

A Novel Method for Measuring Dead Space in Respiratory Protective Equipment

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ABSTRACT

Dead space (V_D) is a critical factor that influences performance when wearing a respiratory protective equipment (RPE). A method was developed to measure V_D during use and without interfering with the RPE. The method can also be used on other types of personal protective equipment such as motorcycle helmets

and welding visors. The inhaled CO_2 concentration is measured continuously with a fast responding mass spectrometer via a thin capillary placed at the opening of one of the nostrils in the middle of the gas flow. At the same time inhaled volume is measured with a respiratory impedance plethysmograph placed around the thorax and abdomen. The 2 signals, $\text{CO}_2\%$ and volume, are sampled via a computer, and inhaled CO_2 volume, mean inhaled $\text{CO}_2\%$ and V_D are calculated. Three types of RPE

were tested, namely 2 half-masks and one filtering facepiece, during rest and immediately after moderate work. Six volunteers participated. V_D was about 100% greater with the filtering facepiece than with the 2 half-masks immediately after work. Minute ventilation was increased by about 20%, and the subjects rated the filtering facepiece as slightly less comfortable than the others. However, the European certification test (CEN) with a breathing machine gave lower V_D -values for the filtering facepiece than for the 2 half masks. The certification test for filtering facepieces should probably be redesigned.

INTRODUCTION

The V_D in a respiratory protective equipment is defined as the portion of the inhaled air that is reinhaled from the preceding exhalation, and that consequently has a carbon dioxide (CO_2) concentration that is high and equal to the end tidal CO_2 concentration. The effects of an increased V_D are increased lung ventilation and/or retention of CO_2 in the lungs followed by a feeling of discomfort which could be the result of both increased respiratory muscular activity, possibly fatigue, and the inhalation of warm and humid gas.

Other forms of personal protective equipment, such as welding visors and motorcycle helmets could also influence breathing by an added external V_D (Eklund et al., 1985).

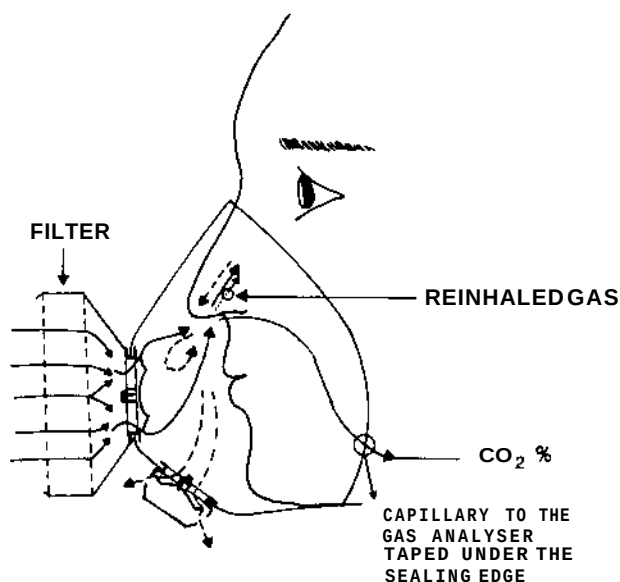


Figure 1.

A typical half-mask with inhalation flow (—) and exhalation flow (---) indicated. The wearer breathes through the nose. The CO_2 measuring technique is shown. Volume changes are measured with an impedance plethysmograph round the thorax and abdomen.

The aim of the present project was to develop a method for measuring the true external V_D when working with different types of personal protective equipment, and that does not interfere with the equipment. In this initial study 3 standard half-masks were tested.

MATERIALS AND METHODS

Measuring Principle

Figure 1 shows a half-mask in which the gas flow is indicated during nasal breathing. CO_2 concentration is measured at the border between internal and external V_D by aspirating a gas sample through a 0.8 mm thin capillary to a fast responding gas analyzer. The capillary is taped to the skin in order not to interfere with the protective equipment. A mass spectrometer (MGA 200, Centronics, Croydon, England) was used. The flow of the gas sample through the teflon capillary was 20 ml/min. Because any water in the capillary will prolong the response time of the mass spectrometer, the capillary was heated to about $40^\circ C$ to reduce the risk of condensation. If any inward leakage is critical for the test the capillary should not be placed under the sealing edge of the mask (c.f. Dahlback, 1985).

The normal response time of a mass spectrometer is too long for this type of measurement. If CO_2 concentration is changed stepwise at the capillary tip, a signal with a rise time between 10% to 90% of the final value of about 70 ms will be achieved. The signal is also delayed by about 100 ms, but this delay is easily handled by the computer. The response time is improved to about 35 ms by digital filtering (see Ariele and van Liew, 1982). The filter time constants were selected at 18 ms for T1 and 9 ms for T2.

Pulmonary ventilation is recorded together with CO_2 concentration. With many types of personal protective equipment, such as for example filtering

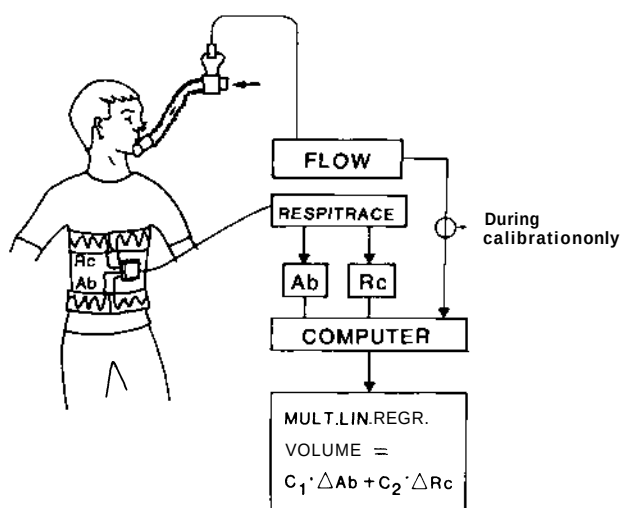


Figure 2.

Volume changes measured with a respiratory impedance plethysmograph (Respirace). One signal from the thorax (ribcage, Rc) and one from the abdomen (Ab) are sampled by the computer. The flowmeter with mouthpiece is used only during calibration, which is done by multiple linear regression of the 2 signals. C_1 and C_2 are the 2 calibration factors stored in the computer.

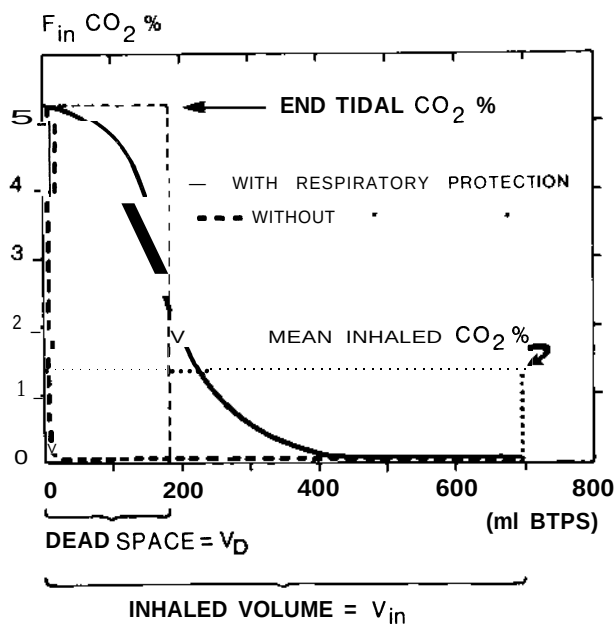


Figure 3.

Diagram showing inhaled CO_2 concentration ($F_{in}CO_2\%$) as a function of inhaled volume (V_{in}). For further discussion see text. The area under — ($F_{in}CO_2\%$ with respiratory protection equals reinhaled CO_2 volume and is equal to the areas below ---- (Dead Space * End Tidal $CO_2\%$) and (Inhaled volume * Mean inhaled $CO_2\%$).

facepieces and welding visors, it is impossible to apply any volume measuring device. A respiratory impedance plethysmograph (RIP, RespiTrace, Ambulatory Monitoring Inc. Ardsley, USA) as used here measures the changes in lung volume with 2 transducers placed around the thorax and the abdomen (see Figure 2). The RIP requires an extensive individual calibration maneuver (c.f. Loveridge et al, 1983). We have developed a computer based procedure in which the volume reference is taken from a fleisch pneumontachograph. Deviations less than $\pm 10\%$ were accepted.

The 2 signals are then plotted via a computer on a diagram (see Figure 3). The first part of the inhalation contains gas from the last part of the preceding exhalation in relation to the volume of the V_D . The last part of the exhalation has a high CO_2 concentration called "end tidal $CO_2\%$ " ($ETCO_2$), which is roughly equal to the concentration in the alveoli. The CO_2 concentration then falls with increasing inhaled volume, and in most equipments reaches room concentration (0.03%). An integration of the CO_2 curve as a function of inhaled volume gives the area under the curve, which is equal to the reinhaled CO_2 volume. V_D is calculated from the assumption that the $V_D * ETCO_2 = \text{reinhaled } CO_2 \text{ volume}$. Mean inhaled $CO_2\%$ is calculated from the relationship mean inhaled $CO_2\% * \text{tidal volume} = \text{reinhaled } CO_2 \text{ volume}$. All volumes are given in BTPS (body

temperature and pressure, saturated gas, $37^\circ C$ and 100% humidified at ambient pressure).

With no equipment in front of the face, the CO_2 concentration drops almost immediately to the concentration in room air.

If inhaled $CO_2\%$ when using a protective equipment has dropped to almost zero during the first part of the inhalation, an increase in tidal volume will not increase V_D , but the mean inhaled $CO_2\%$ will fall. In this type of equipment it is preferable to use the V_D value when describing the properties of the equipment.

In some types of equipment, inhaled $CO_2\%$ will remain at a high level

throughout the inhalation; in other words, the mean inhaled $CO_2\%$ is almost independent of the size of the tidal volume. On the other hand, V_D will increase with increasing tidal volume.

TESTED EQUIPMENT

Three half-masks were tested (see Figure 4). An AGA Silner (Interspiro AB, Lidingo, Sweden) and a Sundstrom SR 62/80 (Sundstrom, Lagan, Sweden) were tested with combi-filters, gas and particle (P2 according to CEN). The third mask was a P1 filtering facepiece for particles (8710, 3M, USA).

In order to evaluate our method, a well defined V_D of 280 ml was constructed on a straight tube (1m long)

mounted on a mouthpiece. A fan extracted any cloud of CO_2 at the end of the tube that could have increased the V_D . The fan was only used with the 280 ml V_D .

PARTICIPANTS

Three women and three men took part. Their ages ranged from 29 to 41 years.

TEST PROGRAMME

This is shown in Figure 5. Each test run started with calibration of the mass spectrometer and the RIP. The subject rested for about 3 min. while breathing through the 280 ml V_D . At the end of this period 2 V_D measurements were made, each consisting of 3 to 4 breaths.

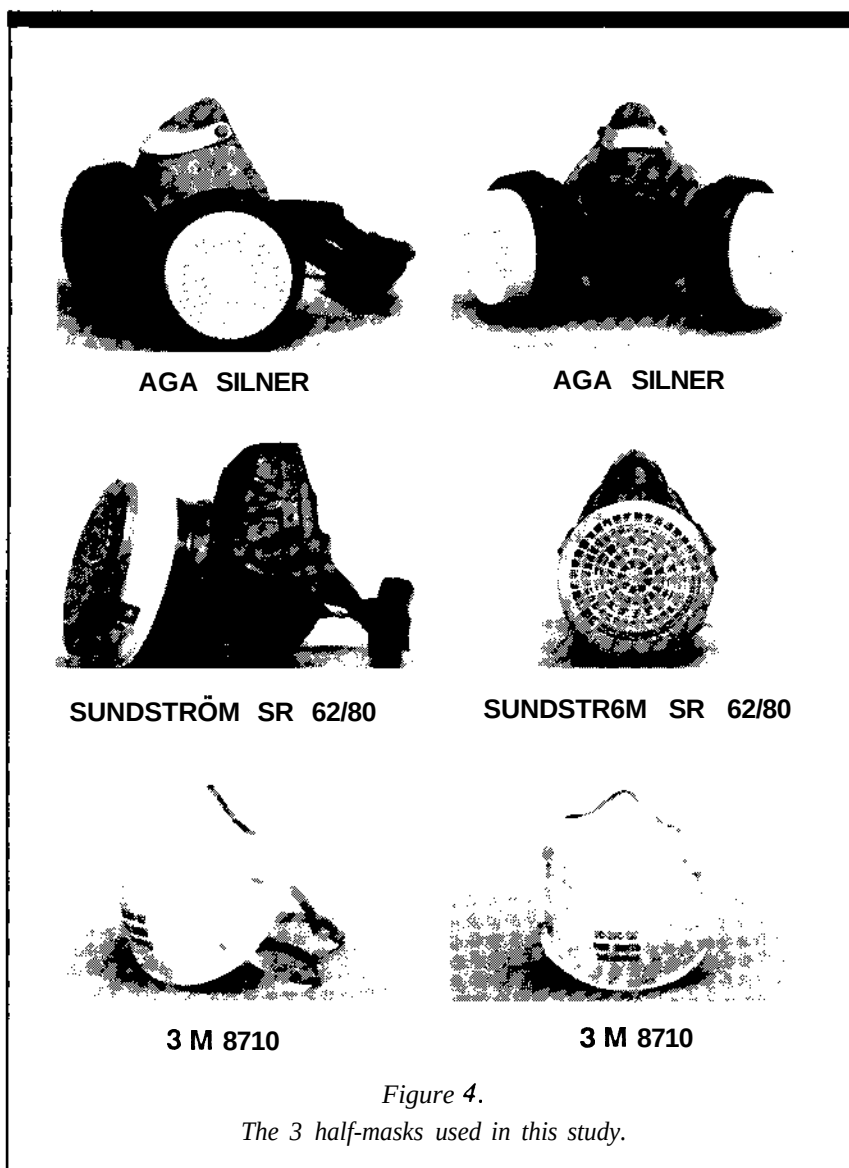


Figure 4.

The 3 half-masks used in this study.

The capillary was then taped at the opening of one of the nostrils, and a new 3 min. rest period followed with nothing in front of the face. Two V_D measurements were made at the end of this period, together with ratings of the perceived exertion (RPE) with regard to breathing resistance and comfort in accordance with the scales in Figure 10. The subject operated a hand driven bicycle ergometer at about 50 W for the next 3 min. Immediately after and 1 min after the work period the V_D was measured, noting the RPE in between. One of the 3 masks (the order chosen randomly) was then put on, and a programme with 5 min rest, 3 min work, and 1 min rest was carried out. V_D was measured at the end of the 5 min rest period and immediately after and 1 min after the work period, the RPE was noted in connection with each measurements. The 2 other masks were then tested in the same way. The test run ended with a rest period, 2 V_D measurements being made with nothing in front of the face (simulating 0 ml V_D) and then with the capillary applied to the 280 ml dead space 2 measurements with this equipment.

STATISTICS

The results were evaluated by analysis of variance. In the case of significant F-ratios in this analysis group mean values were compared by Duncan's New Multiple Range Test (Winer, 1971).

RESULTS AND DISCUSSION

Figure 6 shows the V_D measured during rest without mask and with the 280 ml V_D . Each value is a mean of 7-16 breaths both taken before and after the mask tests. The total mean without mask is 22 ml. This value is probably the combined effect of an error due to the response time of the mass spectrometer and a true V_D created by a cloud of CO_2 outside the airway openings. The results with the 280 ml V_D

show a scatter around the 280 ml line. The total mean for all 6 subjects is 275 ml, which shows that the method has acceptable accuracy.

A plot from a test with the filtering facepiece taken immediately after work is shown in Figure 7. This mask seems to have a well defined V_D . The results vary however between the wearers, and are influenced by how the mask was worn. The wearer's internal V_D can be calculated from the exhalation part of the curve.

VD, mean inhaled CO₂%, and end tidal CO₂% are plotted for the different masks at rest, 0 min, and 1 min after work in Figure 8. The V_D for the 3M

mask was significantly greater immediately after work than that for the AGA (76%, $p<0.05$) and Sundstrom masks (120%, $p<0.01$). The mean inhaled $\text{CO}_2\%$ was 60-80% higher immediately after work in the 3M mask than in the 2 other masks ($p<0.05$). The difference is probably explained by the fact that a filtering facepiece without non-return valves has less effective gas distribution with greater mixing of in- and exhaled gas. The larger V_D in the 3M mask did not cause CO_2 retention in the lungs, as shown by unchanged end tidal CO_2 concentrations.

Consequently the wearers had almost 20% greater minute ventilation (see

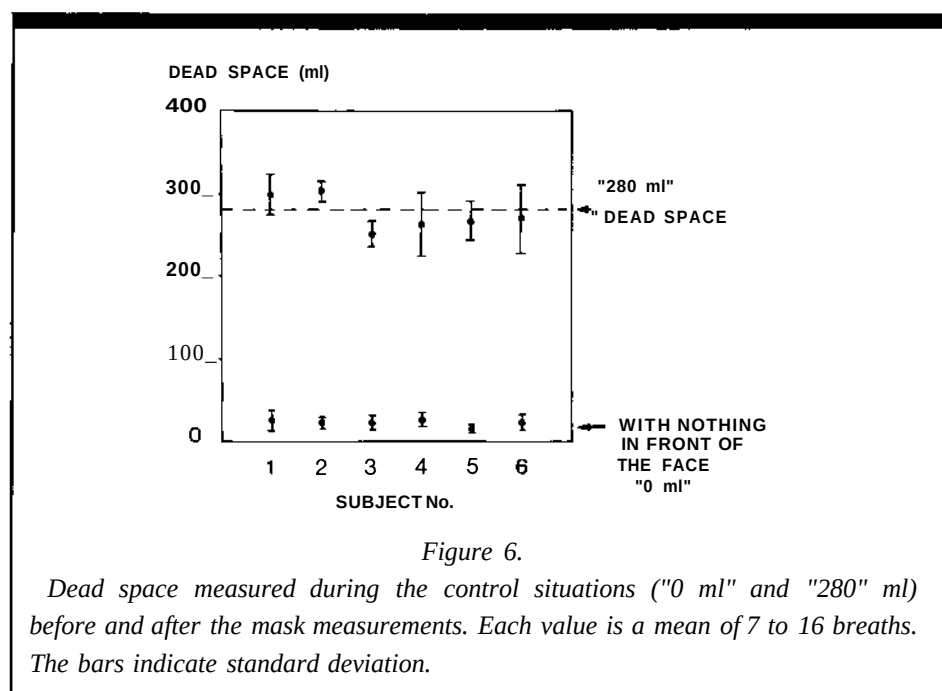
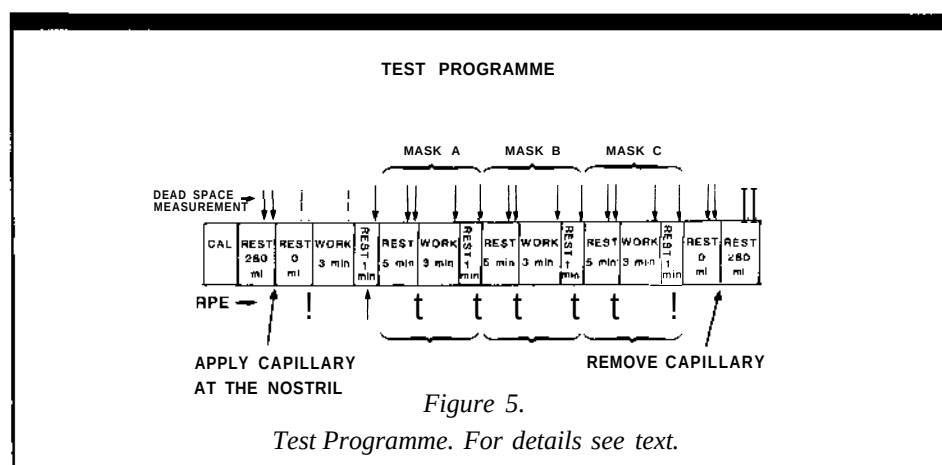


Figure 9) immediately after work with this mask than with the others ($p < 0.01$). The increase in ventilation was as shown in Figure 9 chiefly the result of increased tidal volume which is more efficient than increasing the breathing rate when the V_D is a well defined volume (see Figure 7).

The ratings of perceived exertion with regard to comfort follow the same trend. The 3M mask was rated somewhat more uncomfortable during rest than the others

($p < 0.01$), and also immediately after work compared with the AGA mask ($p < 0.05$) (see Figure 10).

In contrast, breathing was immediately after work rated somewhat more exhausting in the Sundstrom than the 3M mask ($p < 0.05$), probably owing to the enforced nose-breathing and because the upper seal of the Sundstrom mask compressed the nose.

The heart rate was 93 beats/min

during rest, 124 immediately after work and 98 after work irrespective of type of mask.

The 3 masks were also tested at the official Swedish test station according to CEN/TC 79, prEN 140 (1985), which is the draft European standard for measuring V_D with a breathing machine. The results are plotted in Figure 11 together with the pooled data from our 3 measuring points for the 3 masks, at rest and 0 and 1 min after work. The lower mean inhaled $\text{CO}_2\%$ values noted with the CEN method may be largely ascribed to the big tidal volume, 2 l, chosen for this test compared to about 1 l in our human tests. Even the V_D values show considerable differences. In the CEN test the exhaled gas is not heated or humidified, and the exhaled gas flow is separated from the inhaled gas flow at the opening of the mouth of the dummy head. In our test breathing was nasal, which is normal at this workload.

The main difference could however be that when testing filtering facepieces by the CEN-method a fan is used to extract any CO_2 cloud in front of the facepiece in order to get reproducible results. It is essential that the certification test provide results that are valid for the actual working situation. The method presented in the present study can easily be adopted for a breathing machine (Fallhagen et al, 1985).

SUMMARY

A novel method for measuring V_D without interfering with the function of the protective equipment is described.

All types of personal protective equipment can be tested with the new method.

A filtering facepiece protective equipment can be tested with the new method.

The standard CEN method apparently has a larger V_D than an ordinary mask with non-return valves.

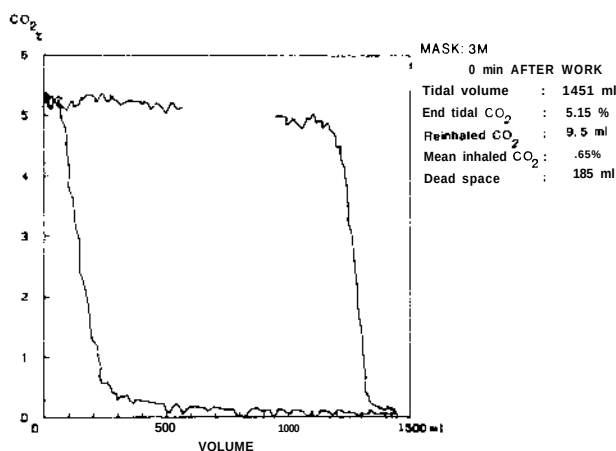


Figure 7.

A curve from a single breath via the filtering facepiece (3M).

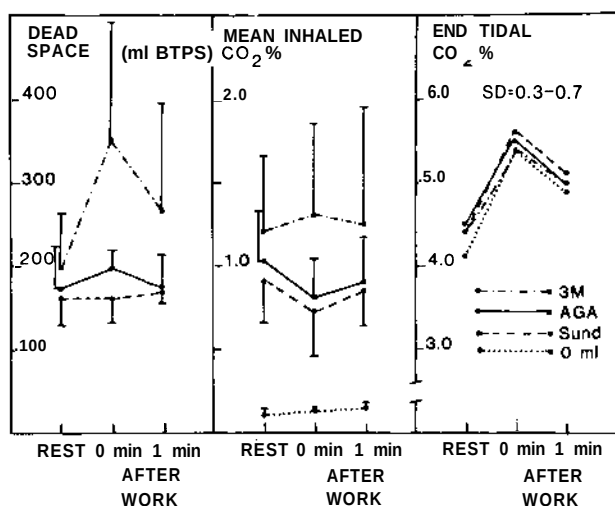


Figure 8.

Dead space, mean inhaled $\text{CO}_2\%$ and end tidal $\text{CO}_2\%$ with the 3 half-masks (see Figure 4) and in the control situation (0 ml) during rest and 0 min and 1 min after the workperiod. The bars indicate standard deviation (for end tidal $\text{CO}_2\%$ standard deviation (SD) varied between 0.3-0.7%). (The significance Levels are given in the text.)

ACKNOWLEDGMENTS

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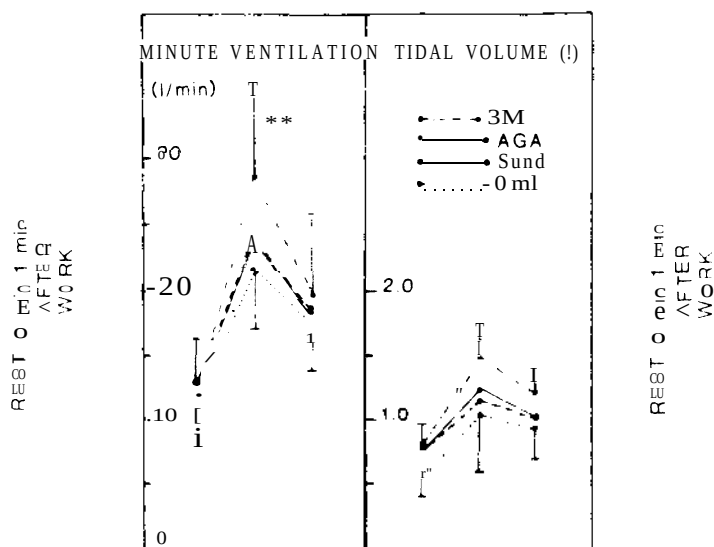


Figure 9.

Minute ventilation and tidal volume with the 3 half-masks (see Figure 4) and in the control situation (0 ml) during rest and 0 min and 1 min after the work period. The bars indicate standard deviation for the 3M filtering facepiece and the "0 ml" test. The standard deviation for the 2 other masks were in the same range ($xx=p<0.01$).

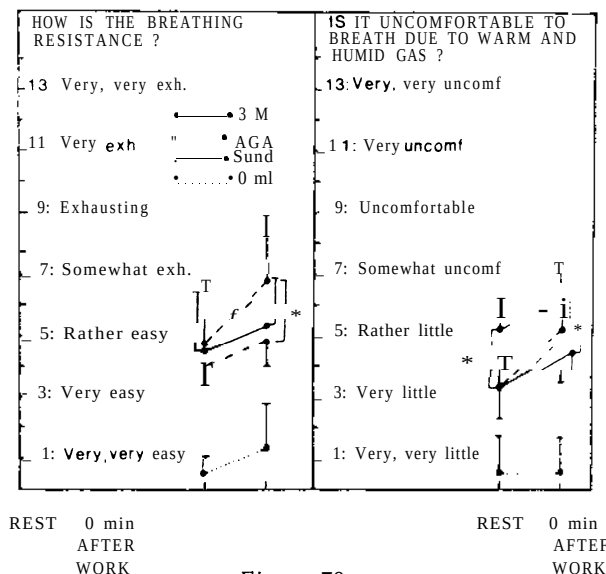


Figure 10.

Ratings of perceived exertion (RPE) with regard to breathing resistance and breathing comfort when using the 3 half-masks (see Figure 4) and in the control situation (0 ml). The bars indicate standard deviation ($xx=p<0.01$, $x=p<0.05$).

Figure 11.

Comparison between the results from the standard European certification test with a breathing machine (CEN-method) and the pooled results from our study with humans, regarding dead space, mean inhaled $CO_2\%$ and tidal volume. (For identification of the 3 half-masks see Figure 4.)

