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Respiratory protective devices — Human factors —

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

Appareils de protection respiratoire — Facteurs humains —

Partie 3: Réponses physiologiques et limitations en oxygène et en gaz carbonique dans l'environnement respiratoire

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Foreword

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ISO/TS 16976-3 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*

Introduction

Due to the nature of their occupations, millions of workers worldwide are required to wear respiratory protective devices (RPD). RPD vary considerably, from filtering devices, supplied breathable gas devices, and underwater breathing apparatus (UBA), to escape respirators used in emergency situations (self-contained self-rescuer or SCSR). Many of these devices protect against airborne contaminants without supplying air or other breathing gas mixtures to the user. Therefore, the user might be protected from particulates or other airborne toxins but still be exposed to an ambient gas mixture that differs significantly from that which is normally found at sea level. RPD that supply breathing air to the user, such as an SCBA or UBA, can malfunction or not adequately remove carbon dioxide from the breathing space, thus exposing the user to an altered breathing gas environment. In special cases, RPD intentionally expose the wearer to breathing gas mixtures that significantly differ from the normal atmospheric gas mixture of approximately 79 % nitrogen and 21 % oxygen with additional trace gases. These special circumstances occur in aviation, commercial and military diving, and in clinical settings.

Breathing gas mixtures that differ from normal atmospheric can have significant effects on most physiological systems. Many of the physiological responses to exposure to high or low levels of either oxygen or carbon dioxide can have a profound effect on the ability to work safely, to escape from a dangerous situation, and to make clear judgements about the environmental dangers. In addition, alteration of the breathing gas environment can, if severe enough, be dangerous or even fatal. Therefore, monitoring and controlling the breathing gas, and limiting user exposure to variations in the concentration or partial pressure of oxygen and carbon dioxide, is crucial to the safety and health of the worker.

This Technical Specification discusses the gas composition of the Earth's atmosphere; the basic physiology of metabolism as the origin of carbon dioxide in the body, respiratory physiology and the transport of oxygen to the cells and tissues of the body; and the subsequent transport of carbon dioxide from the tissues to the lungs for removal from the body. Following the basic physiology of respiration, this Technical Specification addresses the physiological responses to altered breathing environments (hyperoxia, hypoxia) and to the effects of excess carbon dioxide in the blood (hypercarbia). Examples are given from the relevant biomedical literature.

Finally, it deals with the impact of altered partial pressures/concentrations of oxygen and carbon dioxide on respirator use. The content of this Technical Specification is intended to serve as the basis for advancing research and development of RPD with the aim of minimizing the changes in the breathing environment, thus minimizing the physiological impact of RPD use on the wearer. If this can be accomplished, the health and safety of all workers required by their occupation to wear RPD will be enhanced.

Respiratory protective devices — Human factors —

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

1 Scope

This Technical Specification gives:

— a description of the composition of the Earth's atmosphere;

— a description of the physiology of human respiration;

— a survey of the current biomedical literature on the effects of carbon dioxide and oxygen on human physiology;

— examples of environmental circumstances where the partial pressure of oxygen or carbon dioxide can vary from that found at sea level.

This Technical Specification identifies oxygen and carbon dioxide concentration limit values and the length of time within which they would not be expected to impose physiological distress. To adequately illustrate the effects on human physiology, this Technical Specification addresses both high altitude exposures where low partial pressures are encountered and underwater diving, which involves conditions with high partial pressures. The use of respirators and various work rates during which RPD can be worn are also included.

2 Terms and definitions, symbols and abbreviated terms

2.1 Terms and definitions

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

2.1.1
alveoli
s. alveolus
terminal air sacs of the lungs in which respiratory gas exchange occurs between the alveolar air and the pulmonary capillary

NOTE The alveoli are the anatomical and functional unit of the lungs.

2.1.2
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 pressure.

2.1.3
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.

2.1.4
carbaminohaemoglobin
$HbCO_2$
haemoglobin that has bound carbon dioxide at the tissue site for transport to the lungs

2.1.5
dead space
‹anatomical› conducting regions of the pulmonary airways that do not contain alveoli and, therefore, where no gas exchange occurs

NOTE These areas include the nose, mouth, trachea, large bronchia, and the lower branching airways. This volume is typically 150 ml in a male of average size.

2.1.6
dead space
‹physiological› sum of all anatomical dead space as well as under-perfused (reduced blood flow) alveoli which are not participating in gas exchange

NOTE The volume of the physiological dead space can vary with the degree of ventilation. Thus, the physiological dead space is the fraction of the tidal volume that does not participate in gas exchange in the lungs.

2.1.7
dyspnoea
sense of air hunger, difficult or laboured breathing, or a sense of breathlessness

2.1.8
end-tidal carbon dioxide
ET CO_2
volume fraction of carbon dioxide in the breath at the mouth at the end of exhalation

NOTE End-tidal carbon dioxide corresponds closely to alveolar carbon dioxide.

2.1.9
haemoglobin
Hb
specific molecules contained within all red blood cells that bind oxygen or carbon dioxide under normal physiological states and transport either oxygen or carbon dioxide to or from the tissues of the body

2.1.10
hypercarbia
hypercapnia
excess amount of carbon dioxide in the blood

2.1.11
hyperoxia
volume fraction or partial pressure of oxygen in the breathing environment greater than that which is found in the Earth's atmosphere at sea level, which contributes to an excess of oxygen in the body

NOTE This can occur when a person is under hyperbaric conditions (i.e. diving), subjected to breathing gas mixtures with an elevated oxygen fraction, or during certain medical procedures

2.1.12
hypoxia
volume fraction or partial pressure of oxygen in the breathing environment below that which is found in the Earth's atmosphere at sea level

NOTE Anaemic hypoxia is due to a reduction of the oxygen carrying capacity of the blood as a result of a decrease in the total haemoglobin or an alteration in the haemoglobin constituents.

2.1.13
hypocapnia
volume fraction or partial pressure of carbon dioxide in the breathing environment or in the body that is lower than that which is found in the Earth's atmosphere at sea level

NOTE This usually occurs under hyperventilation conditions (i.e. diving) or in medical settings that contribute to a reduction of carbon dioxide in the body

2.1.14
inotropic
affecting the force of muscle contraction

NOTE A negative inotropic effect reduces and a positive inotropic effect increases the force of muscular contraction (e.g. both skeletal and heart muscle).

2.1.15
medulla oblongata, pons
areas of the brain where the respiratory control centre is located

2.1.16
oxyhaemoglobin
HbO_2
haemoglobin that has bound oxygen from the lungs for transport to the body tissues

2.1.17
partial pressure
pressure exerted by each of the components of a gas mixture to form a total pressure

EXAMPLE Air is a mixture of oxygen, nitrogen, carbon dioxide, inert gases (argon, neon), and water vapour. The volume fraction of oxygen in air is about 20,9 %. At sea level, total atmospheric pressure is 101,3 kPa (760 mmHg). Water vapour pressure is 6,26 kPa (47 mmHg) (fully saturated in the lungs at a body temperature of approximately 37 °C). To find partial pressure of oxygen, subtract vapour pressure from total atmospheric pressure and then multiply the oxygen volume fraction by the dry atmospheric pressure. Thus, 101,3 − 6,3 = 95,1 kPa (760 mmHg − 47 mmHg = 713 mmHg); 0,21 × 95,1 kPa = 19,9 kPa (= 149 mmHg). If the ambient pressure increases (as in diving), the partial pressure of each component gas increases. Thus, at 2 atm absolute, the partial pressure of oxygen in dry gas is 101,3 × 2 = 202,6 kPa (760 mmHg × 2 = 1 520 mmHg); 0,21 × 202,6 = 42,6 kPa (0,21 × 1520 mmHg = 319 mmHg) oxygen.

NOTE 1 Partial pressure is dependent on the volume fraction of the component gas.

NOTE 2 The partial pressure of a gas can increase or decrease while its relative volume fraction remains the same. Partial pressure drives the diffusion of gas across cell membranes and is, therefore, more important than relative volume fraction of the gas.

2.1.18
respiratory quotient
R_Q
ratio of volume of carbon dioxide exhaled to the volume of oxygen consumed as follows

$$R_Q = V\text{CO}_2 / V\text{O}_2$$

where

VCO_2 is the volume of carbon dioxide exhaled;

VO_2 is the volume of oxygen consumed

NOTE R_Q gives an estimate of the content of substrate utilization during steady-state respiration and metabolism. At rest, R_Q = 0,82 reflecting a substrate utilization of a combination of carbohydrates and fats as the primary energy source.

2.1.19
respiratory system
tubular and cavernous organs (mouth, trachea, bronchi, lungs, alveoli, etc.) and structures which bring about pulmonary ventilation and gas exchange between ambient air and blood

2.1.20
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).

2.1.21
ventilation (general)
process of exchange of air between the lungs and the ambient environment

2.2 Symbols and abbreviated terms

APR	air purifying respirator
BSA	body surface area, expressed in m^2
PAPR	powered air purifying respirator
SAR	supplied air respirator
SCBA	self-contained breathing apparatus
UBA	underwater breathing apparatus
PCO_2	partial pressure of carbon dioxide
P_ACO_2	alveolar partial pressure of carbon dioxide
P_aCO_2	arterial partial pressure of carbon dioxide
P_vCO_2	venous partial pressure of carbon dioxide
PO_2	partial pressure of oxygen
P_AO_2	alveolar partial pressure of oxygen
P_aO_2	arterial partial pressure of oxygen
P_iO_2	partial pressure of inspired oxygen
P_vO_2	venous partial pressure of oxygen

V_E minute ventilation (expired)

total volume expired from the lungs in 1 min, in l/min (BTPS)

V_I minute ventilation (inspired)

total volume of air inspired into the lungs in 1 min, in l/min (BTPS)

VO_2 oxygen consumption

volume of oxygen consumed by the human tissues, in l/min, derived from the difference between the minute volume of inhaled oxygen and the minute volume of exhaled oxygen.

VCO_2 carbon dioxide elimination rate

volume of carbon dioxide produced per minute, derived from the product of minute ventilation and the difference between the fractional concentrations of exhaled and inhaled carbon dioxide

3 Oxygen and carbon dioxide in the breathing environment: physiological responses and limitations

3.1 General

The Earth's atmosphere is composed primarily of nitrogen and oxygen along with some trace gases. Atmospheric carbon dioxide occurs in very low concentrations (approximately 0,03 %). Humans require oxygen as a primary element in the production of energy during aerobic cellular metabolism. Low atmospheric oxygen concentrations or partial pressures (such as occur at high altitude) can limit production of metabolic energy, leading to a compromise in physiological function. On the other hand, low concentrations of carbon dioxide in the breathing atmosphere do not appear to have any physiological consequence. Carbon dioxide is produced as a by-product of cellular metabolism and it is this source of carbon dioxide, not the normal atmospheric concentration, which carries a physiological consequence. However, increased environmental levels of carbon dioxide, as in the breathing space of respirators or in confined areas, can also have a profound effect on the respiratory system.

High concentrations of either oxygen or carbon dioxide can have dramatic physiological consequences. Hyperoxia, especially under ambient pressures greater than one atmosphere (atm), such as occur in diving, can be toxic and even fatal to humans. High concentrations of carbon dioxide can also have a profound effect on respiration and metabolism. This overview will address several issues:

— Oxygen and carbon dioxide in normal human physiology;

— Effects of hypoxia and hyperoxia on physiology;

— Effects of hypercarbia on physiology;

— Relevance to respiratory protective devices.

3.2 Oxygen and carbon dioxide gas exchange in the human lung

Normal minute ventilation takes place as a result of neural activity in the respiratory centres in areas of the brainstem known as the medulla oblongata and the pons. The movement of air in and out of the lungs facilitates the gas exchange necessary for normal metabolic function.

Gas exchange does not occur in all regions of the pulmonary system. Anatomical dead space (regions where gas diffusion to the blood does not occur) comprises about 150 ml volume within the pulmonary system. However, the physiological dead space can add a much larger volume depending on activity level. Inhaled gas passes through the regions of dead space to the pulmonary alveoli. Gas exchange occurs in the alveoli, which are in contact with blood capillaries.

The exchange of oxygen into the blood stream and carbon dioxide out of the blood stream into the alveoli is driven by simple diffusion down a partial pressure gradient. The partial pressure of oxygen in the alveoli (P_AO_2) is approximately 13,3 kPa (100 mmHg) whereas the partial pressure of oxygen in the venous blood (P_vO_2) is approximately 5,3 kPa (40 mmHg). Therefore, oxygen will move from the area of higher concentration of oxygen in the alveoli to the area of lower concentration of oxygen in the venous blood. Oxygen will also be transported into the red blood cells along a similar partial pressure gradient to be bound to haemoglobin. Conversely, the partial pressure of carbon dioxide in the venous blood (P_vCO_2) is roughly 6,1 kPa (46 mmHg) and is only 5,3 kPa (40 mmHg) in the alveoli. Therefore, carbon dioxide will move from the venous blood to the alveoli to be exhaled to the atmosphere.

After this gas exchange has taken place, arterial blood contains a P_aO_2 of 13,3 kPa (100 mmHg) and a P_aCO_2 of 5,3 kPa (40 mmHg). The arterial blood arriving at the cells will release oxygen and take up carbon dioxide based on a similar process of moving along a partial pressure gradient. After oxygen delivery to the cells has taken place, the red blood cells have a PO_2 of 5,3 kPa (40 mmHg) and a PCO_2 of 6,1 kPa (46 mmHg). Upon return to the lungs for another round of gas exchange, each gas again moves along its partial pressure gradient to repeat the process. Proper oxygen delivery to the cells and carbon dioxide removal from the body will occur as long as a match exists between ventilation of the lungs and blood perfusion driven by a healthy circulatory system.

3.3 Oxygen and carbon dioxide transport in the blood

Oxygen has a very low solubility in the blood. Therefore, oxygen is transported to the vital organs, working muscles, and brain by a special transport mechanism in the blood. When oxygen from the atmosphere diffuses from the alveoli to the circulation, about 25 % of the oxygen present in the alveoli is rapidly transported into the red blood cells and binds to haemoglobin to form oxyhaemoglobin. Oxyhaemoglobin in the red blood cells is carried through the arterial circulation to the capillaries where the oxygen diffuses from the red blood cells to the cells of the target tissues. The oxygen is then utilized in the aerobic metabolic processes in the cell mitochondria.

Several factors affect the affinity of oxygen for haemoglobin. For any given ambient PO_2, an increase in body temperature, blood lactic acid (↓ pH), increased P_aCO_2, or an increase in 2,3-diphosphoglycerate (DPG, a product of anaerobic metabolism in red blood cells), can decrease the affinity of oxygen for haemoglobin[4]). This phenomenon is known as the Bohr Shift, which makes oxygen delivery easier under acidotic conditions.