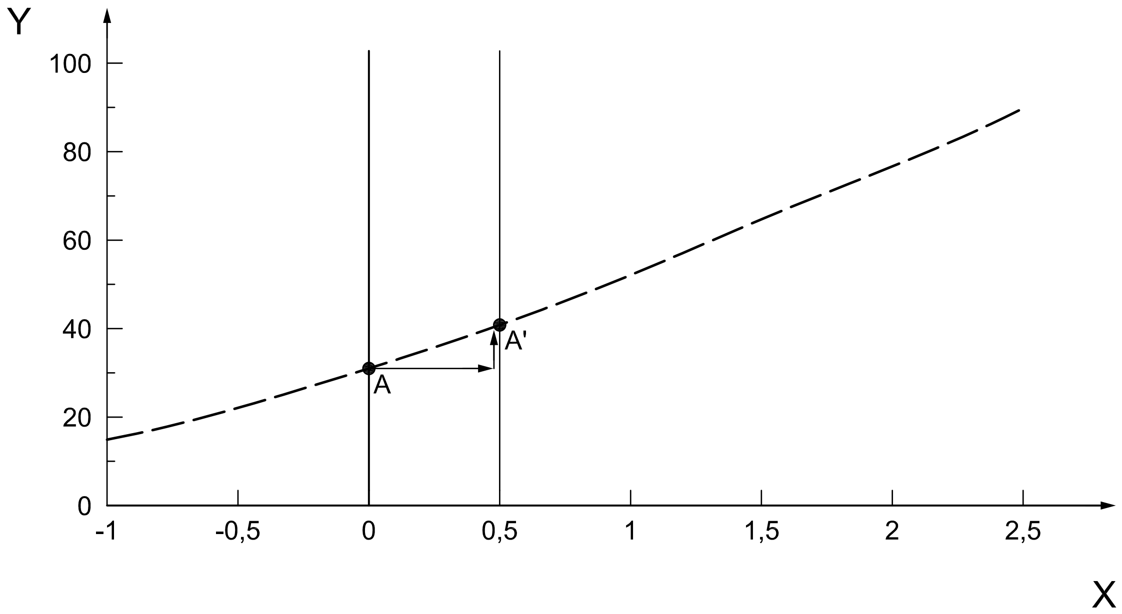
X alveolar pressure, in kPa
Y volume, in percent of VC
A start of an inspiration and end of the following expiration
B end of an inspiration and start of the following expiration
C point on the elastance line partway through an inspiration
D point on the combined line for elastance and internal pressure drop during an inspiration
E point on the combined line for elastance and pressure drop (internal and external) during an inspiration
F point during an expiration where expiratory muscles start to generate pressure to continue expiration
G point during expiration, beyond point F, where the expiratory muscles generate pressure

Figure 4 — Lung volume versus pressure in the presence of an RPD (see 4.2 for details)

4.3 The effect of RPD with static pressure on pressure and volume changes while using an RPD

Some RPD are designed to have a positive pressure to improve protection against contaminants. Figure 5 illustrates how such a pressure influences lung mechanics. For this illustration, a static pressure (i.e. the pressure in the RPD in the absence of gas flow) of +0,5 kPa is assumed. Without the positive pressure, an inspiration starts at point A. The static pressure moves the new relaxation volume (point A') 0,5 kPa horizontally. The elastance curve determines the vertical movement which becomes 10 % VC. Thus, this static pressure is sufficient to move the relaxation volume from 30 % VC to 40 % VC.

Copyrighted material licensed to Dublin Institute of Technology by SAI Global (www.saiglobal.com), downloaded on 12 Jul 12 by Ann McSweeney.
No further reproduction or distribution is permitted. Uncontrolled when printed.



Key

X alveolar pressure, in kPa

Y volume, in percent of VC

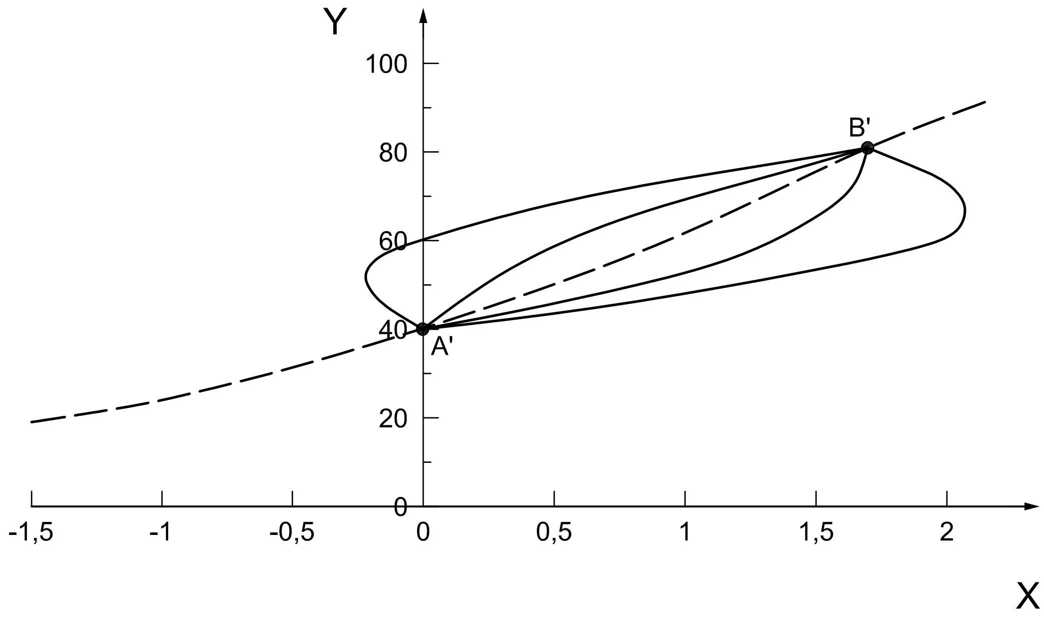
A start of an inspiration

A’ start of an inspiration with a positive static pressure

Figure 5 — Lung volume versus pressure in the presence of an RPD with static pressure (see 4.3 for details)

4.4 The effect of RPD flow resistance and static pressure on pressure and volume changes while using an RPD

For this type of RPD, the static pressure changes the relaxation volume. Using the numbers from the example given in 4.3 and in Figure 5, the new starting point is at 40 % VC. Figure 6 illustrates how the volume versus pressure plot changes. By comparing Figures 4 and 6, it can be noted that the only noticeable difference is the starting and ending points (A’ and B’). Since A’ is the relaxation volume, the pressure generated by the respiratory muscles is zero. However, the pressure measured in the RPD would be 0,5 kPa.



Key

X alveolar pressure (relative to relaxation pressure), in kPa

Y volume, in percent of VC

Figure 6 — Lung volume versus pressure in the presence of an RPD with flow resistance and static pressure (see 4.5 for details)

4.5 Effects of high static pressure

As can be seen from Figure 6, a large static pressure will move the end of a breath (B') towards higher lung volumes and restrict the tidal volume as point B' approaches 100 % VC. In addition, at high lung volumes the lungs and chest get less elastic which makes it harder and harder to reach the desired volume at the end of inspiration. It has been shown that people resist the volume change imposed by static loads, both positive and negative[7][10]. Only a third to half of the volume change that could be expected actually happened. This means that the respiratory muscles are active, generating the required pressure to resist the imposed static pressure. Such muscle activity is a physiological load.

The typical diastolic pressure (i.e. pressure between heart beats) in the blood circulation in the lung is 0,7 kPa to 1,1 kPa[3][15]. Therefore, an excessive positive pressure may also have undesirable effects by reducing the blood flow in the lungs and therefore the venous return. High static pressures will also make expiration more difficult, increasing the work for the expiratory muscles.

5 Work of breathing (WOB)

5.1 Physiological work versus physical work

5.1.1 General

There is a difference between the physiological work and physical work. This is particularly noticed from static work or when work is performed on elastic materials.

5.1.2 Static work

Static work is performed when a muscle is active but no motion results, for instance when holding an arm outstretched. It can be tiring to do so. This is physiological work since the muscle is expending energy. However, from a physical perspective no work is done since there was no motion.

5.1.3 Elastic work

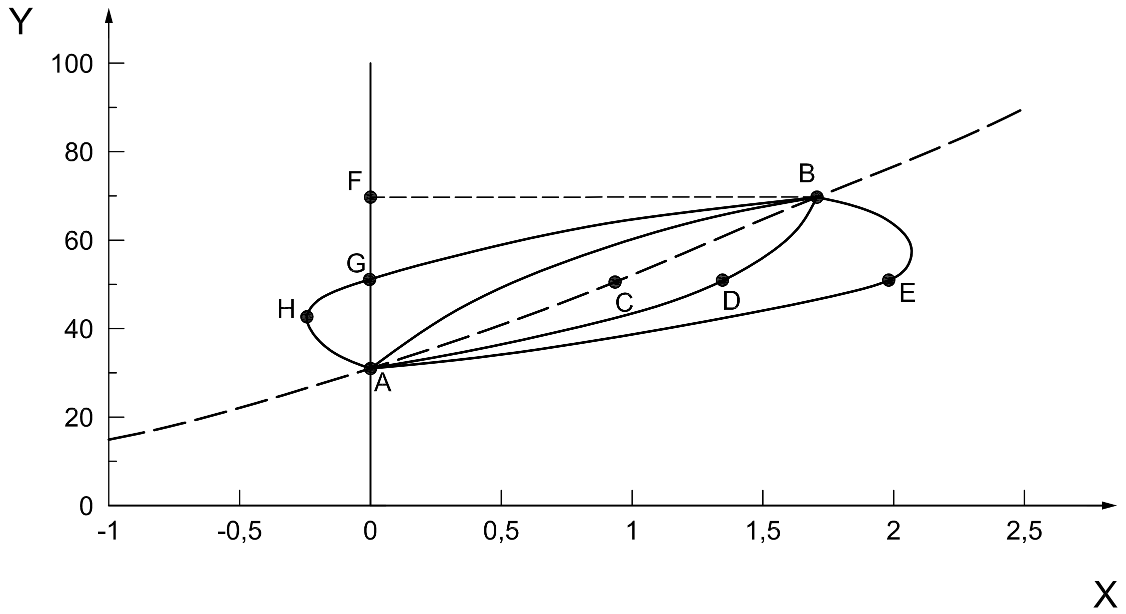
Physiological work is also performed against elastic materials. Consider an ideal rubber band: when the band is stretched, energy is stored and can be returned when the band is returned to its original length. Therefore, no net physical work was performed. If a muscle is used to stretch this rubber band, then effort is expended by the muscle. When the rubber band is allowed to return to its original length under control (not just let go of) more effort is expended. In other words, the energy stored in the band is not returned to the muscle. On the contrary, energy is consumed during both the stretching phase and the returning phase. Since the force generated is always in the same direction but the direction of the resulting movement changes when the rubber band shortens, the product can be either positive or negative.

5.1.4 Positive and negative physical work

From a physical perspective, negative work can be seen as the return of energy. However, from a physiological perspective, both positive physical work and negative physical work cost energy. The physiological cost of negative work is less than for positive work (see, for example, References [1] and [9]).

5.2 Calculations of inspiratory WOB

The inspiratory WOB can be calculated from recordings of pressure and the resulting volume. The work can be divided into three parts: work against the elastance, the internal flow resistance and external, inspiratory flow resistance. The work against the elastance can be seen in Figure 7 as the triangle formed by ACBFA. The work against internal flow resistance can be seen as the area formed by ADBCA. Similarly, the work against the external, inspiratory flow resistance can be seen as the area formed by AEBDA. Thus, the total work (physical as well as physiological) of the inspiration is the area enclosed by the AEBFA.



Key

X alveolar pressure, in kPa

Y volume, in percent of VC

A start of an inspiration and end of the following expiration

B end of an inspiration and start of the following expiration

C point on the elastance line partway through an inspiration

D point on the combined line for elastance and internal pressure drop during an inspiration

E point on the combined line for elastance and pressure drop (internal and external) during an inspiration

F point at zero pressure and the same volume as point B

G point during an expiration where expiratory muscles start to generate pressure to continue expiration

H point during expiration, beyond point F, where the expiratory muscles generate pressure

Figure 7 — Lung volume versus pressure for calculations of WOB: illustration for a person wearing a resistive RPD (see 5.2 and 5.3 for details)

5.3 Calculations of expiratory WOB

The expiratory WOB can be seen for the breath in Figure 7 broken down in two parts. The stored elastic pressure pushes the gas out but inspiratory muscles are generating pressure to control the expiratory flow. Part 1 of the work is represented by the area formed by BFGB. Since the pressure generated is positive but the flow has changed direction, the physiological work is negative. Part 2, the positive physical and positive physiological work generated by the expiratory muscles, is represented by the area enclosed by GHAG.

5.4 Calculations of total WOB

5.4.1 Calculations of the wearer's WOB while using an RPD

The total WOB is the sum of the inspiratory and expiratory physical work as explained in 5.2 and 5.3. For the breath in Figure 7 the physical positive work by the inspiratory muscles is the area AEBFA. Negative physiological work by the inspiratory muscles is BFGB. Positive work by the expiratory muscles is represented by the area GHAG.

It is obvious that the WOB for an RPD and its wearer is difficult to predict and calculate. The parameters needed (e.g. flow resistance, elastance, cost of negative work) are hard to quantify in all situations and vary between individuals. It is not practical to provide theoretical calculations for all situations. However, empirical data are available to guide in finding acceptable levels of WOB.

5.4.2 Calculations of WOB for an RPD only

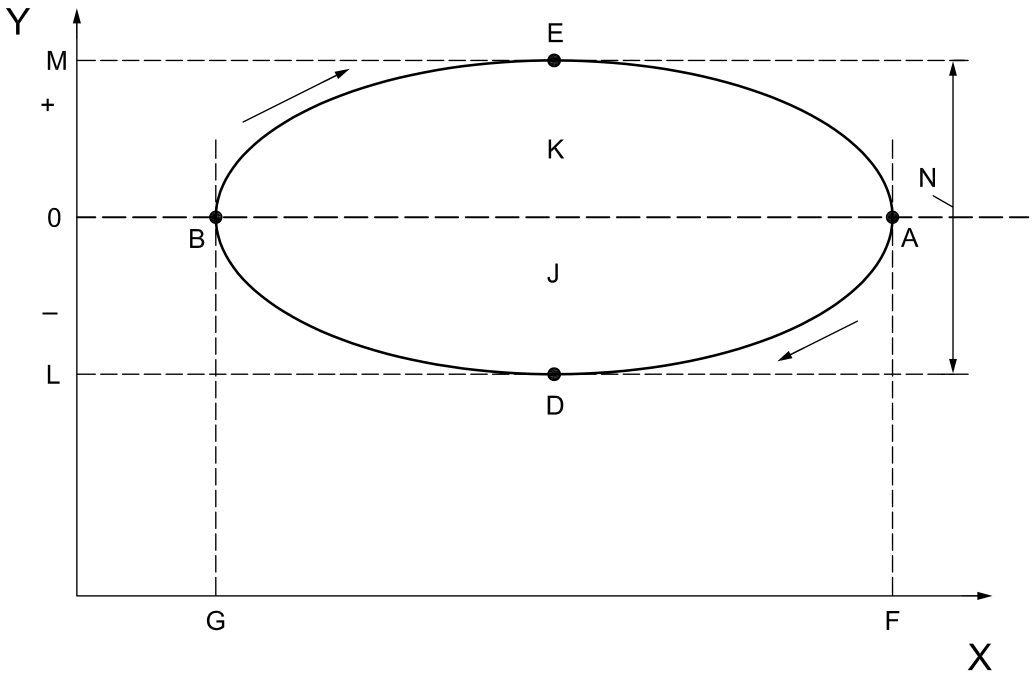
A brief description is warranted to show the link between a person's volume-pressure loop and an RPD's pressure-volume loop. It is also worth noting that, for an RPD, the air flow is imposed on it by the wearer and this causes a pressure change. Therefore, for an RPD, the volume is the independent variable and the pressure the dependent one.

NOTE 1 Measurements for the WOB for an RPD alone are shown in ISO 16900-12.

Figure 8 shows an example of a pressure-volume loop for just an RPD. Axis X shows volume changes and axis Y shows the pressure. An inspiration starts at point A and follows the line ADB and ends at point B. The tidal volume is the difference in volume between points F and G. The expiration follows line BEA. The inspiratory WOB is the area J enclosed by ADBA. The expiratory WOB is the area K enclosed by BEAB. Any elastic behaviour of the RPD would be shown as pressure difference between points A and B.

Commonly, the WOB/V_T varies from 0,1 kPa at rest up to over 4 kPa at 135 l/min.

NOTE 2 See ISO 16900-12 for more information.



Key

X volume
Y pressure
A start of an inspiration and end of the following expiration
B end of an inspiration and start of the following expiration
D lowest pressure point during the inspiration
E highest pressure point during the expiration
F volume at the start of inspiration
G volume at the end of inspiration
J area representing inspiratory WOB
K area representing expiratory WOB
L lowest inspiratory pressure
M highest expiratory pressure
N peak to peak pressure

Figure 8 — Pressure-volume loop for an RPD (see 5.4.2 for details)

5.5 Breathing resistance

Peak inhalation breathing pressure (historically called "inhalation breathing resistance") is the lowest pressure during inspiration (L in Figure 8). Peak exhalation breathing pressure (historically called "exhalation breathing resistance") is the highest pressure during expiration (M). However, the WOB includes all parts and dynamic behaviour of an RPD during a breath, not just the peak pressures.

5.6 Physiologically acceptable WOB

Several authors[2][4][5][6][13][14][16][17] have proposed limits on the respiratory effort imposed by an RPD. Data have recently been summarized[12] from these studies and new data added from exercise testing at high workloads in a laboratory with and without an unassisted filtering RPD. In deciding on acceptable levels of WOB, considerations were given to the effects of flow resistance in three ways:

a) lack of reduction in minute ventilation,

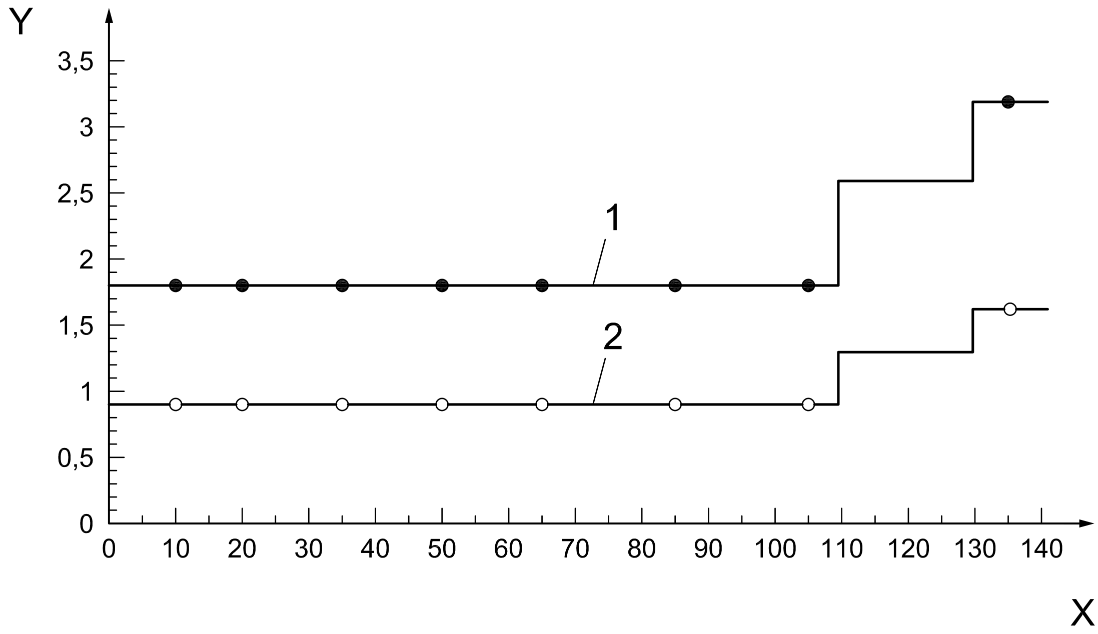
b) lack of reduction in exercise endurance,

c) avoidance of respiratory distress in 80 % to 90 % of the people studied.

The limits are expressed as normalized WOB, i.e. WOB divided by the tidal volume. This is equivalent to volume-averaged pressure and has the unit of pressure (kPa).

The ability to tolerate added respiratory loads may be affected by certain diseases.

Most RPD have differences between the inspiratory and expiratory flow resistance. Therefore, the WOB should be calculated separately for inspiration and expiration. It was concluded[12] (see Figure 9) that for long duration exercise (up to 1 h) the inspiratory WOB/V_T should not exceed 0,9 kPa. The authors[12] noted that people who could maintain high minute ventilations could also sustain higher levels of WOB/V_T. Thus, for short-term limits with a minute ventilation exceeding 110 l/min, the inspiratory WOB/V_T should be less than 1,3 kPa, while for minute ventilations exceeding 130 l/min the inspiratory WOB/V_T should be less than 1,6 kPa. The authors argued, based on two published studies, that the expiratory WOB/V_T can be as large as the inspiratory WOB/V_T. The authors further proposed that the peak inspiratory pressure should not exceed 1,2 kPa for minute ventilations up to 110 l/min; it should not exceed 1,8 kPa for minute ventilations in the range 110 l/min to 130 l/min and for minute ventilation above 130 l/min it should not exceed 2,0 kPa. Table 1 shows a summary of these values for the eight classes of minute ventilations as defined in ISO/TS 16976-1.



Key

X minute ventilation, in l/min

Y WOB per tidal volume, WOB/V_T, in kPa

1 maximum total WOB/ V_T

2 maximum level for each of inspiratory and expiratory WOB/V_T

NOTE The dots indicate the eight classes of minute ventilations as defined in ISO/TS 16976-1.

Figure 9 — Physiologically acceptable levels of WOB/V_T

Table 1 — Physiologically acceptable levels of WOB/V_T, peak pressures and elastance tabulated for the eight classes of minute ventilations as defined in ISO/TS 16976-1

Minute ventilation	WOB/V_T		Peak pressures		Elastance
	Inspiratory	Expiratory	Inspiratory	Expiratory	
(l/min)	(kPa)	(kPa)	(kPa)	(kPa)	kPa/l
10	0,9	0,9	1,2	1,2	1,0
20	0,9	0,9	1,2	1,2	1,0
35	0,9	0,9	1,2	1,2	1,0
50	0,9	0,9	1,2	1,2	1,0
65	0,9	0,9	1,2	1,2	1,0
85	0,9	0,9	1,2	1,2	1,0
105	0,9	0,9	1,2	1,2	1,0
135	1,6	1,6	2,0	2,0	1,0

6 Other respiratory loads

6.1 Static load

Subclause 4.4 showed how the relaxation volume changes with externally applied static pressure and pointed out that tidal volume may become restricted. A slight increase in lung volume is likely to increase the diameter of the airways which would decrease the flow resistance. A few studies have been conducted on the effects of static pressure in divers. These are summarized in Reference [17], which states that static loads for exercising people should not exceed +1,0 kPa to +1,5 kPa and should not be more negative than –1 kPa.

6.2 Elastic loads

As discussed in 5.1.3, there is a physiological load associated with elastic materials. The elastic behaviour of the chest and lungs are referred to as **compliance** in respiratory physiology while for an RPD it is referred to as **elastance**. An RPD can exhibit elastance if a mask or a hose deforms during heavy breathing. An RPD with spring loaded bags or bellows (such as closed-circuit RPD) has elastance since the pressure changes with volume. Apparently, only one study has determined acceptable levels of external elastance[17]. The investigators found that an imposed elastance of 0,7 kPa/l was acceptable but 1,4 kPa/l was not. In these experiments with diving subjects the breathing resistance was kept at a minimum. People wearing tight wetsuits or tight elastic straps may experience an additional elastic load. Two other limits on elastance[8][11] have set the limit to be 1,0 kPa/l which is set as the limit here (see Table 1).

6.3 Other loads

Restrictive straps may force a person to change body posture which may restrict breathing, thus making it harder to use the RPD. A change in body posture may also change the lung and chest compliance.

Inspired CO_2 (e.g. from the respiratory interface dead space and/or from incomplete CO_2 removal in a rebreather) forces a wearer to increase the minute ventilation. The weight of an RPD will also force the wearer to work harder and increase the minute ventilation. Increased minute ventilation amplifies the effects of the respiratory loads. The WOB should therefore be judged at the resulting minute ventilation, not at the nominal minute ventilation.

6.4 How respiratory loads add up

It is not obvious how flow resistance, static load and elastic loads add to a total load. After all, flow resistance acts primarily at the highest flow (typically in the middle of the breath), an elastic load acts mostly at large volumes (end of a breath) while a static load is always present. However, there is an easy way to add the loads[17]: they are additive if each load is expressed as a fraction of the maximum value when acting alone in that situation. This means that the total acceptable respiratory load can be calculated by adding the relative value for each load:

$$\text{Total \%} = \text{\% WOB}/V_T + \text{\% static load} + \text{\% elastic load}$$

For instance, assume that an RPD has an inspiratory WOB/V_T of 0,5 kPa and an expiratory of WOB/V_T of 0,4 kPa at 65 l/min. The total WOB/V_T would be 0,9 kPa. At 65 l/min the acceptable WOB/V_T is 1,8 kPa. Thus, the %WOB/V_T is 0,9/1,8 kPa = 0,5, i.e. the measured WOB/V_T is 50 % of what is acceptable at that workload. Any other respiratory loads are handled the same way and the total can be calculated. If the sum approaches or exceeds 100 % the wearer will be restricted.

It is possible to change one of the parameters, say the static load, which may influence the practical value of the WOB/V_T.

7 Summary

The physiologically acceptable WOB has to be considered separately for an inspiration and an expiration. The maximum acceptable WOB for each of the inspiratory and expiratory WOB/V_T, as well as peak pressures (breathing resistance), depend on the minute ventilation. The values given apply to all types of RPD.

Bibliography

[1] ABBOTT, B.C., BIGLAND, B., RITCHIE, J.M. *The Physiological Cost of Negative Work*. J. Physiol 1952; 117: 380-390

[2] BENTLEY, R.A., GRIFFIN, O.G., LOVE, R.G., MUIR, D.C.F., SWEETLAND, K.F., *Acceptable Levels for Breathing Resistance of Respiratory Apparatus.* Arch. Environ. Health, 1973; 27 (4): 273-2`0

[3] BERNE, R.M., LEVY, M.N.. *Cardiovascular Physiology.* Fifth Edition, the C.V. Mosby Company, St. Louis, MO; 1986

[4] CARETTI, D.M., WHITLEY, J.A. *Exercise Performance during Inspiratory Resistance Breathing under Exhaustive Constant Load Work.* Ergonomics 2007; 41 (4): 501-511

[5] COOPER, E.A. *Suggested Methods of Testing and Standards of Resistance for Respiratory Protective Devices.* J. Appl. Physiol. 1960; 15 (6): 1053-1061

[6] DENO, N.S., KAMON, E., KISER, D.M. *Physiological Responses to Resistance Breathing During Short and Prolonged Exercise*. Am. Ind. Hyg. Assoc. J., 1981; 42 (8): 616-623

[7] DERION, T., REDDAN, W.G., LANPHIER, E.H. *Static lung load and posture effects on pulmonary mechanics and comfort in underwater exercise*. Undersea Biomedical Research, 1992; 19(2): 85-96

[8] European Committee for Standardization, *Respiratory Equipment — Self-contained Re-breathing Diving Apparatus*, European Standard EN 14143, European Committee for Standardization

[9] HESSER, C.M., LINNARSSON, D., BJURSTEDT, H. *Cardiorespiratory and Metabolic Responses to Positive, Negative and Minimum-load Dynamic Leg Exercise*. Respiration Physiol 1977; 30: 51-67

[10] HICKEY, D.D., NORFLEET, W.T., PÅSCHE, A.J., LUNDGREN, C.E.G. *Respiratory function in the upright, working diver at 6.8 ATA (190 fsw).* Undersea Biomedical Research, 1987; 14(3): 241-262

[11] NATO Standard Agreement 1410: Standard unmanned test procedures and acceptance criteria for underwater breathing apparatus

[12] SHYKOFF, B.S., WARKANDER, D.E. *Physiologically Acceptable Resistance of an Air Purifying Respirator*, Ergonomics 2011; 54(12): 1186-1196

[13] SILVERMAN, L., LEE, R.C., LEE, G., DRINKER, K.R., CARPENTER, T.M. *Fundamental Factors in the Design of Protective Respiratory Equipment: Inspiratory Airflow Measurements of Human Subjects with and without Resistance,* Final Report OSRD Contract OEMar306. Harvard, MA: Harvard School of Public Health, 1943

[14] SILVERMAN, L., LEE, G., PLOTKIN, T., AMORY, L., YANCY, A.R. *Fundamental Factors in the Design of Protective Respiratory Equipment: Inspiratory and Expiratory Air Flow Measurements on Human Subjects with and without Resistance at Several Work Rates*, Report OSRD no 5732. Harvard, MA: Harvard School of Public Health, 1945

[15] VANDER, A.J., SHERMAN, J.H., LUCIANO, D.S. *Human Physiology; the Mechanisms of Body Function*. Sixth edition. McGraw-Hill Inc, New York, 1994

[16] WARKANDER, D.E., NORFLEET, W.T., NAGASAWA, G.K., LUNDGREN, C.E.G. *Physiologically and Subjectively Acceptable Breathing Resistance in Divers' Breathing Gear*. Undersea Biomed Res. 1992; 19: 427-445

[17] WARKANDER, D.E., LUNDGREN, C.E.G. *Development of Comprehensive Performance Standards for Underwater Breathing Apparatus* [online]. Buffalo, NY, Center for Research and Education in Special Environments, State University of New York at Buffalo, 2001. Available from: http://archive.rubicon-foundation.org/ 7598 [Accessed 10 Dec 2010]

[18] ISO 16900-12, *Respiratory protective devices — Methods of test and test equipment — Part 12: Leak test methods*[1)]

1) Under preparation.

Copyrighted material licensed to Dublin Institute of Technology by SAI Global (www.saiglobal.com), downloaded on 12 Jul 12 by Ann McSweeney.
No further reproduction or distribution is permitted. Uncontrolled when printed.

ICS 13.340.30

Price based on 16 pages