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COMPREHENSIVE PERFORMANCE LIMITS FOR DIVERS' UNDERWATER BREATHING GEAR: CONSEQUENCES OF ADOPTING DIVER-FOCUSED LIMITS

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19. ABSTRACT An underwater breathing apparatus (UBA) imposes loads on the diver: anything from the UBA's weight to those imposed on the respiratory muscles, some of the weakest muscles in the body. The types of respiratory loads imposed by a UBA are breathing resistance, elastic loads, hydrostatic imbalance (static lung load), inertial loads and CO_2. Historically, the limits on resistive effort have been based on the performance of the best commercially available UBAs around 1980. The most widely used set of limits (Morrison and Reimers, 1981) states in the conclusions that "it is fair to say that there are *inadequate physiological data on which to base reliable performance standards for underwater breathing apparatus.*" It adds that "Suggested standards can only be regarded as an interim measure and subject to change." The limits proposed in this report are based on the diver, not the UBA, and they state how much of each respiratory load is acceptable and how the loads interact: the resistive effort (WOB/V_T, in kPa) should not exceed $WOB/V_T = 2.49 - 0.016 *$ depth (with depth in msw) or $WOB/V_T = 2.49 - 0.00485 *$ depth (with depth in fsw). The elastance should not exceed 0.7 kPa/L independent of depth and ventilation. The maximum tolerable hydrostatic imbalances, measured relative to the suprasternal notch, should be in the range of +0.4 to +2.9 kPa for a vertical diver and in the range of -0.3 to +1.7 kPa for a horizontal diver. The total acceptable respiratory load can be calculated by adding the relative value for each load. Any CO_2 presented to the diver forces an increased respiratory minute ventilation thereby magnifying the effect of the other respiratory loads imposed by the UBA. The dead space in a UBA and the CO_2 in the inspired gas can be major influences in determining whether a UBA is acceptable. During tests of CO_2 scrubber endurance, the empirically determined ratio of CO_2 flow to minute ventilation (4%) should be used. Adopting these limits will mean that some rebreathers that had been nominally not acceptable are actually acceptable. The limits make little difference in the acceptability of currently available open circuit UBAs. These physiologically based limits should be adopted for use in the U.S. Navy.

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CONTENTS

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INTRODUCTION

An underwater breathing apparatus (UBA) allows a diver to stay underwater for extended periods of time. However, this ability comes at a price. The UBA imposes loads on the diver: anything from the UBA's weight to the loads imposed on the respiratory muscles, some of the weakest muscles in the body.

TYPES AND SOURCES OF THE RESPIRATORY LOADS

The respiratory loads imposed by a UBA are illustrated in Figure 1. Breathing resistance is created by hoses, narrow gas passages, valves, and, if present, the CO_2 absorbent. An elastic load is imposed, because the mean depth of the breathing bag (UBA's counter lung) changes during breathing. The diver is forced to increase minute ventilation because of the CO_2 load from the inspired gas and the dead space in the face mask. This increased minute ventilation thereby increases the effects of the other loads. Gas and water are accelerated and decelerated with each breath, changes which impose inertial effects. A static lung load is imposed, because the depth of the lung pressure centroid* differs from that of the breathing bag, a pressure difference called hydrostatic imbalance. Any such pressure difference makes the diver breathe at either higher or lower lung volumes, which the diver tries to resist by muscle tension.

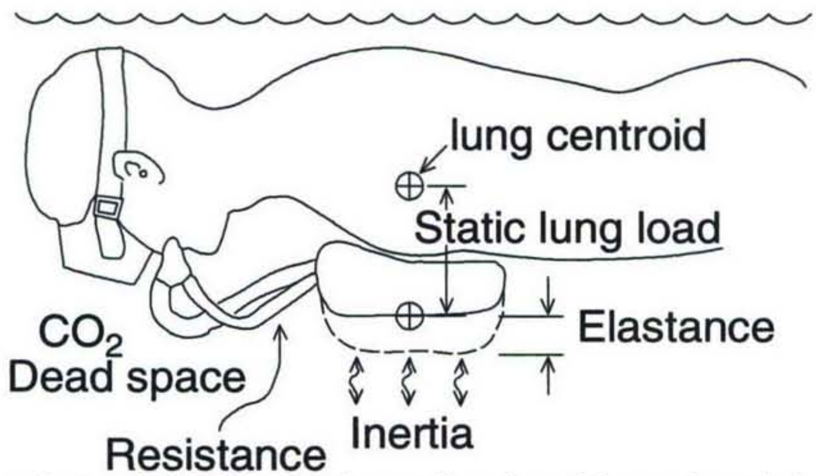

Figure 1. Respiratory loads imposed on a diver breathing a closed-circuit UBA with the breathing bag (counter volume) on the chest.

* The lung centroid is a functional reference and is defined as the equivalent pressure point at which a person's expiratory reserve volume (the volume at which the respiratory muscles are relaxed) is the same as in the non-immersed condition. A negative imbalance causes breathing at low lung volumes and causes inhalations to feel difficult. A positive imbalance causes breathing at high lung volumes and causes exhalations to feel difficult.

HISTORICAL LIMITS ON BREATHING RESISTANCE

Breathing resistance is typically the most obvious load and was the first load for which limits were set. Since the early 1980s two sets of limits on breathing resistance in UBAs have been used worldwide. In 1981 Middleton and Thalmann proposed a set of limits based on the performance of some of the best commercially available UBAs.[1] The limits varied with the type of UBA (e.g., open circuit scuba, rebreather, etc.; Figure 2 and Table 1), and some varied with minute ventilation related to the diver workload as well. All these limits, called "performance goals" in Navy Experimental Diving Unit (NEDU) Technical Manual 01-94,[2] have been adopted by the U.S. Navy. The limits for the work required to overcome breathing resistance (also called "resistive effort") is typically expressed as the work (in joules) for a breath divided by the size (in liters) of that breath — thus, as work of breathing per volume, with the units J/L being equivalent to kPa. In daily speech it is often called "resistive effort" or, in a technically incorrect phrase, "work of breathing."

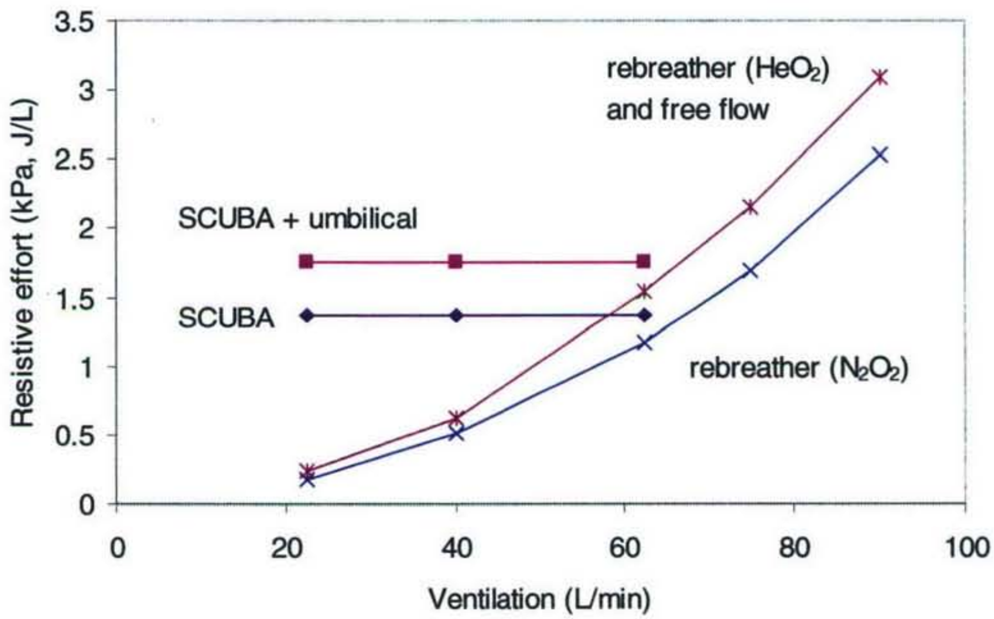

Figure 2. Limits on breathing resistance as proposed by Middleton and Thalmann.[1]

The limits were clearly equipment based. For instance, for open circuit scuba the value of 1.37 kPa at a respiratory minute ventilation of 62.5 L/min and a depth of 132 feet of sea water (fsw) was determined by "examining the data to find the point at which the state-of-the-art equipment significantly outperformed the rest of the group."[1] The equipment-based approach is also evident when the resistive effort from a surface-supplied UBA is examined: the resistive effort typically increases (Figure 2 and Table 1). The same thinking is apparent in the limits for a rebreather — the resistive effort tends to have the shape shown in Figure 2.

Table 1.
Resistive effort goals as defined by NEDU for the different categories of UBAs and the different test parameters used to achieve certain respiratory minute ventilations. Technical Manual 01-94[2] uses these definitions: Category 1. Open Circuit Demand UBA; Category 2. Open Circuit Umbilical-Supplied Demand UBA; Category 3. Open Circuit Umbilical-Supplied Free Flow UBA; Category 4. Closed- and Semi-closed Circuits, Breath-Powered UBA; and Category 5. Semi-closed Circuit, Ejector or Pump-Driven UBA.

			Category 1	Category 2	Categories 3 and 5	Category 4	Category 4
Minute ventilation	breathing frequency	tidal volume	0 to 198 fsw, air	0 to 198 fsw, air; 0 to 1000 fsw, HeO_2	0 to 200 fsw, air; 0 to 1500 fsw, HeO_2	0 to 150 fsw, air	0 to 1500 fsw, HeO_2
(L/min)	(breaths per minute)	(L)	(kPa)	(kPa)	(kPa)	(kPa)	(kPa)
22.5	15	1.5	1.37	1.76	0.231	0.170	0.231
40	20	2.0	1.37	1.76	0.617	0.509	0.617
62.5	25	2.5	1.37	1.76	1.542	1.172	1.542
75	30	2.5	-	-	2.159	1.696	2.159
90	30	30	-	-	3.085	2.529	3.085

In 1982, Morrison and Reimers published the results of a literature review,[3] Figure 3. In this review they proposed a "comfort limit" of

$$WOB_{max} = 0.5 + 0.02 * \dot{V}_E,$$

where $\dot{V}_E$ is the minute ventilation in L/min. A less restrictive limit called a "tolerance limit,"

$$WOB_{max} = 0.5 + 0.04 * \dot{V}_E,$$

was added with the acknowledgment that "for practical purposes a second limit of tolerance is proposed."

The limits of Morrison and Reimers formed the basis of the limits established for the North Sea, limits established through a collaboration between the Norwegian Petroleum Directorate and the U.K. Department of Energy. The European standard for open circuit scuba (EN-250)[4] uses the "tolerance limit" but requires testing only at a minute ventilation of 62.5 L/min; thus, its limit is 3.0 kPa. The European rebreather standard EN 14143[5] uses a limit that is halfway between the comfort and tolerance limits:

$$WOB_{max} = 0.5 + 0.03 * \dot{V}_E.$$

The limits discussed so far in this report are all based on the performances of UBAs available around 1980. Morrison and Reimers[3] write in their conclusions: "it is fair to say that there are *inadequate physiological data on which to base reliable performance standards for underwater breathing apparatus*" [authors' emphasis]. They add that "Suggested standards can only be regarded as an interim measure and subject to change."

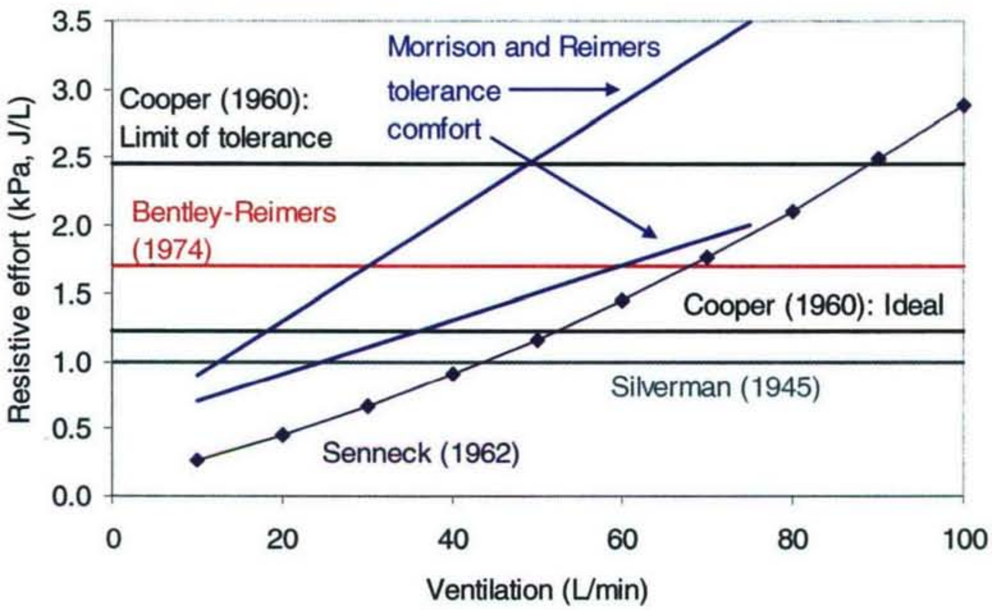

Figure 3. Limits on breathing resistance[6-10] in the review by Morrison and Reimers,[3] with their proposed limits.

LIMITS BASED ON DIVER TOLERANCE

Partly in response to Morrison and Reimers' quoted conclusions above, the University at Buffalo has, with Navy support, performed more than 1,000 experimental dives with various combinations of breathing resistance and other respiratory impediments. Experiments were performed with immersed divers exercising at 60% of their maximum aerobic capacities for 25 minutes at depths down to the greatest that standard air decompression tables allow.

The findings have been presented in several reports to the Navy,[11-14] presented at international scientific meetings[15-33] and published in scientific literature[34-37]. One of the publications on acceptable breathing resistance[37] has been labeled "the most complete study of hyperbaric breathing limits".[38]

All the findings were compiled in a final report, *Development of Comprehensive Performance Standards for Underwater Breathing Apparatus* by Warkander and Lundgren,[14] a report proposing physiologically and subjectively acceptable limits on respiratory loads. The report pointed out that some previous limits on resistive effort have fixed values, while others vary with minute ventilation. For instance, a fixed value for resistive effort means that the power that the respiratory muscles must develop is proportional to that which the large muscles performing the rest of the body's work must develop. If the resistive effort were allowed a linear increase with minute ventilation, then the respiratory muscles are expected to tolerate an increase that may be proportional to the square of the minute ventilation. On these grounds, the report argued that the limit on resistive effort must be a fixed value independent of minute ventilation.

It also pointed out that diving depth is a factor that had not been considered in earlier unmanned testing limits. Yet as depth and, correspondingly, gas density increase, the effort required to move the gas in and out of the lungs increases. Since the respiratory muscles do not get any stronger with increasing depth, the effort that is available to overcome the loads imposed by the UBA has to decrease with increasing depth. Clarke[39] may have been the first to link the probability of an "untoward event" during a dive to depth and flow rate. However, the Warkander and Lundgren report[14] appears to be the first to quantify how much the external resistance has to decrease as depth increases.

The report concluded with the following observations:

A respiratory load acting *alone*
The resistive effort (expressed as work of breathing per volume, WOB/V_T) should not exceed:

$$WOB/V_T = 2.49 - 0.016 * depth \qquad \text{(depth in msw, effort in kPa)}$$
$$WOB/V_T = 2.49 - 0.00485 * depth \qquad \text{(depth in fsw, effort in kPa)}$$

The elastance should not exceed 0.7 kPa/L independent of depth and ventilation.

The hydrostatic imbalance: For a diver in the prone position, hydrostatic imbalances of about -1 and +1.5 kPa (-10 and +15 cm H_2O) referenced to the lung centroid are the maximum tolerable. For a diver in the upright position, hydrostatic imbalances of about -1 to +1 kPa (-10 to +10 cm H_2O) referenced to the lung centroid are the maximum tolerable. Table 2 shows these values referenced to other reference points. It should be noted that the hydrostatic loads imposed in the studies referenced by Warkander and Lundgren[14] have been in increments of 10 cm H_2O (1 kPa). As these authors point out, depending on a person's body size, the distance between the actual lung centroid and the sternal notch must vary somewhat, at least in the upright position. Therefore, all limits may well have an uncertainty of some 5 cm H_2O (0.5 kPa).

Table 2.
Maximum tolerable hydrostatic imbalances (kPa).

	Reference point	
Diver orientation	Lung centroid	Suprasternal notch
Upright (vertical)	-1 to +1.5	+0.4 to +2.9
Prone (swimming face down)	-1 to +1	-0.3 to +1.7

Respiratory impediments acting *together*
When acting alone, each respiratory load is expressed as a fraction of its maximum value; when the respiratory loads act together, however, they are additive.[14] This means that the total acceptable respiratory load can be calculated by adding the relative value for each load.

CO_2 loads
Any CO_2 in the inspired gas forces the diver to increase his minute ventilation. The CO_2 can originate from the breathing gas, a CO_2 scrubber, or the mask's dead space that traps CO_2 from previous breaths. The increased ventilation magnifies the effect of the other respiratory loads imposed by the UBA. The proposed NATO STANAG 1410[40] states that a UBA is permitted to supply the diver with an inspired level of CO_2 as high as 2 kPa (2% SEV).

RATIO OF CO_2 PRODUCTION TO MINUTE VENTILATION

The endurance of a CO_2 absorber in a rebreather depends on many factors, including absorbent temperature and "dwell time," the time that the gas is in contact with the absorbent. A cold absorbent does not absorb CO_2 very fast, and the longer the gas is inside the absorber, the better the absorption will be. It follows that the combination of minute ventilation and CO_2 concentration is important during unmanned determinations of the endurance of a CO_2 absorber, and this combination should closely match what a diver actually exhales.

In testing the endurance of a CO_2 absorber at NEDU, researchers often discuss how much CO_2 should be injected for a given ventilation. The empirical ratio of CO_2 production to minute ventilation needs to be clarified. During many of the Navy-sponsored experimental dives performed at the University at Buffalo, the subjects' expired air was collected in Douglas bags and analyzed. The potential usefulness of these recordings provided the impetus for recovering data files saved in old file formats.

PURPOSE OF THIS REPORT

The purpose of the present report is to determine what the practical results would be if Warkander and Lundgren's comprehensive approach to respiratory load limits[14] are adopted by the U.S. Navy. The consequences of recent proposed changes in the STANAG 1410 on limitations of inspired CO_2 will be discussed.

METHODS

DETERMINATION OF LOADS IMPOSED BY UBAS

Results from previous testing of scuba, umbilical-supplied regulators, and closed-circuit UBAs at NEDU were obtained from reports and from an NEDU database called BRXALL. These results were compared to the recommendations by Warkander and Lundgren.[14]

INFLUENCE OF CO_2 LOADS

An increased inspired CO_2 level forces the diver's minute ventilation to increase for a given CO_2 level. The amount of this increased minute ventilation, expressed as a ratio between the changed and unchanged minute ventilation ($\dot{V}_{E,factor}$), can be described by

$$\dot{V}_{E,factor} = P_{CO_2}/(P_{CO_2} - P_{in}CO_2), \qquad \text{(Eq. 1)}$$

where $P_{in}CO_2$ is the average inspired CO_2 level and P_{CO_2} is the CO_2 level maintained by the diver.

Human experimentation has shown that the minute ventilation increases, on the average, by 58% per liter of external dead space (V_D).[41]

$$\dot{V}_{E,factor} = 1 + 0.58 * V_D, \qquad \text{(Eq. 2)}$$

if V_D is expressed in liters.

With Equations 1 and 2, it is possible to derive equations to calculate what a certain dead space equals in terms of average inspired CO_2 for different levels of CO_2:

$$V_D = P_{in}CO_2/(P_{CO_2} - P_{in}CO_2)/0.58 \qquad \text{(Eq. 3), and}$$

$$P_{in}CO_2 = P_{CO_2} * 0.58V_D/(0.58V_D + 1). \qquad \text{(Eq. 4)}$$

RESULTS

RESISTIVE EFFORT

Open Circuit Scuba

Data were obtained from recent testing of 20 models of scuba regulators (Figure 4).[42] The graph shows that the proposed limit does not restrict any regulator being used to dive to 132 fsw. Sixteen regulators would likely be approved for diving to 198 fsw.

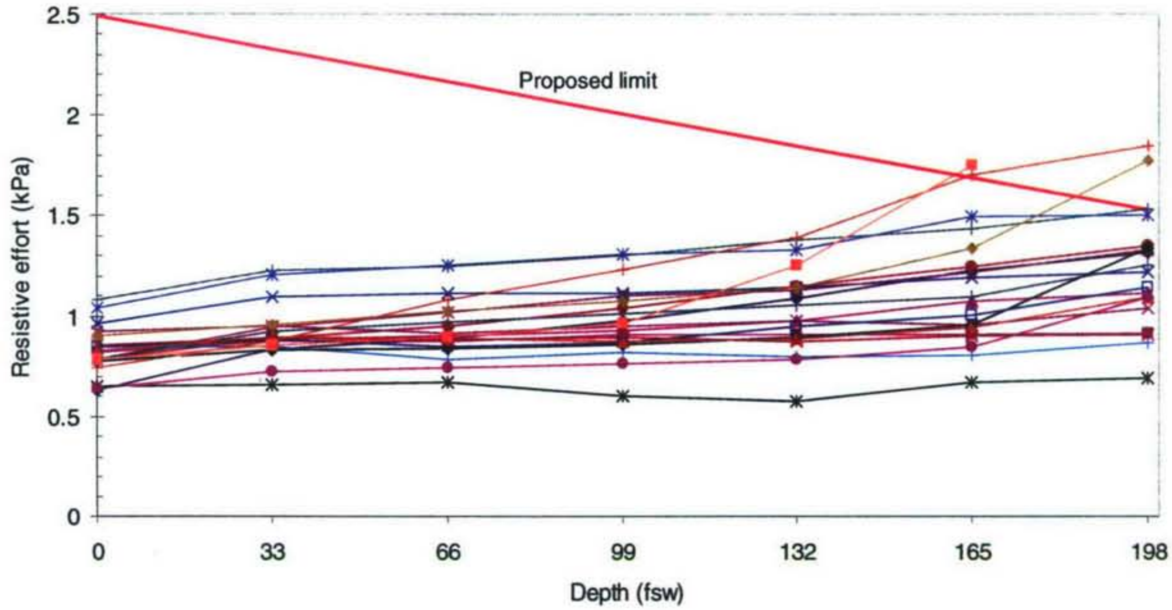

Figure 4. The proposed limit and resistive efforts from 20 regulators breathed at 62.5 L/min. The statistical analysis has been omitted for clarity.

Umbilical-supplied Regulators

No distinction between an umbilical-supplied and a free-swimming scuba diver is made in the proposed limits. This lack of distinction may appear to make umbilical-supplied limits tighter than they are today. However, results from recent testing of modern umbilical-supplied UBAs (Kirby Morgan XLDS RDC-3 and Interspiro DP-2) are available.[43] Under the proposed limits, the Interspiro DP2 would still be approved for diving down to 198 fsw. Similarly, the depth limit for the XLDS RDC-3 with the MK 20 mask would remain at 132 fsw. However, for the XLDS RDC-3 with the MK 21 helmet the maximum depth would change from 165 fsw to 132 fsw.

Closed-circuit UBAs

Analysis was concentrated on the two closed-circuit UBAs used in the Navy, the MK 16 and the MK 25.

MK 16

Historical data from one MK 16 MOD 1 were obtained and plotted in Figure 5. From these data points and the *current* performance goals,[2] this MK 16 could be approved for diving to 66 fsw at a minute ventilation of 62.5 L/min with an N_2O_2 mixture. For the lowest workload tested, 22.5 L/min, the current goal is so low that this UBA could not be approved even at the surface.

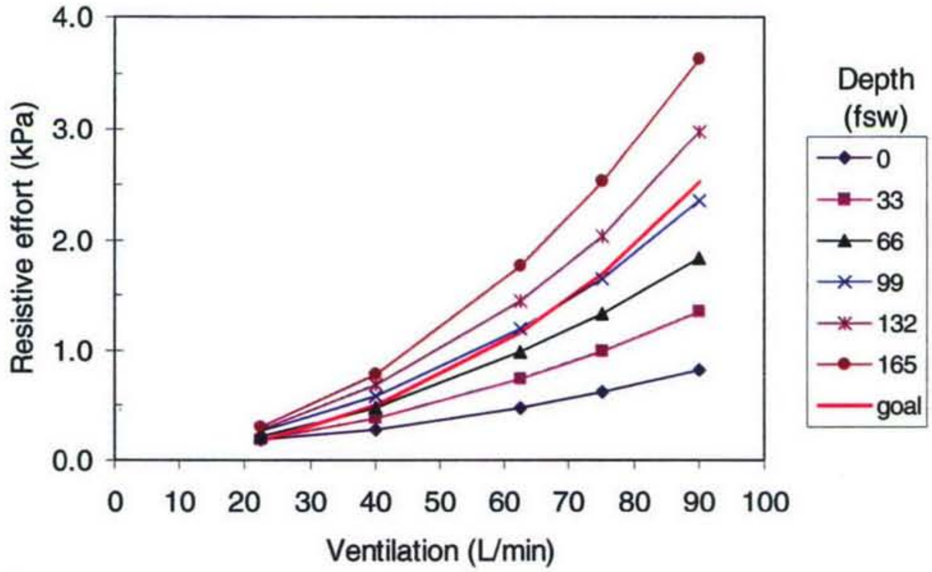

Figure 5. Data plotted together with the current goal for one MK 16 MOD 1 tested in the prone position.

It has long been recognized that the goals have been set unrealistically low. If the proposed limits are applied, however, other depth limits can be set. Figure 6 illustrates the effect of such a change. The resistive effort increases with increasing depth, while the proposed limit decreases with depth. The two lines have intercepted before 165 fsw, an indication that diving to 132 fsw should be acceptable. As does Figure 5, Figure 6 also demonstrates that the current limits would likely restrict this UBA to depths less than 99 fsw.

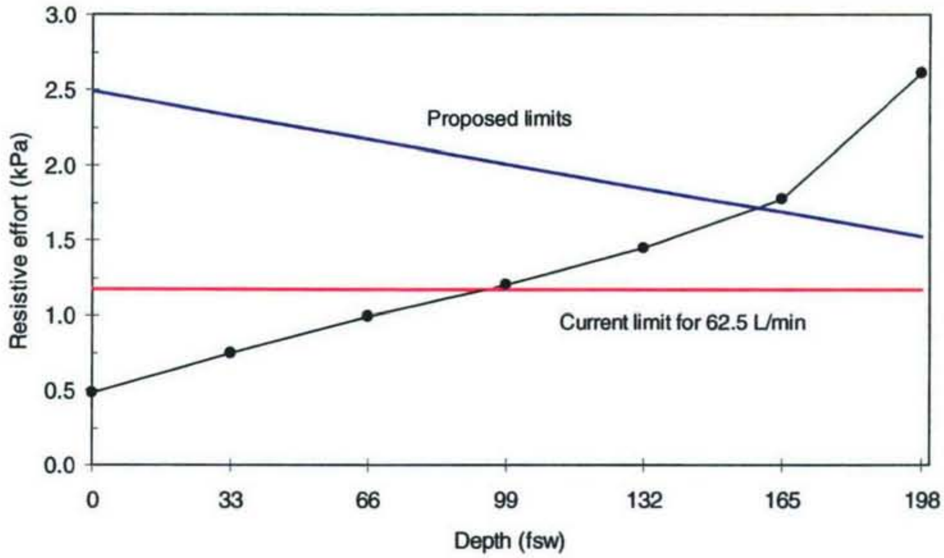

Figure 6. Current performance goal and the proposed limit are plotted together with actual data from one MK 16 MOD 1 tested in the prone position with a minute ventilation of 62.5 L/min.

MK 25

Resistive effort data for the MK 25 (LAR V) were extracted from data generated from NEDU test plan 94-03[44] (database BRXALL) and are presented in Figure 7. The resistive effort for the MK 25 is always greater than the current performance goal. Figure 8 shows the same data as Figure 7 but plots that data against depth instead of minute ventilation.

Figure 8 illustrates how the proposed limits actually permit diving with the MK 25 UBA at a minute ventilation of 62.5 L/min to a depth of 33 fsw if Sofnolime 408® is used. However, if Sofnolime 812® is used, then diving is limited to 15 fsw. In terms of resistive effort, diving is permitted to at least 60 fsw at minute ventilations of 40 L/min and less.

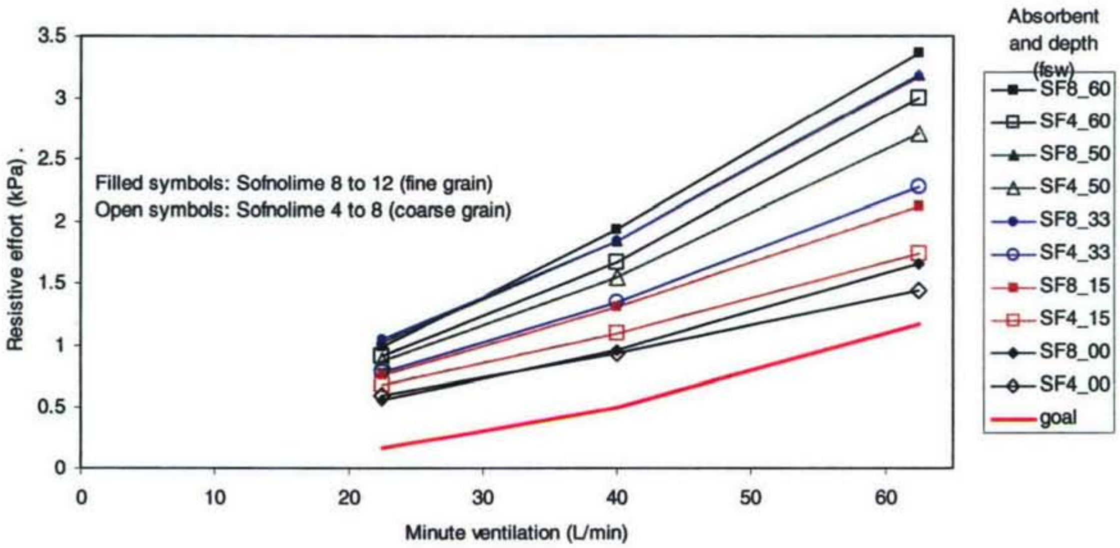

Figure 7. Resistive effort data from one MK 25 UBA plotted against minute ventilation. The current NEDU performance goal is also shown. The MK 25 was tested with two absorbents at depths down to 60 fsw (about 18 msw). In the legend, "SF8" refers to Sofnolime 812® and "SF4" refers to Sofnolime 408®; the numbers "00" through "60" refer to the depth.

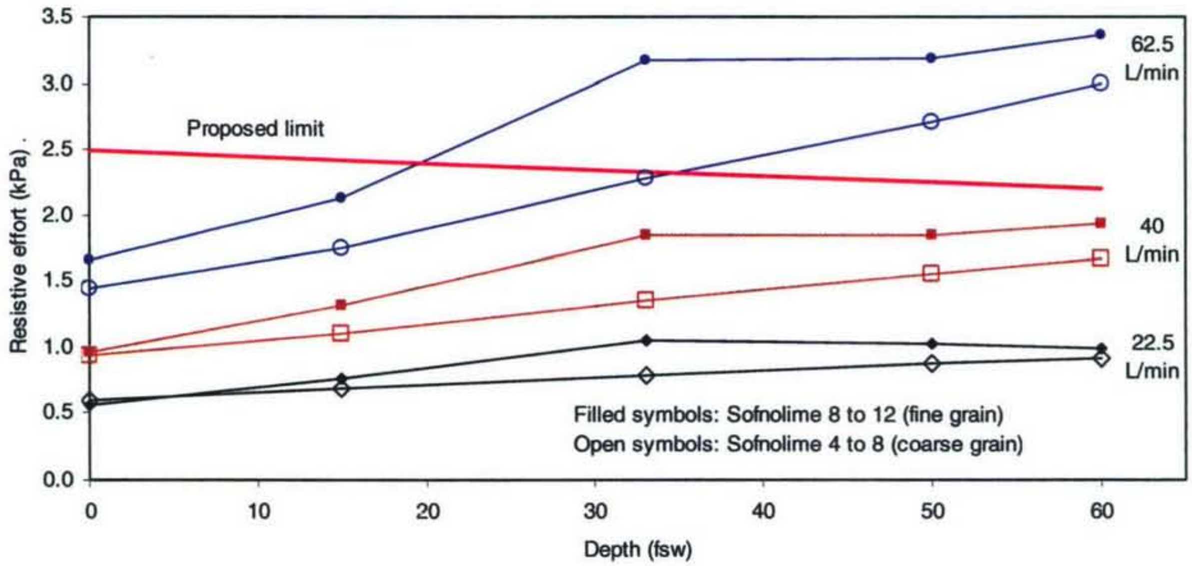

Figure 8. Resistive effort of one MK 25 UBA and the proposed limit plotted against depth. Two absorbents were tested at depths down to 60 fsw (about 18 msw). The statistical analysis has been omitted for clarity.

ELASTANCE AND HYDROSTATIC IMBALANCE

Open circuit demand valves

A demand valve has no elastance of practical importance. The hydrostatic load is determined by the vertical distance between the lung centroid and the demand valve (usually the button on the side of the valve). Since the demand valve is typically level with the diver's mouth, all open circuit demand valves have about the same hydrostatic imbalance. The vertical distance between the lung centroid and the mouth for an upright diver is typically given as 17 cm,[2] equivalent to about 1.7 kPa. For a prone diver the distance is about 10 cm, equivalent to about 1 kPa. For a vertical, head-up diver the mouth is shallower (i.e., at a lower pressure) than the lung centroid, a position which induces a negative hydrostatic load.

Rebreathers

The elastance and the hydrostatic load in a rebreather are not fixed values; they vary with diver orientation and the volume of gas in the breathing bag. NEDU has recently revised its procedures for elastance and hydrostatic load testing[45] in rebreathers to reflect this fact.

MK16 Elastance in the face-down position is 0.13 kPa/L; in the upright, and with either shoulder down, it is 0.35 kPa/L. The hydrostatic load varies with diver orientation: upright = +1.7 kPa, face down = -2.7 kPa, left shoulder down = +0.48 kPa, and right shoulder down = 0.2 kPa relative to the suprasternal notch.

The Divex Stealth EOD-M The measurements for hydrostatic imbalance are presented in Table 3; those for elastance in Table 4.

Table 3.
Hydrostatic imbalance (kPa) relative to the suprasternal notch with different diver positions and different amounts of gas in the rebreathing bag.

Position	Bag volume		
	Empty at end of inspiration	Middle	Full at start of inspiration
Vertical	1.5	1.8	2.2
Face down	0.5	1.6	2.6
Left shoulder down	0.8	1.6	2.2
Right shoulder down	3.3	3.9	4.3

Table 4.
Elastance (kPa/L) with different diver positions and different amounts of gas in the rebreathing bag.

Position	Bag volume		
	Empty at end of inspiration	Middle	Full at start of inspiration
Vertical	0.22	0.35	0.37
Face down	0.27	0.36	0.69
Left shoulder down	0.72	0.74	0.48
Right shoulder down	0.75	0.90	0.97

MK 25 The MK 25 has not been tested under the new procedure,[45] but with its chest-mounted breathing bag it is expected to have a positive hydrostatic load in a face-down position.

INFLUENCE OF CO_2 LOADS

Results of calculations based on Equations 1 and 2 are illustrated for a diver who maintains either the textbook CO_2 value of 5.3 kPa (40 mm Hg; Figure 9) or a slightly increased CO_2 level of 6.0 kPa (45 mm Hg; Figure 10). The average CO_2 level maintained at 15 fsw by an exercising diver breathing against a low resistance has been measured to be 5.9 to 6.4 kPa (44 to 48 mm Hg).[37] The CO_2 level increases further with increasing resistance and depth. Thus, a CO_2 level of 6.0 kPa has to be considered common among exercising divers exposed to a low external breathing resistance. The fact that these values are averages means that some divers, who are CO_2 retainers, let the CO_2 level climb higher than average, while others, CO_2 defenders, maintain a low CO_2 level even at the expense of experiencing dyspnea.[37]

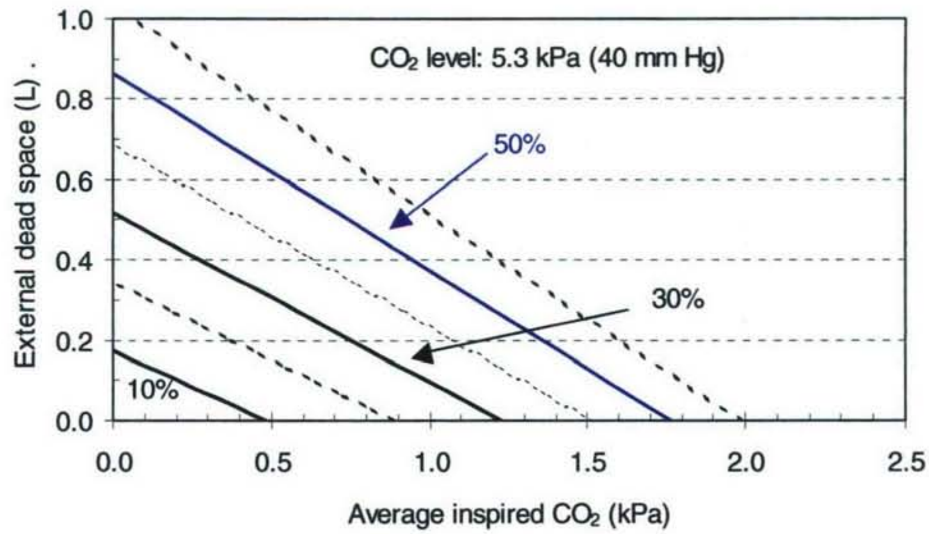

Figure 9. Equivalence between external dead space and average inspired CO_2 for different levels of increased minute ventilation for a diver maintaining a CO_2 level of 5.3 kPa (40 mm Hg).

For instance, for a typical working diver maintaining a CO_2 level of 6.0 kPa (Figure 10), a dead space of 0.20 L (a full face mask with a well-fitting oro-nasal mask — e.g., a MK 20 mask) induces an increase in minute ventilation of about 11%, and this corresponds to an average inspired CO_2 of about 0.55 kPa. If this diver instead uses a mask (e.g., a MK 21 helmet) that does not fit well, the dead space is likely to be around 0.4 to 0.5 L, which corresponds to an increase in minute ventilation of about 25% and an average inspired CO_2 level of about 1 kPa.

Figures 9 and 10 can also illuminate how the combination of dead space and CO_2 influence the inspired gas supply. Assume that a diver wears a mask with a dead space of 0.20 L and uses a rebreather in which the scrubber has reached the end of its useful time (CO_2 level of 0.50 kPa, 0.5% surface equivalent). The dead space is equivalent to an inspired CO_2 level of 0.55 kPa. If the diver maintains his CO_2 level, the CO_2 from the dead space is added to the 0.5 kPa from the UBA to make an average inspired CO_2 level of 1.05 kPa. Figure 10 shows that an inspired CO_2 level of 1.05 kPa increases the minute ventilation by about 22%. If a diver has so overused the rebreather that the scrubber leaves behind 1.5 kPa (for a total CO_2 of about 2 kPa), then the minute ventilation has to increase by more than 50%. If the diver were a CO_2 defender and instead maintained a CO_2 level of 5.3 kPa (40 mm Hg), then his minute ventilation has to increase by more than 60% (the right-most interrupted line in Figure 9).

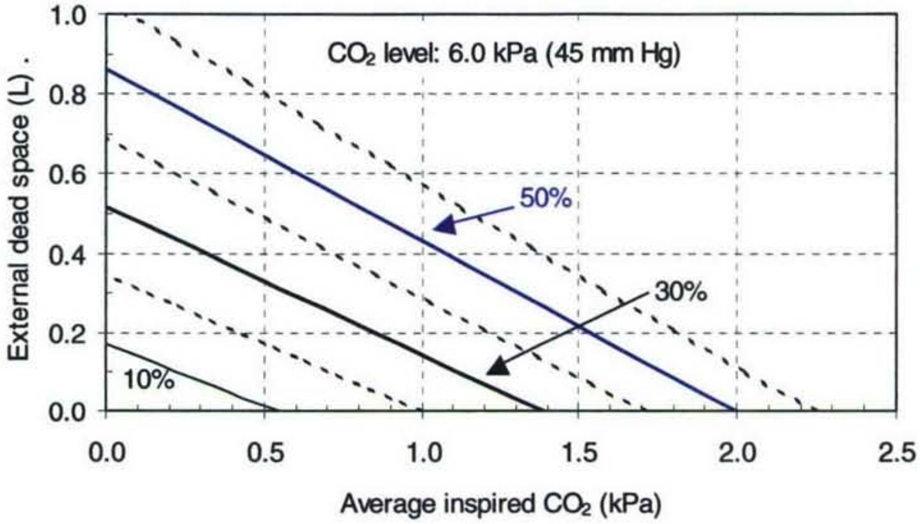

Figure 10. Equivalence between external dead space and average inspired CO_2 for different levels of increased minute ventilation for a diver maintaining a CO_2 level of 6.0 kPa (45 mm Hg).

RATIO OF CO_2 PRODUCTION TO MINUTE VENTILATION

During many of the Navy-sponsored experimental dives performed at the University at Buffalo, the subject's expired air was collected in Douglas bags and analyzed. These collections were all from air dives in which the depth was either 15 fsw (4.5 msw) or 190 fsw (57 msw). The breathing resistance ranged from minimal to higher than what is acceptable for an unmonitored subject. The breathing resistance was applied on the inspiratory side, the expiratory side, or both. With data recovered from an extensive number (n = 997) of such bag collections, the collections showed that the average ratio of CO_2 production to respiratory minute ventilation was 3.89% (SD = 0.50%, 99% confidence interval: 3.84 to 3.93%). With collections (n = 246) for which the external breathing resistance was as low as possible (controls), the ratio was 3.77% (SD = 0.46%, 99% confidence interval: 3.70 to 3.85%).

DISCUSSION

CONSEQUENCES OF EXCESSIVE RESPIRATORY LOADS

It is easy to criticize any limit, because there is always somebody who has exceeded the limit without any apparent problems. It must be remembered that the proposed limits are based on studies in which subjects worked hard (60% of their maximum oxygen uptake) for 25 minutes. Therefore, it is possible to sustain a respiratory load greater than the proposed limit for a shorter time or a lesser load for a longer time than the proposed limit. Compare these limits to the situation of somebody carrying a backpack: it may be possible to carry a very heavy pack for a few minutes, but not for hours. On the other hand, a pack that can barely be carried all day may seem ridiculously light when it is first picked up.

When exposed to excessive respiratory loads, a diver has either to try to work against the loads or to reduce them by breathing more slowly. Working against the loads may cause fatigue followed by slower breathing. Slower breathing means either that the level of CO_2 will rise (CO_2 retention) or that the diver will be forced to work more slowly — like a runner having to walk.

A diver who has a low sensitivity to CO_2 will reduce his minute ventilation, thereby allow his CO_2 levels to rise (CO_2 retention) and cause loss or impairment of consciousness, and, according to Lanphier and Camporesi,[46] be at risk for CO_2 narcosis, increased susceptibility to O_2 convulsions, severe effects on thermoregulation, and increased likelihood of decompression sickness. A CO_2 defender will maintain his minute ventilation at the cost of dyspnea.

ACCEPTABLE RESISTANCE

The proposed limits of resistive effort have been included in the latest revision of the NATO standard STANAG 1410.[40]

The proposed limits make a big difference for rebreathers: both MK 16 and MK 25 rebreathers can now be approved on the basis on physiological data. With the inclusion of the influence of diving depth, the need for different rebreather designs for shallow and deep diving becomes apparent.

In practice, the proposed limits make little difference in terms of acceptable resistive effort for open circuit demand regulators, both self-contained and umbilical-supplied.

ELASTANCE AND HYDROSTATIC IMBALANCE

The vertical distance between the lung centroid and the mouth for an upright diver is typically given as 17 cm,[2] equivalent to about 1.7 kPa. This value is greater than what is acceptable for a scuba diver, and such a diver should not be working in an upright position even with a regulator lacking any breathing resistance. Every diver at some time has been vertical in the water and knows that it is possible to breathe. Therefore, what the limits tell us is that a diver cannot be expected to work very hard for very long in a vertical position.

The elastance and the hydrostatic load in a rebreather are not fixed values: these values vary with diver orientation and the volume of gas in the breathing bag. During descent the bag volume is typically minimal (e.g., the bag hits the add valve), and during ascent the bag volume is typically big (e.g., the bag hits an exhaust valve). At a stable depth the diver can add or release gas to be breathing in the middle of the bag volume. Therefore, the hydrostatic imbalance and elastance must be determined at a minimum of three bag volumes — empty, midrange, and full. Only recently has NEDU implemented such testing,[45] so the number of UBAs tested is limited. Even so, this testing method has revealed differences among the placements of the breathing bags.

A rebreather with a front-mounted bag (e.g., the MK 25) imposes a positive hydrostatic load on a diver swimming face down. Normal diver anatomy means that the bag is at least 7 cm deeper than the lung centroid; thus, the hydrostatic imbalance is likely to be at least +0.7 kPa relative to the lung centroid.

A rebreather with over-the-shoulder bags (e.g., the Divex Stealth EOD-M) tends to have little hydrostatic imbalance on a diver swimming with the face down and small bag volume. If the rebreathing bag is full (e.g. diver added gas to gain buoyancy or because of gas expansion during normal ascent) the imbalance is large. If the diver is swimming with either shoulder down, the hydrostatic imbalance can also become great. In the latter situations the gas collects in the upper bag, but when an exhalation fills the upper bag the diver suddenly has to generate enough pressure to push the gas into the lower bag. This result is evident in very large imbalances (Table 2, right shoulder down) and elastance (Table 3, either shoulder down). Obviously, the hydrostatic imbalance is determined by placement of the add and exhaust valves.

With a back-mounted rebreathing bag (e.g., the MK 16), the normal anatomy of a diver swimming face down dictates that it is essentially impossible to have a hydrostatic imbalance less than -2 kPa. Therefore, a diver cannot be expected to work very hard for very long with a back-mounted rebreathing bag — or a diver could work harder and/or longer with the rebreathing bag put in a different place. Bag elastance is low when the diver is swimming face down. The hydrostatic load changes dramatically — from -2.7 to +1.7 kPa — by going from a horizontal to a vertical orientation.

COMBINED RESPIRATORY LOADS

The total respiratory load can be calculated by adding how much each of its components — resistance, hydrostatic imbalance, and elastance — contributes when each is expressed as a fraction of its maximum.[14]

Open circuit demand regulator

If the diver were swimming face down (prone), the regulator may be about 10 cm deeper than the lung centroid, so the hydrostatic imbalance is likely to be some +1 kPa relative to the lung centroid. The limit in this position is +1.5 kPa, a limit which means that the diver's relative hydrostatic load is about 67%. In practice, it is difficult to say what the load would be: if the diver were to lift his head to be able to look forward, the load might become 0 or even negative.

The resistive effort for most of the regulators tested was in the range of 0.9 to 1.1 kPa for dives to 132 fsw with a minute ventilation of 62.5 L/min.[42] Since the proposed resistive effort limit at this depth is 1.85 kPa, the relative resistive effort is in the range from 49% to 59%.

The total relative load is the sum of the two loads (no elastance). For the prone diver mentioned two paragraphs above who keeps his head horizontal, the total load is 116% to 126%. This regulator would not support hard work that lasts a long time. To be within the 100% limit, the relative resistive effort would have to be less than 100% - 67% = 33%. For a dive at 132 fsw the resistive effort would have to be less than 33% of 1.85 = 0.62 kPa. Only one of the four best regulators reported on[42] meets this limit — and then only at the surface. However, if the diver lifts his head, the total load could be reduced to less than 60%, and then all of the regulators tested would be acceptable. An alternative way of looking at the effect of limits is to determine at which depth the regulator meets the total limit. A depth reduction increases the limit, and typically the required resistive effort decreases. Unfortunately, for these four regulators the depth limit is shallower than 66 to 99 fsw if the diver cannot lift his head.

For a vertical diver the hydrostatic load is likely to be from -1.5 to -2 kPa if the regulator is in the diver's mouth. This load is about 1.5 to 2 times greater than what a diver who works hard for a long time can sustain.

This discussion emphasizes the importance of hydrostatic imbalance. For the swimming diver this load could be 67% of the total limit. For a vertical diver the hydrostatic load is far greater than what is acceptable. Most modern regulators are now made so that resistive effort, acting alone, is low enough to be acceptable for a diver working hard for a long time. It is apparent that future efforts should concentrate on designing regulators that can reduce hydrostatic load.

Rebreathers

Chest-mounted breathing bag

A rebreather with a chest-mounted rebreathing bag (e.g., the MK 25) would likely impose a hydrostatic imbalance of about +0.7 kPa (related to the vertical distance between lung centroid and the chest) on a prone diver. This imbalance would be a relative load of 0.7/1.5 = 47%. For a dive to 20 fsw the limit on resistive effort is 2.39 kPa. The remaining 53% of the total load corresponds to a maximum resistive effort of

1.27 kPa (53% of 2.39 kPa), roughly the resistive effort of the MK 25 (Figure 8) for a minute ventilation of 40 L/min.

At 20 fsw and a minute ventilation of 62.5 L/min the resistive effort of the MK 25 is 1.75 kPa — i.e., 73% of the total limit. Together with the hydrostatic imbalance, this total load adds up to 73% + 47% = 120%. A diver could not be expected to sustain a level above 100% for a long time.

Back-mounted breathing bag

For a rebreather with a back-mounted breathing bag such as the MK 16, the hydrostatic load for a prone diver is -2.7 kPa relative to the suprasternal notch, i.e., -2 kPa relative to the lung centroid (200% of the acceptable load). In this position the elastance is 0.13 kPa/L (19%). Even before any resistive effort is considered, the total load is more than twice what is acceptable. Even if the diver swims with an up-angle of 30°, the imbalance is still about -1.7 kPa. It follows that somebody planning to swim at a high work rate for a long time should avoid using a back-mounted breathing bag.

In a vertical position the hydrostatic load is about +1.7 kPa relative to the suprasternal notch, i.e., about +0.3 kPa relative to the lung centroid (30%). The elastance is 0.35 kPa/L (50%), and with a minute ventilation of 62.5 L/min the resistive effort is 1.7 kPa (92%) at 132 fsw. Thus, the total load is about 1.7 times what is acceptable. If the minute ventilation were 22.5 L/min instead, the resistive effort would be only 0.39 kPa (21%), and the total load would be about 101% — a load that could be sustained for a long time.

Over-the-shoulder rebreathing bag

For a vertical diver using a rebreather with over-the-shoulder rebreathing bags, numbers from the Stealth EOD-M (Tables 2 and 3) show that the hydrostatic imbalance is about +1.8 kPa relative to the suprasternal notch, i.e., 0.4 kPa relative to the lung centroid (40%), with a small influence from the bag volume. The elastance is about 0.35 kPa (50%). Thus, this design leaves more room for resistive effort. The numbers are about the same for a diver swimming in the prone position. However, if a diver were to swim with the left shoulder down, the hydrostatic imbalance would be about the same, but the elastance would about double (100% of the acceptable limit). With the diver swimming with his right shoulder down, the elastance is increased and the situation is even worse. Much of the hydrostatic imbalance depends on the placement of the exhaust valve and the valve that adds gas.

Influence of CO_2 loads

Inhaled CO_2 forces the diver to breathe more (Figures 9 and 10), and Figure 11 illustrates how the CO_2 load influences the acceptability of resistive effort. The resistive effort at 62.5 L/min is acceptable down to 132 fsw (Figure 11's filled square at 62.5 L/min is below the horizontal line for 132 fsw). The diver is assumed to breathe on a rebreather with a mouthpiece having a dead space of 0.06 L. This dead space increases the minute ventilation slightly (4%, per Equation 2), but the resistive effort is still acceptable to 132 fsw, as the filled circle along the 132 fsw line shows. If the CO_2 scrubber is releasing 0.5 kPa of CO_2, then the minute ventilation increases to 71 L/min, at which point the resistive effort is just permissible (the two 132 fsw lines intersect). If the scrubber were to release 1 kPa of CO_2, then the ventilation would have to increase to 78 L/min, and the resistive effort would be acceptable only to 99 fsw (follow the interrupted, vertical downward line at 78 L/min, filled circles). If the CO_2 were to increase to 1.5 kPa, the resistive effort at the resulting minute ventilation (87 L/min) would be acceptable at 66 fsw. If the diver uses a full face mask with a well-fitting oro-nasal cup and 0.5 kPa is released by the scrubber, the increased minute ventilation (77 L/min) makes the resistive effort acceptable to 99 fsw (open circles). Using the proposed NATO STANAG 1410[40] limit on inspired CO_2 (2 kPa) would mean that the minute ventilation would have to increase by 50% to 94 L/min, and the UBA would be restricted to 66 fsw. Obviously, a CO_2 load can make an otherwise acceptable UBA unacceptable.

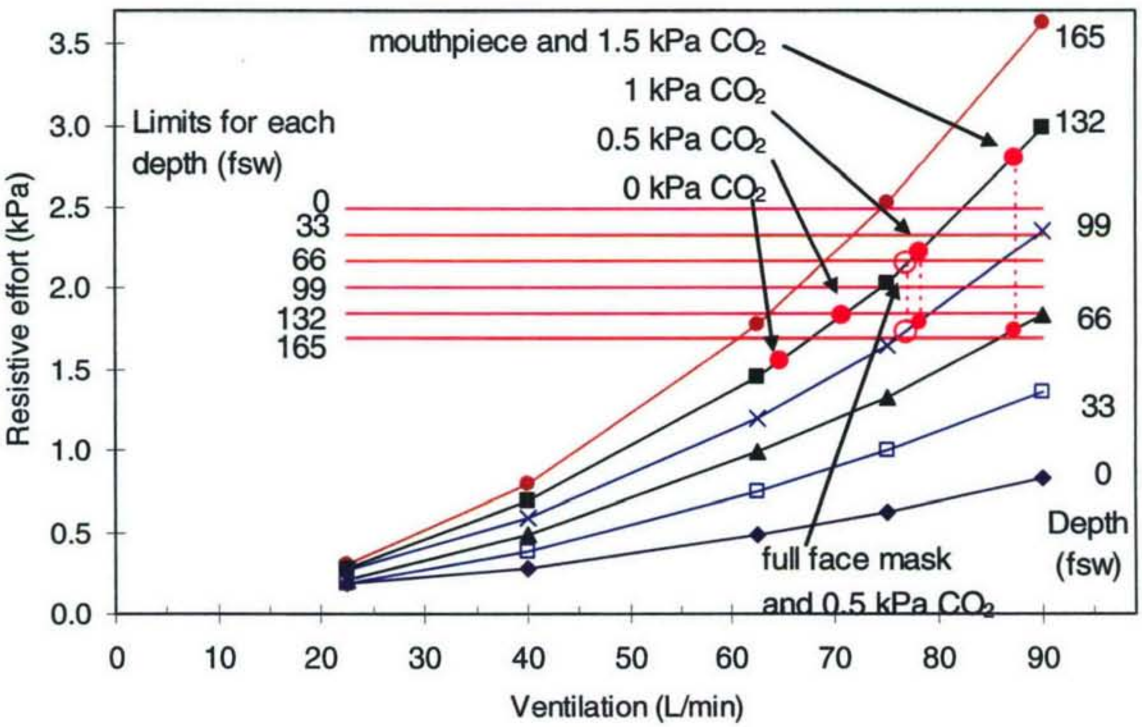

Figure 11. How CO_2 in the inspired gas influences a diver breathing on a UBA with a mouthpiece (red, filled circles) and a full face mask with a well-fitting oro-nasal cup (red, open circles). Horizontal lines show the proposed limits for resistive effort for each depth. Data are from Figure 5.

RATIO OF CO_2 PRODUCTION TO MINUTE VENTILATION

The Middleton and Thalmann report[1] specifies that, during unmanned testing, a CO_2 injection rate of 4% of the minute ventilation for all minute ventilations should be used. This number is also specified in the NORSOK standard U-101;[47] in the European standards for closed-circuit UBAs, EN 14143;[5] as well as in the proposed NATO standard STANAG 1410.[40] However, NEDU Technical Manual 01-94[2] specifies two different flow ratios: on pages 3-14, 4-33, 4-36, 4-50, and 6-6 it uses a flow ratio of 4%, but on page 4-50 it specifies a flow ratio of 3.375% — a CO_2 flow of 1.35 L/min and a minute ventilation of 40 L/min. Apparently NEDU is the only testing facility that does not consistently use the 4% ratio. The data from the experimental dives in Buffalo show that the rule of thumb ratio of 4% is the one that most closely approximates diver physiology.

The actual workload that the diver is performing for a particular task should determine how a CO_2 absorber (i.e., the CO_2 flow) should be tested. Either the minute ventilation or the CO_2 flow needs to be known. Using the 4% ratio allows the other parameter to be determined.

For a test that simulates a diver who breathes 40 L/min, the empirically determined CO_2 flow would be 1.6 L/min (4%), a rate matching NORSOK U-101, EN14143 and NATO STANAG 1410. If the CO_2 flow is only 1.35 L/min, the endurance time of a CO_2 scrubber is likely to be too long.

For a test that simulates a diver producing CO_2 at rate of 1.35 L/min, an empirical flow ratio of 4% means a minute ventilation of 34 L/min. The endurance time from this test would most likely be longer than if the minute ventilation were 40 L/min: the dwell time for the gas in the absorber is longer, and the additional gas flow does not cool the absorbent as much as the minute ventilation of 40 L/min does. The allowable dive time could be increased. Empirical tests will be needed to determine the magnitude of the difference between 34 and 40 L/min.

With a CO_2 flow of 1.35 L/min, however, using a minute ventilation of 40 L/min instead of 34 L/min will give an unknown (if any) safety margin, since the absorption process of CO_2 is highly complex. A better way would be to determine the endurance by breathing as a diver does with a 4% flow ratio and then shortening the allowable dive time by a desired and known safety margin.

NEDU faces three choices when deciding on the combination of CO_2 flow and minute ventilation: (A) maintain the 1.35/40 combination (thereby to maintain consistency with most of the recent NEDU tests), (B) switch to the 1.35/34 combination to be physiologically correct, and (C) use the 1.6/40 combination to be physiologically correct and to use a combination that matches NORSOK, EN14143 and NATO STANAG and thereby allows comparisons to what is used in testing facilities worldwide.

STATISTICAL ANALYSIS OF TEST RESULTS

NEDU's current performance goals for open circuit scuba[2] and Table 1 state that the resistive effort should not exceed 1.37 kPa for minute ventilations up to 62.5 L/min and for depths to 132 or 198 fsw (about 40 and 60 msw). With the permitted standard deviation of 0.2 kPa and the standard use of five regulators, the group mean can actually be as high as 1.56 kPa and still not statistically exceed the goal. This resistive effort should be compared to the maximum proposed resistive efforts of 1.85 and 1.53 kPa for the two depths, respectively. In other words, at the greatest depth there may not be a practical difference, while at intermediate depths the proposed limits allow a higher resistive effort than the NEDU's goals.

The common statistical decision-making approach is to determine whether a measured average is *below* a given limit, rather than whether such a measured average *does not exceed* the limit. With the common approach, the actual average that is acceptable depends on the variability among the tested regulators. For instance, if we use the numbers from the previous example (a standard deviation of 0.2 kPa among five regulators), the measured averages have to be 1.66 and 1.34 kPa to be statistically below each limit. If the resistive effort for regulators has less variability than an SD of 0.2 kPa, then their measured average could be higher than it is without statistically being above the limit (most regulators reported on in NEDU TR 04-38[42] had a standard deviation of about 0.1 kPa).

On the other hand, if the average resistive effort for a group of regulators were statistically just a bit too high, another regulator could be tested and normal statistical procedures would reveal whether that addition brings the regulator statistically below the limit. Such a procedure allows a manufacturer or testing facility added flexibility. At NEDU the normal procedure is to test at least five UBAs to be able to draw any conclusions. If an average is far below the limit, it may then be possible to test fewer than five regulators and still show that an average is statistically below the limit. No separate, arbitrary limit for standard deviation needs to be devised; the statistical test takes care of it. Such a change speeds up testing by not always requiring that at least five regulators be tested.

CONCLUSIONS

The UBA breathing performance limits that have been used since around 1980 have improved the performance of UBAs by focusing on breathing resistance. However, focusing on the diver instead of the UBA will make it possible to bring forth UBAs with improved performance.

The proposed limits state how much of each of the respiratory loads (resistive effort, elastance, and hydrostatic imbalance) is acceptable and how they interact:

The resistive effort (WOB/V_T) should not exceed:

$WOB/V_T = 2.49 - 0.016 * depth$ (depth in msw, effort in kPa)
$WOB/V_T = 2.49 - 0.00485 * depth$ (depth in fsw, effort in kPa)

The elastance should not exceed 0.7 kPa/L independent of depth and ventilation.
The maximum tolerable hydrostatic imbalances, relative to the suprasternal notch, should be in the range +0.4 to +2.9 kPa for a vertical diver and in the range -0.3 to +1.7 kPa for a horizontal diver.
The total acceptable respiratory load can be calculated by adding the relative value for each load.
Any CO_2 presented to the diver forces an increased minute increased ventilation and thereby magnifies the effect of the other respiratory loads imposed by the UBA.

Adopting these limits will mean that some rebreathers that had been nominally not acceptable actually are acceptable. The limits make little difference in the acceptability of currently available open circuit UBAs.

The dead space in a UBA and the CO_2 in the inspired gas can be major influences in determining whether a UBA is acceptable.

Most modern regulators are now made so that the resistive effort is low enough to be acceptable for a diver working hard for a long time. It is apparent that future efforts should be concentrated on designing regulators that can reduce the hydrostatic load, since any reduction in it improves diver endurance.

RECOMMENDATIONS

Adopt the proposed limits for the respiratory loads.

Manufacturers and testing facilities should be made aware that hydrostatic imbalance is a dominating respiratory load.

During tests of the endurance of CO_2 scrubbers, the empirically determined ratio of CO_2 flow to minute ventilation (4%) should be used.

The limits on resistive effort in the proposed STANAG 1410 should be adopted.

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