DEVELOPMENT OF COMPREHENSIVE PERFORMANCE STANDARDS FOR UNDERWATER BREATHING APPARATUS

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FINAL REPORT

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TABLE OF CONTENTS

ABSTRACT

Every type of underwater breathing apparatus (UBA) imposes loads on the diver's respiratory system. It is essential for the diver's safety and performance that the UBA adheres to appropriate performance standards. These external loads can be classified as breathing resistance, elastance, hydrostatic imbalance (static lung load) and inertia. The internal loads from the diver's airway resistance, compliance and gas density add to the respiratory loads. A mathematical model was developed using data and knowledge of respiratory physiology from the scientific literature. This model allowed calculations of the effort required to overcome the external and internal loads (separately or in combination). Limits for the different external respiratory loads were set based on the respiratory model and data available from experimental studies.

An effect of the diving depth on the maximum breathing resistance was confirmed and quantified. It is reasoned that the additional effort be expressed as power of breathing rather than work of breathing.

Respiratory impediments acting alone. The acceptability limits were found to be the following:

Breathing resistance: the maximum power of breathing (POB_{ext}) is (A - B · depth) · ventilation, where POB_{ext} is the total allowable external resistive power (W), $A=4.15 \cdot 10^{-2}$ W/(L/min BTPS) and $B=2.62 \cdot 10^{-4}$ W/(msw · L/min BTPS).

Elastance: The maximum allowable elastance is 0.7 kPa/L independent of depth and ventilation.

Hydrostatic imbalance: For a diver in the prone position, hydrostatic imbalances of about –10 and +15 cm H_2O (-1 and +1.5 kPa) referenced to the lung centroid are the maximum tolerable. For a diver in the upright position, hydrostatic imbalances of about -10 to +10 cm H_2O (-1 to +1 kPa) referenced to the lung centroid are the maximum tolerable.

Respiratory impediments acting together. When the respiratory loads act together they are additive if each load is expressed in terms of its maximum value when acting alone. This means that the total acceptable respiratory load can be calculated by adding the relative value for each load.

We suggest that the findings in this report be incorporated in the Navy's Performance Standards for Underwater Breathing Apparatus.

INTRODUCTION

All underwater breathing apparatus impose respiratory loads on the diver. The loads can be classified in terms of resistance, elastance, hydrostatic imbalance (static lung load) and inertia, see Figure 1. In addition to these loads, the dead space in the breathing apparatus and CO_2 in the inspired gas impose a greater demand for ventilation which enlarges the effects of the other loads.

It is essential for the diver's safety and performance that a diver's underwater breathing apparatus (UBA) adheres to appropriate performance standards. The current NEDU performance standards (24) define limits on acceptable levels of breathing resistance, elastance and static lung loading. However, these acceptable levels have been set for each impediment acting *alone*. This is similar to what other organizations do. A typical real-world UBA has at least two respiratory loads present. For instance, even the simplest UBA, the snorkel, imposes breathing resistance, static lung loads and dead space. Recently, Navy sponsored research on the effects of *combined* respiratory impediments was completed at CRESE (8, see also 20, 21, 22). One of the conclusions drawn in this study was that resistive and elastic loads are additive in their physiological effect. According to the current Navy performance standards a UBA that has the highest allowable resistance in combination with the highest allowable elastance would be acceptable. However, in light of this recent study (8) such a combination of loads would not be acceptable. Obviously, the standards must be updated with this new knowledge.

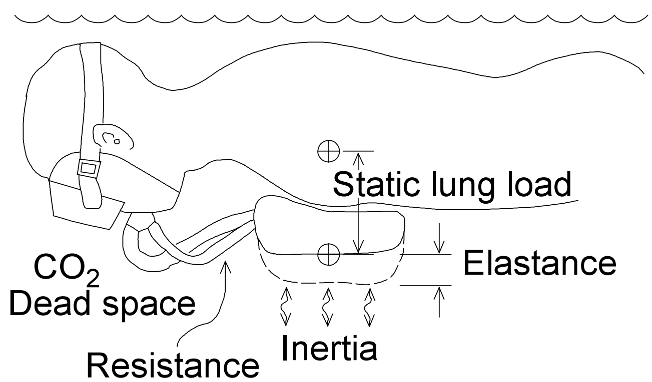


Figure 1. Illustration of the respiratory loads imposed on a diver who is breathing on a closed circuit UBA with the breathing bag (counter volume) on the chest. Breathing *resistance* is imposed by hoses, narrow passages and valves. A *static lung load* (hydrostatic imbalance) is imposed because of the difference in depth between the lung pressure centroid and the breathing bag. An *elastic load* is imposed because the mean depth of the bag changes during breathing. The *CO_2 load* from the inspired gas and the *dead space* in the face mask force the diver to increase his breathing which increases the effect of the other loads. Gas and water is accelerated and decelerated with each breath imposing *inertial* effects.

It is noteworthy that the limits set by the current performance standards do not change with depth. Work by Dr J Clarke, NEDU, has shown that depth indeed has an influence (2). This notion also has support in an earlier study on acceptable levels of breathing resistance (16) performed at CRESE. In this study the limits (in terms of physiological acceptability) were typically reached at the greatest depth. It seems reasonable that depth should have an influence since the breathing resistance in a diver's own airways increases as the gas density increases with diving depth, a more detailed review can be found in Clarke (3).

The aim of the present project was to compile the available data on acceptable and unacceptable loads. These data were obtained from the Navy sponsored research (going back over 20 years) already carried out at CRESE, data available from the Navy Experimental Diving Unit and the Naval Medical Research Institute and also from the literature. A computerized mathematical model of the respiratory system was used to calculate the work of breathing in different situations. This model and the experimental data were used together to determine acceptable loads both when they act separately and when they act together.

THE RESPIRATORY MECHANICS MODEL

General

A mathematical model of the respiratory system was assembled based on data and knowledge of respiratory physiology available in the scientific literature (23). Such a model had never been put together before and it has allowed calculations of the total work and power of breathing. A screen printout can be found in Appendix A. The ventilation level could be set to be one of the standard testing ventilations or a custom combination; the duty cycle could also be varied. The ambient pressure (diving depth) could be set independently. The model was built in such a way that internal and external loads could be added independently. This allowed the effects of the UBA and the respiratory system to be studied separately or interacting.

Internal loads

The internal loads such as airway resistance, compliance, expiratory reserve volume, relaxation volume, gas density were included. The descriptions of airway resistance by Rohrer (12), Clarke *et al.* (1), Maio and Farhi (9) and VanLiew (15) were included as options. The preferred one is the one by VanLiew (15) because it included a description of how the airway resistance changes with diving depth and lung volume.

External loads

There were several options for the type of external resistance that was imposed; from orifice resistors to work-of-breathing limits to empirical values from an existing UBA. Selectable elastances and static lung loads were included. Determination of the effects of CO_2 from inspired gas or mask dead space was beyond the scope of this project.

WORK OF BREATHING *VS.* POWER OF BREATHING

Historically, the respiratory work imposed by the UBA has been calculated as work-of-breathing (WOB) but has typically been expressed as work per volume (WOB/V, with the unit Joule per liter). Work is calculated as the product of pressure and volume. Therefore, WOB/V is the product of pressure and volume divided by volume. This returns pressure. Strictly speaking, WOB/V is the volume averaged pressure that a UBA requires during a breath. This means that the common terminology of expressing work as pressure is incorrect. Efforts to avoid such errors have been made. For instance, the US Navy Experimental Diving Unit uses the expression “resistive effort”.

In most other situations, the effort required by a device is expressed as power. Power is much easier to comprehend than work or pressure and a much more common measure, e.g. the workload on an ergometer is set as power as are the ratings for electric lights, motors and car engines.

Translating values from WOB/V to POB is not difficult (see equation 1) and can provide further insights.

$$POB = \frac{\dot{V}_E}{60} \bullet WOB/V \qquad (1)$$

where $\dot{V}_E$ is the diver’s ventilation (L/min) and 60 is the number of seconds in a minute.

Figure 2 illustrates the conversion. NEDU’s limit for open circuit SCUBA of 1.44 kPa (or J/L) translates into a straight line with a slope of 0.024 W/(L/min). For the reasons described above, the results presented in this report will primarily be expressed as power (POB) not as work (WOB).

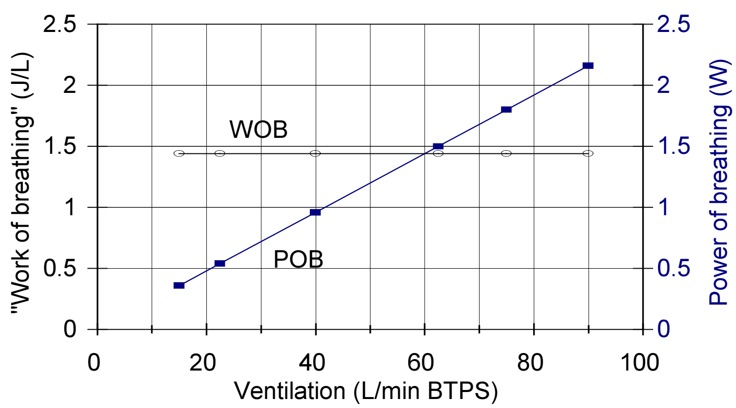


Figure 2. Conversion of a given limit expressed as WOB/V into POB. The ventilation levels are the ones typically used in unmanned testing of UBAs.

LIMITS OF THE DIFFERENT RESPIRATORY LOADS

Respiratory impediments acting alone

The different loads will be discussed in short form in the following.

Resistive loads

The results from the Navy sponsored research (6) on the effects of breathing resistance performed at CRESE, "the most complete study of hyperbaric breathing limits", (3) were re-analyzed by specifically looking at the influence of depth, see Appendix B. Briefly, in these experiments the subjects were exposed to different levels of breathing resistance at a shallow depth and also at the greatest depth that the standard air decompression tables allow. These experimental results showed that the total resistive power demand on the respiratory muscles should not exceed 4 W. This further supports the idea that the allowable POB from the UBA should change with both depth and ventilation according to the following formula:

$$POB_{ext} = (A - B \cdot depth) \cdot ventilation, \qquad (2)$$

where POB_{ext} is the total allowable external resistive power (W), $A=4.15 \cdot 10^{-2}$ W/(L/min BTPS) and $B=2.62 \cdot 10^{-4}$ W/(msw · L/min BTPS). The equation is illustrated in Figure 3.

Previous limits on WOB have been typically been specified either as a constant value independent of ventilation or as a value that increases with ventilation. To allow easier comparisons of the new results to previous performance standards, the external power of breathing has been expressed as work of breathing per volume or mean pressure (WOB/V), Figure 4.

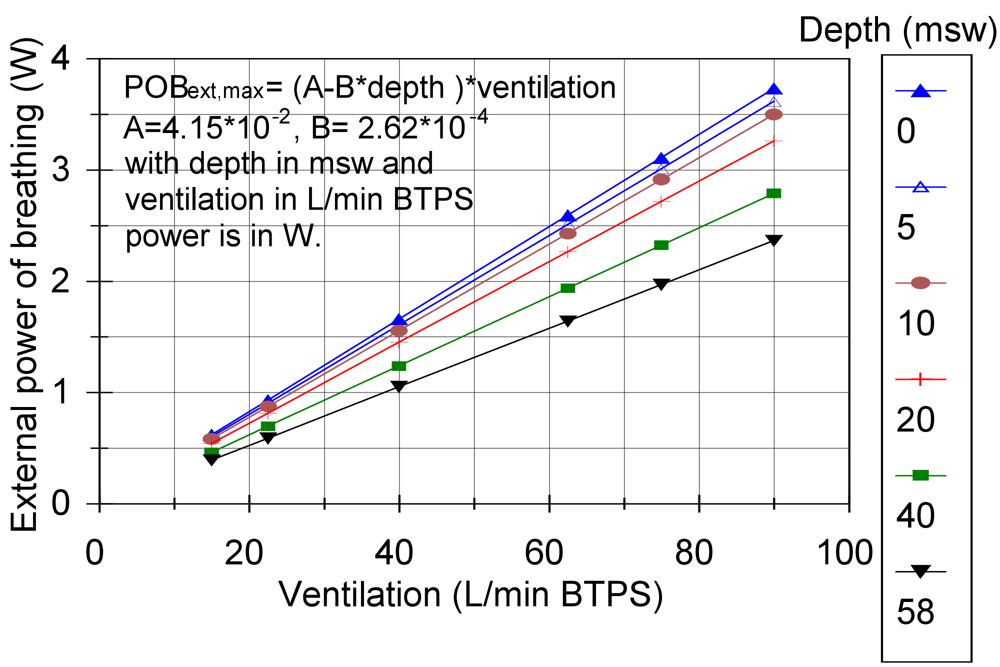


Figure 3. Maximum allowable external power as a function of ventilation and depth. The influence of depth is shown by the different lines and symbols. The values are calculated for the ventilation levels commonly used in unmanned testing of UBAs.

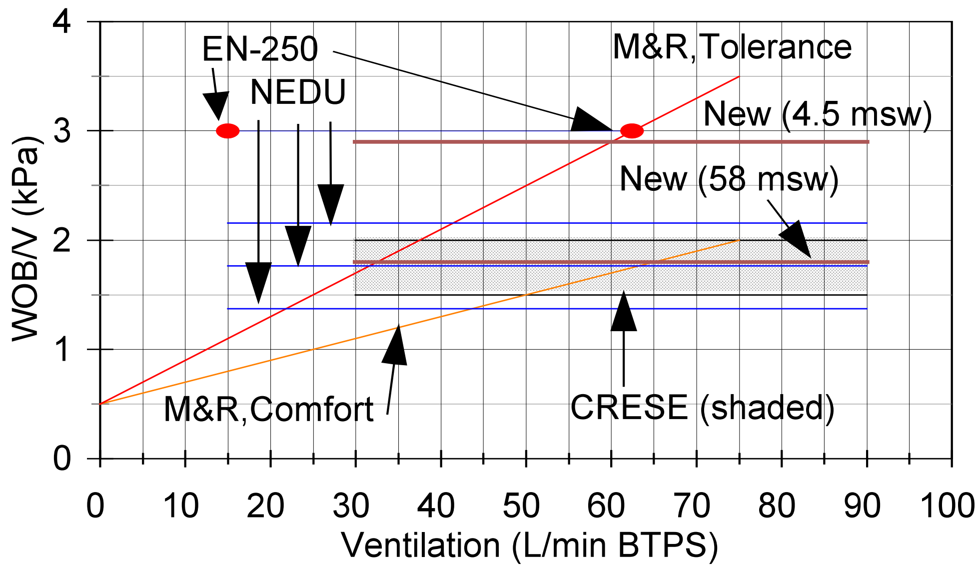


Figure 4. Plot of previous "work of breathing" and the new limits. M&R stands for the comfort and tolerance limits by Morrison and Reimers. The two red dots show the limits set by the European norm EN-250. The shaded area is the range defined by Warkander *et al.* (1990). The three blue lines indicate NEDU's limits for different types of UBAs. The two brown lines (labeled "New") indicate the re-analyzed CRESE data, the lower line being from the great depth (58 msw) and the upper from the shallow depth (4.5 msw).

As can be seen in Figure 4, many limits are set as constant values when expressed as WOB/V. Equation (1) above shows that such constant values translate into a respiratory power that increases linearly with increasing ventilation level. This seems physiologically reasonable since increased ventilation signifies increased whole body workload and the respiratory load is then a certain percentage of the whole body workload. Figure 4 also shows two limits (M&R, 10) that increase with increasing ventilation. Such lines translate into respiratory power limits that increase with the square of the ventilation. This kind of an approach would mean that the permissible POB would go up with the square of the workload, which can hardly be considered physiological.

The new limit for the great depth seems to be in the range of the more conservative limits. The limit for the shallow depth is higher than many other limits but matches the EN-250. It must be noted that most previous limits that were set for diving were based on manned tests of a real world UBA. Such UBAs impose loads other than just resistance. In other words, what may seem like a less restrictive load may not really be so because the proposed limits are for the resistance only.

Conclusion: The limit for power of breathing for resistive loads should increase linearly with ventilation. If it is expressed in terms of WOB/V it should be a constant value.

Elastic loads – Elastance

Limits on acceptable levels on elastic loads were only found in one study (7, 17). In this study, the subjects were exposed to different levels of elastic loads at a shallow depth and also at the greatest depth that the standard decompression tables allow. Briefly, the experimental results showed that an elastic load of 7 cm H_2O/L was acceptable but a load of 14 cm H_2O/L was not. There was no difference in acceptability with changes in depth. The results from the respiratory mechanics model also show that depth does not make any particular difference in the maximum pressure swings that the respiratory muscles have to exert, Figure 5.

It is also apparent from Figure 5 that the pressure swing (internal + external) at an elastic load of 7 cm H_2O/L is lower than for 14 cm H_2O at all depths. The increase in respiratory load by the increase in the elastance was greater than the increase in load imposed by the increased depth.

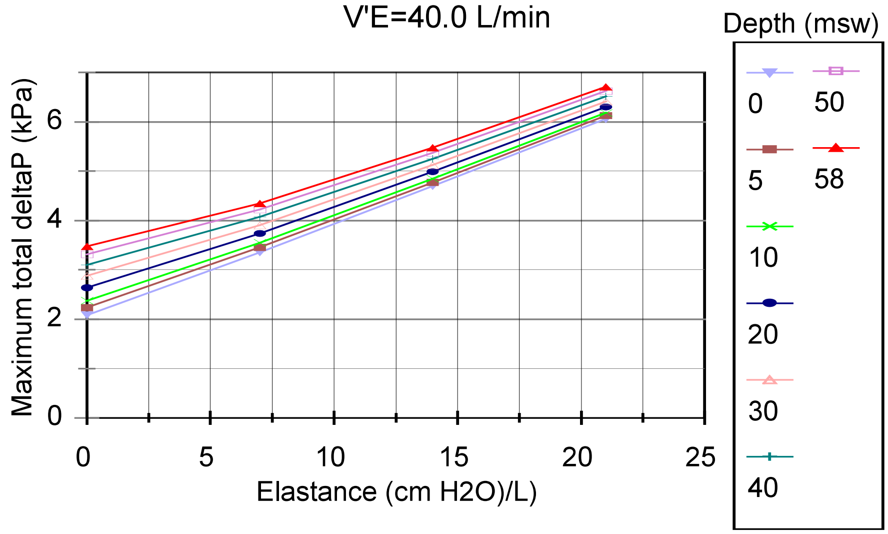


Figure 5. Relative increase in power of breathing at different depths for a ventilation level of 40 L/min BTPS. Results from the respiratory mechanics model.

Conclusion: The maximum acceptable elastic load is 7 cm H_2O per liter independent of depth.

Hydrostatic imbalance – Static lung loads

Hydrostatic imbalance is also known as static lung loading and pressure breathing (positive or negative).

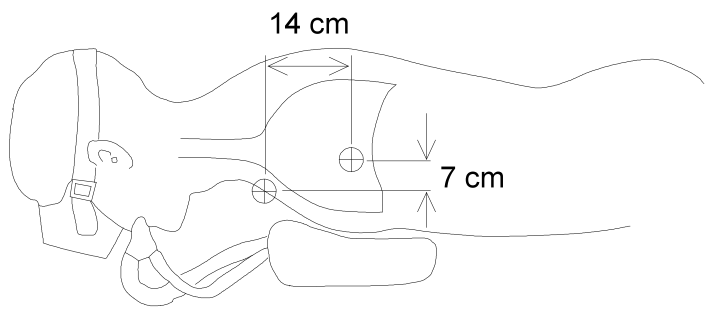


Figure 6. Illustration of the position of the lung pressure centroid and sternal notch.

One of several often confusing aspects of static hydrostatic imbalance is that it is possible to have different points of reference. Three such points come naturally: the mouth, the sternal notch and the lung centroid. The mouth and the sternal notch are easy to identify on a person and a manikin. The lung centroid is a functional reference and is defined as the equivalent pressure point at which a person's expiratory reserve volume is the same as in the non-immersed condition (negative imbalance causes breathing at low lung volumes and positive imbalance causes breathing at high lung volumes).

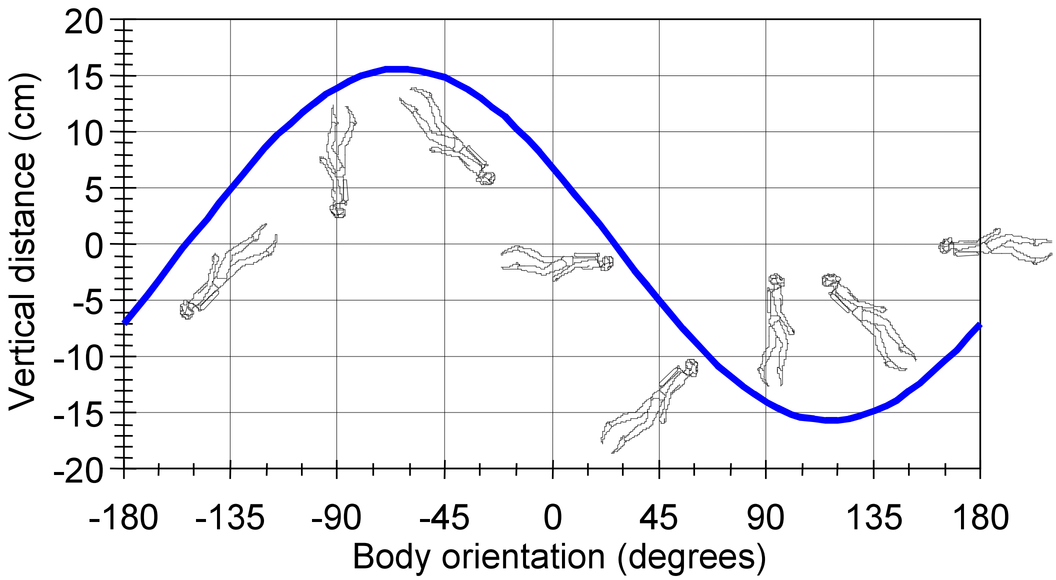


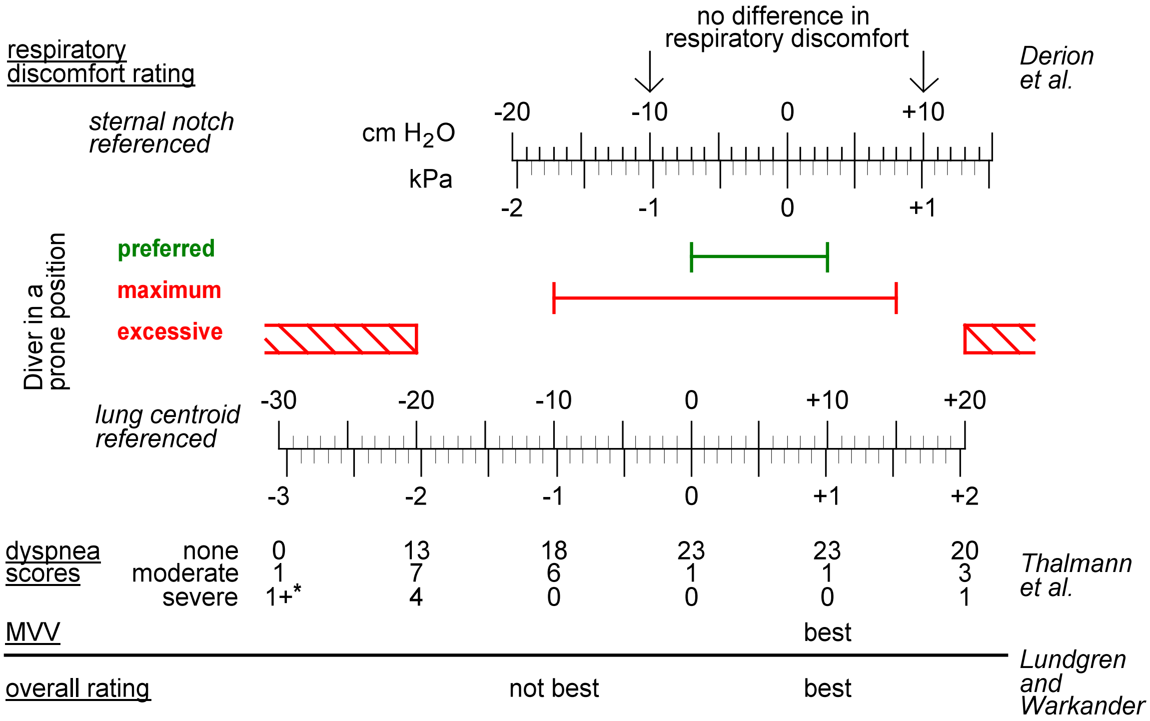
Figure 7. Vertical distance between the lung centroid and the sternal notch for different orientations of a diver. For instance, at 90 degrees (upright) the sternal notch is at a depth that is about 14 cm less deep. This distance (in cm) follows the equation 15.6*sin(α–26.6°) where α is the diver's angle.

From a physiological function point of view, it may be preferable to have hydrostatic imbalances referenced to the lung centroid. However, during experimental set-ups and during breathing apparatus testing, a reference point that is consistent and easy to find is preferable. Figure 7 shows how the vertical distance between the sternal notch and the lung centroid changes with a diver's orientation in the water. This Figure allows conversion between sternal notch and the lung pressure centroid.

Several studies have been performed on the effects of hydrostatic imbalance on a diver. They have primarily used indices such as respiratory discomfort and dyspnea scores to judge the magnitude of influence. Two body positions have been studied: prone and upright.

The diver in the prone position.

Three studies are summarized in Figure 8. Derion *et al*. (4) imposed two imbalances, +10 and –10 cm H_2O (+1 and –1 kPa) relative to the sternal notch. The subjects were exercising just below the surface. No difference in respiratory discomfort ratings was found.



* Because of severe dyspnea only the first subject was allowed to attempt this load.

Figure 8. Summary of studies of the influence of the hydrostatic imbalance on divers in the prone (horizontal) position (0° in Figure 7). In the rightmost column are the names of the investigators. In the leftmost column is the name of the parameter studied. The two scales refer to the hydrostatic imbalance that was imposed, the top one is referenced to the sternal notch and the lower one is referenced to the lung centroid. The investigators chose loads that were an even 10 cm apart on their respective scales. See text for further details.

Thalmann *et al.* (14) studied six different imbalances in the range +30 to –30 cm H_2O (+3 to –3 kPa) relative to the lung centroid during exercise at four depths down to 58 msw (190 fsw, 6.8 atm abs., 690 kPa). The imbalances with the least dyspnea scores were 0 and +10 cm H_2O (0 and 1 kPa). Imbalances of +20 and –20 cm H_2O or greater generated severe dyspnea. The load of –10 cm H_2O generated moderate dyspnea in 25% of the dives. The MVV (maximum voluntary ventilation) was the highest with an imbalance of +10 cm H_2O.

Lundgren and Warkander compared several parameters (e.g. MVV, lack of dyspnea and improved CO_2 levels) obtained from subjects at two depths during rest and exercise. They found that an imbalance of +10 cm H_2O (1 kPa) was preferable to –10 cm H_2O (-1 kPa).

Discussion Based on the results from Thalmann *et al.* (14) imbalances of –20 and +20 cm H_2O or higher are excessive because they induced severe dyspnea. Thalmann *et al.* and Derion *et al.* (4) agree that imbalances in the 0 and +10 cm H_2O range are similar. This is not contradicted by Lundgren and Warkander. Thus, imbalances in the range 0 and +10 cm H_2O are the best and an imbalance of –10 cm H_2O is slightly worse. The data from Derion *et al.* indicates that an imbalance of about +15 might be acceptable.

Conclusion

For a diver in the prone position a hydrostatic imbalance in the range 0 to +10 cm H_2O (0 to 1 kPa) referenced to the lung centroid should be preferred. Imbalances of –10 and +15 cm H_2O are tolerable. Imbalances equal to or greater than -20 and +20 cm H_2O are excessive. Therefore, the maximum imbalance can be set to be –10 and +15 cm H_2O (-1 and +1.5 kPa).

The diver in the upright position.

Four studies are summarized in Figure 9. Derion *et al*. (4) also studied the subjects when they were in the upright position. The imbalances were +10 and –10 cm H_2O relative to the sternal notch of the exercising subject. Again, no difference in the respiratory discomfort was found.

Hickey *et al.* (5) studied exercising subject at two depths. Four evenly spaced imbalances in the range –20 to +10 cm H_2O (-2 to +1 kPa) relative to the lung centroid were imposed. The fewest dyspnea scores were reported when the imbalance was +10 cm H_2O. Imbalances of –10 and 0 cm H_2O gave similar scores to each other.

Norfleet *et al.* (11) studied the difference between –20 and 0 cm H_2O on exercising subjects at two depths. The -20 cm H_2O imbalance had many more reports of moderate dyspnea.

Taylor and Morrison (13) studied subjects exposed to four levels of hydrostatic imbalance in the range –20 to +10 cm H_2O (-2 to +1 kPa). The subjects were exercising just below the surface and at 50 msw (164 fsw, 6.05 atm abs, 613 kPa). The best ratings of respiratory discomfort (least discomfort) were given at –10 and 0 cm H_2O (-1 and 0 kPa). The ratings at –20 and +10 cm H_2O were not different.

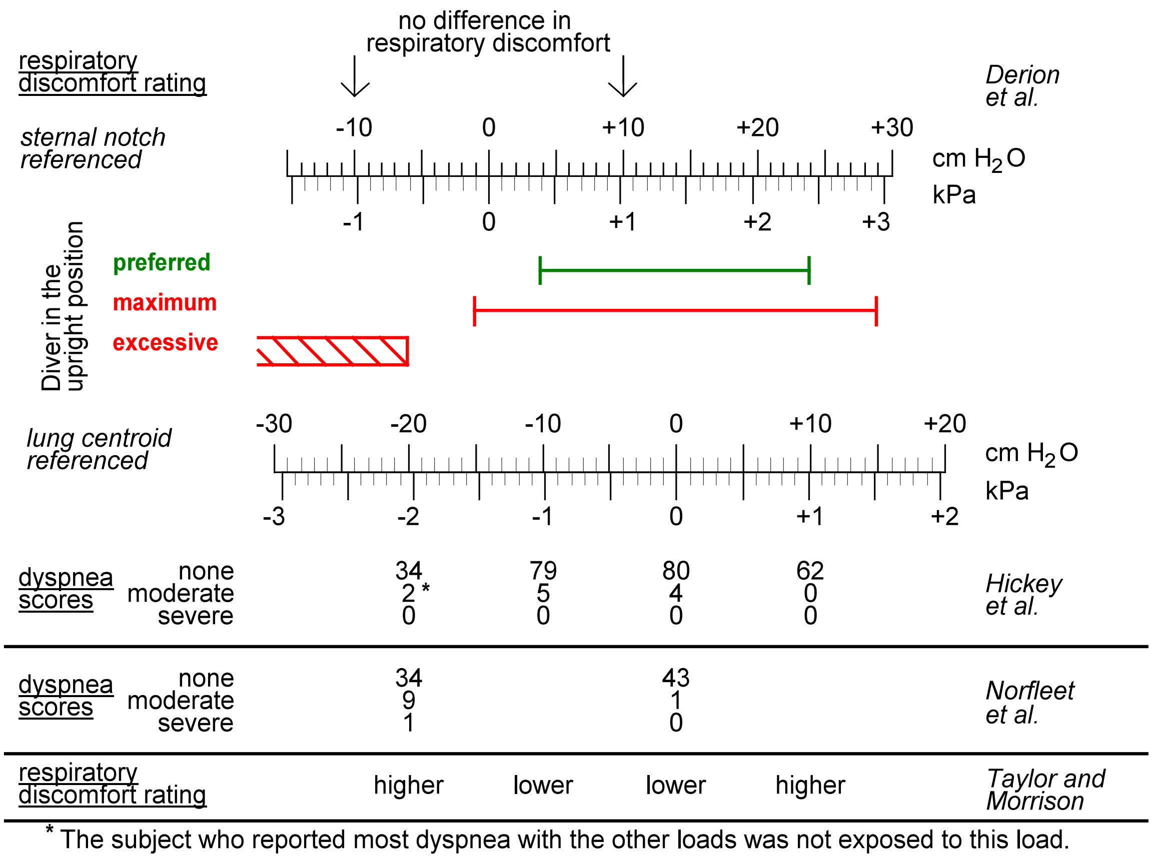


Figure 9. Summary of studies of the influence of the hydrostatic imbalance on divers in the upright position (90° in Figure 7). In the rightmost column are the names of the investigators. In the leftmost column is the name of the parameter studied. The two scales refer to the hydrostatic imbalance that was imposed, the top one is referenced to the sternal notch and the lower one is referenced to the lung centroid. The investigators chose loads that were an 10 cm apart on their respective scales. See text for further details.

Discussion

Based on the results from Norfleet *et al.* (11) an imbalance of –20 cm H_2O relative to the lung centroid is excessive since it induced severe dyspnea. Hickey *et al.* (5) agrees with Taylor and Morrison (13) that –10 and 0 cm H_2O are similar. However, these two studies contradict each other at +10 cm H_2O. Derion *et al*. (4) equates imbalances of –14 and –4 cm H_2O relative to the lung centroid. Obviously, the limits are not distinct. However, it seems that imbalances in the range –10 to +10 are equally tolerable and caused the least amount of respiratory distress.

Conclusion

For a diver in the upright position, hydrostatic imbalances in the range -10 to +10 cm H_2O (-1 to +1 kPa) referenced to the lung centroid are preferred. An imbalance of -20 cm H_2O (-2 kPa) is excessive. Imbalances of +20 cm H_2O (+2 kPa) or higher were not tested. Therefore, the maximum imbalance can be set at –15 and +15 cm H_2O (-1.5 and +1.5 kPa).

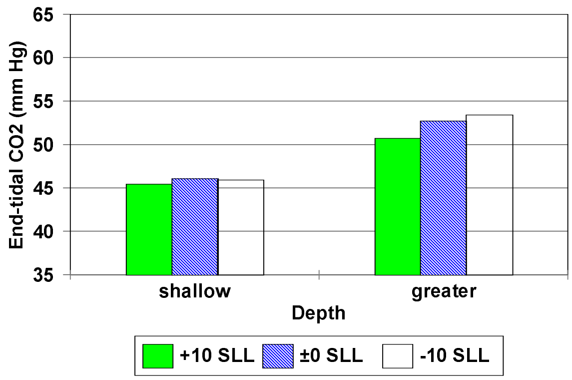
A note on hydrostatic imbalances
It should be noted that the loads imposed in all these studies have been spaced 10 cm H_2O (1 kPa) apart. Additionally, the distance between the actual lung centroid and the sternal notch must vary somewhat depending on a person's body size (at least in the upright position). Therefore, all limits may well have an uncertainty of some 5 cm H_2O (0.5 kPa).

Respiratory impediments acting together

In one study, Lundgren (7) exposed subjects to an imbalance of –10 cm H_2O (-1 kPa) in combination with either a marginal resistive load or a marginal elastic load with the subject in the prone position. Such combinations either induced excessive dyspnea or excessive CO_2 levels. Thus, elastic and resistive loads do interact with hydrostatic imbalances and that loads that are acceptable when used individually cannot be assumed to be acceptable when other loads are present.

Combinations of loads were investigated further in a larger study by Lundgren and Warkander (8, 18, 19, 20, 21, 22). A total of 352 successful experiments were performed with 9 subjects. The experiments were performed at two depths: a shallow depth of 15 fsw (4.5 msw, 1.45 atm abs, 147 kPa) and the greatest depth that the standard US Navy decompression tables allow, i.e. 190 fsw (58 msw, 6.8 atm abs, 690 kPa). Exercise was performed for 25 minutes at 60% of each subject's maximum oxygen uptake. Combinations of resistive and elastic loads were added to hydrostatic imbalances with the subject in the prone position. The loads were combined in an additive way such that the loads were added as a percentage of each load's maximum acceptable level (%R + %E + %imbalance = 100%). The experiments were divided into three groups in terms of the amount of hydrostatic imbalance. The assigned imbalances were –10 and +10 cm H_2O (assumed to be 50% of the acceptable imbalance) or 0 (relative to the lung centroid). The maximum allowable resistance was set to induce a work of breathing of 1.5 to 2.0 kPa (16) and the acceptable level of elastance was 0.7 kPa/L (7). For each level of imbalance, there were five combinations of resistance and elastance. For instance, when the imbalance was 0, the combinations of resistance and elastance were (%R/%E): 100/0, 75/25, 50/50, 25/75, 0/100. Additionally, there was a control experiment where the loads were as small as could be achieved.

The investigators concluded that the resistive and elastic loads were additive for each level of imbalance. Comparing the effects of the hydrostatic imbalances they found that a hydrostatic imbalance of +10 cm H_2O (1 kPa) is preferable to imbalances of –10 or 0 cm H_2O. The positive imbalance showed consistent statistically significant improvements overall (not all individual parameters showed statistically significant changes). The staircase shaped changes are illustrated in Figure 10. Note that the best values were observed with the positive imbalance.



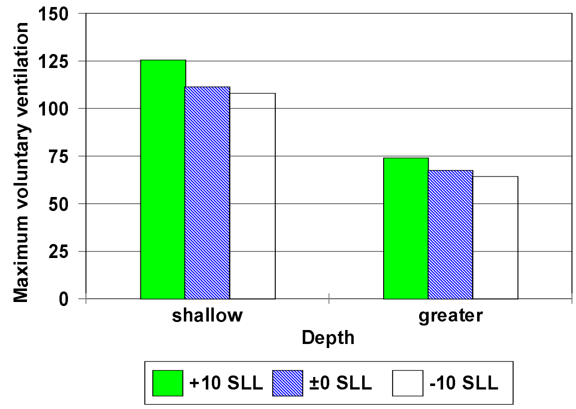


Figure 10. End-tidal CO_2 and maximum voluntary ventilation measured at two depths. A lower end-tidal CO_2 means that it is closer to normal. A higher maximum voluntary ventilation means that the subject can breathe more. The label +10SLL refers to a hydrostatic imbalance of +10 cm H_2O relative to the lung centroid. The same labeling pattern applies to the other two loads.

Conclusion

Combined loads of resistance, elastance and hydrostatic imbalance are additive when expressed as percentage of each load's acceptability limit.

GENERAL CONCLUSIONS

Respiratory impediments acting alone

Based on the findings discussed above the following limits apply for the three types of loads when they act alone:

Breathing resistance

The maximum allowable power of breathing depends on the ventilation and the diving depth according to Equation 1, repeated here:

$POB_{ext} = (A - B \cdot depth) \cdot ventilation$, where POB_{ext} is the total allowable external resistive power (W), $A=4.15 \cdot 10^{-2}$ W/(L/min BTPS) and $B=2.62 \cdot 10^{-4}$ W/(msw · L/min BTPS).

Elastance

The maximum allowable elastance is 0.7 kPa/L independent of depth and ventilation.

Hydrostatic imbalance

For a diver in the prone position, hydrostatic imbalances of about –10 and +15 cm H_2O (-1 and +1.5 kPa) referenced to the lung centroid are the maximum tolerable.

For a diver in the upright position, hydrostatic imbalances of about -10 to +10 cm H_2O (-1 to +1 kPa) referenced to the lung centroid are the maximum tolerable.

Respiratory impediments acting together
When the respiratory loads act together they are additive if each load is expressed in terms of its maximum value when acting alone. This means that the total acceptable respiratory load can be calculated by adding the relative value for each load.

Practical application of the presented information

Assume that a diver is swimming in the prone position. The ventilation is 40 L/min and the depth is 10 msw (33 msw). The following respiratory loads are imposed by the breathing apparatus:
External resistive power: determined to be 0.4 W. The maximum resistive power (given by Equation 01) in this situation is $(4.15 \cdot 10^{-2} - 2.62 \cdot 10^{-4} \cdot 10) \cdot 40 = 1.56$ W. The current load is then 0.4/1.56 = 26% of the maximum allowed.
Elastance: known to be 0.2 kPa/L. This is 0.2/0.7 = 29% of the maximum allowed.
Hydrostatic imbalance: determined to be +0.5 kPa. This load is 0.5/1.5 = 33% of the maximum allowed.
These three loads add up to a total of 26%+29%+33% = 88%. Since the total load is below 100% the breathing apparatus should be acceptable.

In the situation just described, the elastance and the hydrostatic imbalance add up to 62% of the total. This means that the external resistive load could be allowed to be as high as 100% - 62% = 38% of its maximum. The maximum resistive power would be 0.4/0.38 = 1.05 W. If the diver were to go deeper and (for the purpose of this example) the resistive power of the UBA were independent of depth, Equation 1 can be used to determine the maximum depth at which that the diver should use the equipment. With the same ventilation the depth could increase to 58 msw (190 fsw) before the allowable POB_{ext} reached 1.05 W.

RECOMMENDATION
We suggest that the findings in this report be incorporated in the Navy's Performance Standards for Underwater Breathing Apparatus.

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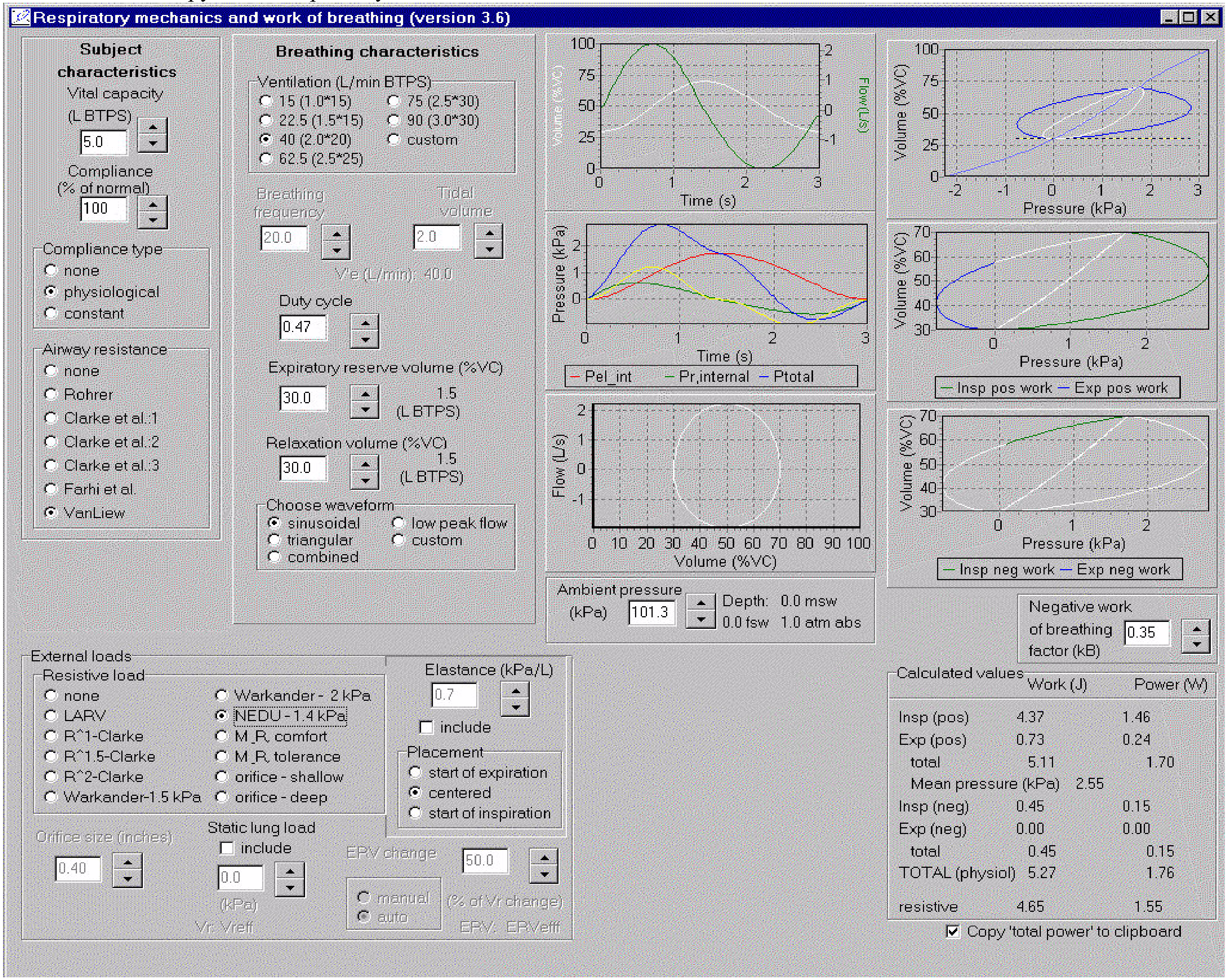
APPENDIX A. Screen copy of the respiratory mechanics model.



APPENDIX B

ACCEPTABLE LEVELS OF BREATHING RESISTANCE DERIVED FROM EXPERIMENTS AT CRESE.

Dan Warkander, Ph.D.

BACKGROUND

The data on acceptable breathing resistance from experiments at CRESE were published in Undersea and Hyperbaric Research (Warkander, *et al.*, 1990). The limits for external breathing resistance were set to be a volume-averaged pressure (WOB/V) in the range of 1.5 to 2.0 kPa in the ventilation range 30 to 90 L/min. The experiments were performed at two depths; a shallow depth (4.5 msw, 15 fsw, 147 kPa, 1.45 ATA) and the greatest depth that the standard US Navy diving tables allow (58 msw, 190 fsw, 690 kPa, 6.8 ATA). Exercise was performed for 25 minutes on an underwater cycle ergometer at 60% of each subject's maximum aerobic capacity, i.e. fairly hard work for a relatively long time. The limits were set based on a subjective criterion (dyspnea scores) in combination with an objective criterion (the divers' CO_2 levels). Results from both depths were combined.

METHOD AND RESULTS

Studies of the acceptable level of external breathing resistance by Clarke *et al.* (1989) have shown that the allowable external resistance should go down with increasing depth. The computer model predicts the same thing since the internal work increases with increasing depth. The respiratory muscles will probably not have a better endurance (except for some possible improvement because of increased PO_2) at depth which means that less and less can be allowed from external loads.

The data from these manned experiments at CRESE were reanalyzed by separating the two depths. Specifically, the old files were read from CDs and the data on WOB/V and ventilation level were re-plotted by depth (Figures B1 and B2).

At the shallow depth, the resistances were acceptable up to and including the moderate level. This means that a WOB/V limit of about 2.9 kPa would be acceptable at this depth.

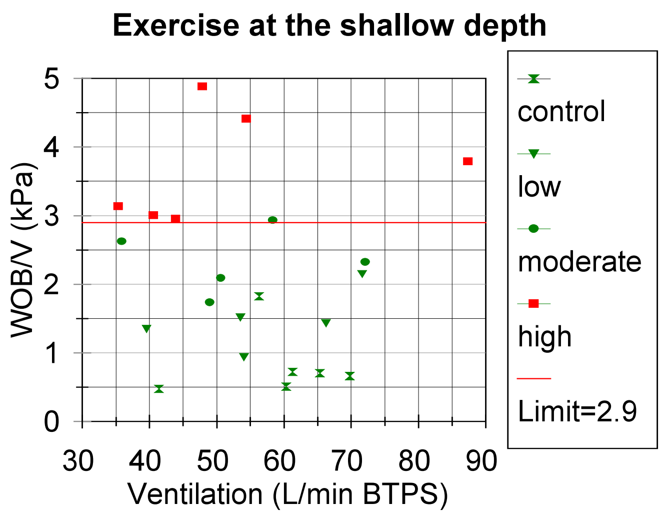


Figure B1. Plot of mean volume-averaged pressure and ventilation for the 4 levels of resistance at the shallow depth. The red, horizontal line shows the line (drawn by eye) for the upper limit at this depth.

At the great depth, the resistances were acceptable only up to and including the low level. This means that a WOB/V limit of about 1.8 kPa would be acceptable at this depth.

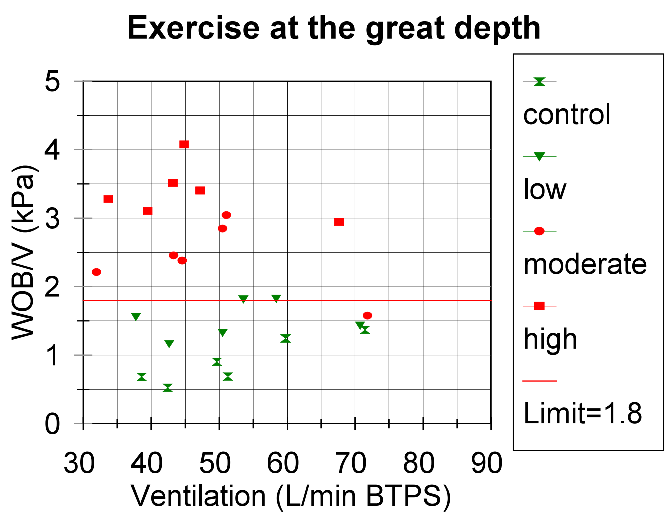


Figure B2. Plot of mean volume-averaged pressure and ventilation for the 4 levels of resistance at the great depth. The red, horizontal line shows the line (drawn by eye) for the upper limit at this depth.

By visual inspection there appears to be no reason for having the limit any different than a constant value (horizontal line) for these two depths.

Tables 6 and 7 in Warkander *et al.* provided the measured external power of breathing for the various resistances and depths. These data are shown in Figure B3. The external power of breathing for the highest acceptable resistance at the shallow depth was 2.14 W and at the great depth it was 1.40 W. These two limits are plotted in Figure B4 together with a straight line between them.

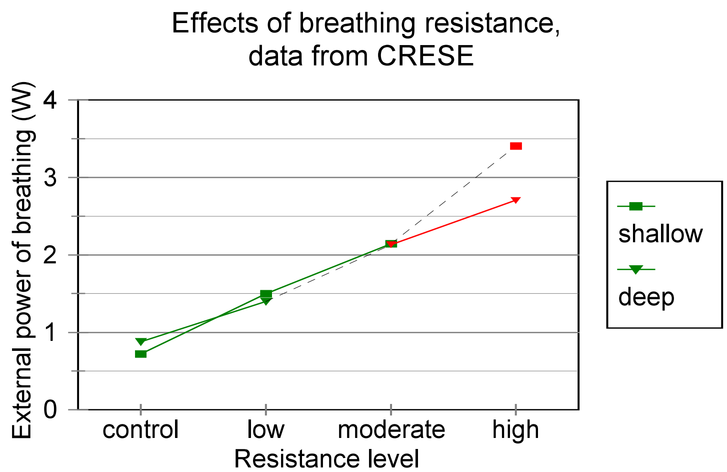


Figure B3. Plot of the external power of breathing measured for the 4 levels of resistance at both depths. The green lines and markers indicate acceptable levels of resistance. The red line and red markers indicate excessive breathing resistance. The black, interrupted lines connect the red and green lines.

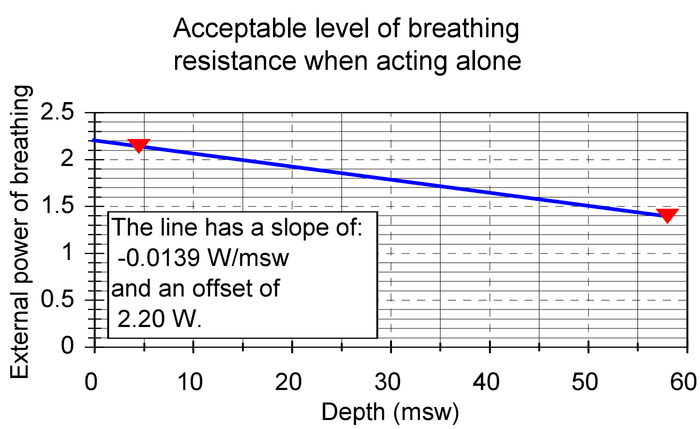


Figure B4. Plot of maximum acceptable external power of breathing for different depths. The two triangles show the limits for the two depths, respectively. The blue line connects the two.

By extrapolation of the straight line in Figure B4, it can be seen that no external resistance would be permitted at depths greater than 158 msw (518 fsw).

ALLOWABLE TOTAL POWER OF BREATHING

By adding the internal and external power of breathing the total power of breathing could be calculated. The internal POB was calculated using the respiratory mechanics model (program version 3.6) for the measured ventilation levels of 55.8 L/min BTPS at the shallow depth and 49.7 L/min BTPS at the great depth (an average of 53 L/min). The total POB for the shallow depth was 4.0 W and for the great depth it was 3.9 W.

By knowing the maximum total power of breathing and how the internal power changes with depth and ventilation, the allowable external power can be summarized by the equation

$POB_{ext} = (A + B \cdot depth) \cdot ventilation,$

where POB_{ext} is the total allowable external resistive power (W), $A=4.15 \cdot 10^{-2}$ W/(L/min BTPS) and $B=-2.62 \cdot 10^{-4}$ W/(msw · L/min BTPS). The equation is illustrated in Figure B5.

How does the limit on respiratory power apply to other ventilation levels?

Option 1: In previous standards, the WOB/V has most often been kept at a fixed value. In terms of POB, this translates into a straight line through the origin and a known point. The influences of ventilation and depth are illustrated in Fig B5. The POB_{max} increases linearly with ventilation. This seems physiological since increased ventilation signifies increased workrate and therefore increased cardiac output. It is interesting to note that such a relationship means that the respiratory muscles can work harder if the rest of the body does it. This relationship does not indicate an upper limit of the power of breathing at least not for the work loads tested.

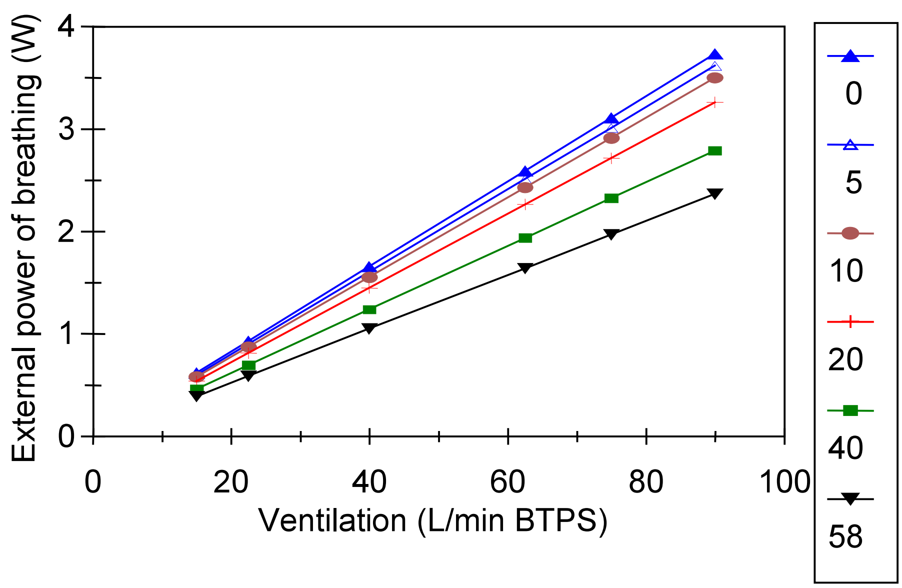


Figure B5. Permissible external power as a function of ventilation and depth.

Option 2: The WOB/V limit is sometimes specified to increase with ventilation. This would be a $POB_{limit} = k^* \dot{V}_E^2$ type equation. The ventilation increases almost linearly with the total work load (metabolic rate), at least up to the anaerobic threshold (about 60% of the maximum oxygen uptake). Such an approach would mean that the permissible POB would go up with the square of the workload, which does not seem physiological.

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