# Effects of inspiratory and expiratory resistance in divers' breathing apparatus

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Warkander DE, Nagasawa GK, Lundgren CEG. Effects of inspiratory and expiratory resistance in divers' breathing apparatus. Undersea Hyper Med 2001; 28(2):63–73.—This study was performed to determine if inspiratory breathing resistance causes greater or smaller changes than expiratory resistance. Unacceptable inspiratory resistances were also determined. Five subjects exercised at 60% of their $\dot{V}O_{2max}$ while immersed in a hyperbaric chamber. The chamber was pressurized to either 147 kPa (1.45 atm abs, 4.5 msw, 15 fsw) or 690 kPa (6.8 atm abs, 57 msw, 190 fsw). Breathing resistance was imposed on the inspiratory or expiratory side and was as high as 0.8–1.2 kPa · liter$^{-1}$ · s$^{-1}$ (8–12 cm $H_2O$ · liter$^{-1}$ · s$^{-1}$) at a flow of 2–3 liter · s$^{-1}$ at 1 atm abs., the other side being unloaded. The subjects reacted to the imposed load by prolonging the phase of breathing that was loaded. Inspiratory breathing resistance caused greater changes than expiratory resistance in end-tidal $CO_2$, dyspnea scores, maximum voluntary ventilation, and respiratory duty cycle. Using previously published criteria for acceptable levels of dyspnea scores and the $CO_2$ levels, we found that an inspiratory resistance inducing a volume-averaged pressure of 1.5 kPa is not acceptable. Similarly, an expiratory resistance should not induce a volume-averaged pressure exceeding 2.0 kPa.

*exercise, performance, diving*

Breathing resistance is present in every kind of breathing apparatus. There is generally no particular reason why a breathing apparatus should impose the same amount of resistance during inspiration as during expiration. However, the designer of such a breathing apparatus has often some latitude to decide whether components would induce resistance during inspiration or expiration. This is, for instance, the case with $CO_2$ absorbers used in a rebreathing (closed circuit) apparatus. However, information is lacking on divers' tolerance to the relative distribution of inspiratory and expiratory resistance. Other loads, such as elastance and static lung loading, are often present in a breathing apparatus. This study concentrated on the effects of strictly resistive loads. These resistive loads were in addition to the airway resistance. The airway resistance varies during a breath. Typically, the expiratory resistance is somewhat larger than the inspiratory resistance. This is due to flow phenomena within the airways and also because the vocal cords can move during breathing (1).

In a study (2) with five subjects performing moderate exercise on a treadmill in a conventional laboratory setting, the subjects reported that the "perceived discomfort" and the "perceived limitation of exercise duration" were the same whether a resistance was imposed during inspiration or during expiration. Later, the same investigators (3) used about the same levels of exercise and breathing resistance in 11 subjects and found that inspiratory resistance had more pronounced effects, as judged by the scorings, than expiratory resistance. During resting conditions, other investigators (4) found that inspiratory and expiratory resistances of the same magnitude induced the same amount of dyspnea.

Apart from these studies, remarkably little attention has been paid to how the distribution between inspiratory and expiratory resistance will affect the tolerance to and the effects of the breathing resistance.

The present study was designed to investigate the effects of a given breathing resistance that was placed on either the inspiratory or the expiratory side, the other side being unloaded while the total respiratory work was constant. The breathing resistance was imposed during realistic and demanding conditions. The subjects were immersed and leg exercise was performed at a relatively heavy workload. The experiments were done at the greatest depth (190 fsw, 57 msw, 690 kPa, 6.8 atm abs) that the standard U.S. Navy air decompression tables allow, and control experiments were performed at a shallow depth (15 fsw, 4.5 msw, 147 kPa, 1.45 atm abs). The imposed resistance levels were quite large. In fact, a previous study (5) showed that when they were acting during both inspiration and expiration (i.e., symmetrical resistance) they were unacceptably high. Thus, the present study was also designed to determine acceptable levels of asymmetrical resistance.

The information gathered would be useful in several ways. It would help designers of breathing gear to decide where in a breathing circuit to place components causing unavoidable breathing resistance, such as a $CO_2$ absorber, and provide testing standards for breathing gear and help explain physiologic mechanisms.

## METHODS

The five subjects were non-smoking males who all were certified scuba divers. Their ages ranged between 18 and 25 yr, their body masses between 63 and 90 kg, heights between 171 and 183 cm. The protocol had been approved by the Institutional Review Board for Human Experimentation of the University of Buffalo. The subjects had given their informed consent to participate. Abbreviations are explained in Table 1.

*Experimental procedure*: The experimental set-up has been described before (6). Therefore, only a brief description follows. The experimental dives were performed in the wet part of a hyperbaric chamber. They were performed at two depths; the shallow depth was 4.5 msw (15 fsw, 147 kPa, 1.45 atm abs) and the greater was as deep as the U.S. Navy standard decompression tables allow, i.e., 57 msw (190 fsw, 690 kPa, 6.8 atm abs). Exercise was performed in the prone position on an underwater ergometer. The workload was set to correspond to 60% of each subject's non-immersed maximum oxygen uptake as determined on a cycle ergometer (7).

**Table 1: List of Abbreviations**

| | |
|---|---|
| BTPS | body temperature and pressure, saturated with |
| $etCO_2$ | water vapor end-tidal $CO_2$ |
| f | breathing frequency |
| ERV | expiratory reserve volume |
| $FEV_{10}\%$ | forced expiratory volume in 1 s, expressed as a fraction of the forced vital capacity |
| HR | heart rate |
| MVV | maximum voluntary ventilation |
| $PetCO_2$ | end-tidal $CO_2$ |
| $Pm_{in}$ | peak inspiratory pressure |
| $Pm_{ex}$ | peak expiratory pressure |
| R | respiratory exchange ratio |
| STPD | standard temperature (0°C) and pressure (101.3 kPa), dry gas |
| SLL | static lung load |
| $T_i$ | time during inspiration |
| $T_e$ | time during expiration |
| $T_i/T_{tot}$ | respiratory duty cycle |
| VC | vital capacity |
| $\dot{V}_E$ | minute ventilation |
| $\dot{V}O_2$ | oxygen consumption |
| $V_t$ | tidal volume |
| WOB/V | volume averaged pressure, the same as work of breathing per volume |

Static breathing gas pressure (also known as static lung load) was equal to the water pressure at a plane 7 cm dorsal to the sternal notch. Hence, no static load was imposed (8). The subjects breathed air.

Breathing resistance was imposed by a disc with an orifice in it. This type of orifice gives a pressure drop related to the square of the flow. The disc was either placed on the inspiratory or the expiratory side of the breathing circuit. The control situation exposed the subject to the lowest possible resistance (by using hoses with an inner diameter of 51 mm). This resistance was 0.2 kPa · $liter^{-1}$ · $s^{-1}$ (2 cm $H_2O$ · $liter^{-1}$ · $s^{-1}$) at a flow of 3 liter · $s^{-1}$ when measured at sea level. In addition, two levels of resistance (cf 5) were used. A high resistance was selected for each subject in training runs and was such that the subject could endure it for 25 but not for 30 min when it was imposed on both the inspiratory and expiratory side. Typically, this resistance (when applied to either the inspiratory or expiratory side) was 0.8–1.2 kPa · $liter^{-1}$ · $s^{-1}$ (8–12 cm $H_2O$ · $liter^{-1}$ · $s^{-1}$) at a flow of 2–3 liter · $s^{-1}$ when measured at sea level. A moderate resistance was also used and was 85% of the high resistance. The size of the orifice was increased to compensate for the increased gas density and generate the required resistance at the greater depth.

After the chamber was pressurized, the subject entered the water and rested for 5 min. Determinations of VC, $FEV_{1.0}$, and MVV followed. The subject then started to exercise for an intended duration of 25 min. The subject was free to terminate the experiment at any time. An experiment would be terminated by the experimenter had the end-tidal $CO_2$ exceeded 8.7 kPa (65 mmHg) or if a subject did not respond adequately to instructions.

*Data recording and analysis*: The subject breathed to and from a bag-in-box system which allowed spirometry and collection of expired gases. Analysis of end-tidal $O_2$ and $CO_2$ was done by a mass spectrometer (Perkin-Elmer MGA 1100, Perkin-Elmer Inc., Pomona, CA) which sampled the gas in front of the subject's mouth. The durations of inspiration ($T_i$) and expiration ($T_e$) were determined from the spirometer trace. The respiratory duty cycle was calculated as $T_i/T_{tot}$, where $T_{tot} = T_i + T_e$. The ERV was determined from the spirometer signal by requesting the subject to exhale to residual volume.

The level of dyspnea was scored by the subject using a four-tiered scale; a 0 indicated a lack of shortness of breath, a 1 indicated a feeling of dyspnea but not strong enough to make the subject doubt his ability to continue another 5 min, a 2 indicated dyspnea pronounced enough to make the subject doubt his ability to continue another 5 min, and a 3 meant severe dyspnea necessitating immediate termination of the experiment.

Pressure swings in the mask were measured by a pressure transducer (Validyne DP15, Validyne Inc., Northridge, CA). The respiratory work performed when breathing against the imposed resistance (external work of breathing) was calculated separately for inspiration and expiration. The work of breathing per volume, i.e., the volume-averaged mean pressure, (5,9) was calculated as $WOB_{tot}/V_t$, where $WOB_{tot}$ is the sum of inspiratory and expiratory work of breathing.

All signals were recorded on an FM tape recorder (Honeywell 101, Honeywell Inc., Denver, CO). Reduction of data was performed on a computer by programs written in-house. The sampling frequency was 100 Hz. Each experiment was divided into 5-min periods in which parameters related to ventilation were sampled for at least 1 min. Further, a dyspnea score was obtained (except during rest) and a VC maneuver was performed. Work of breathing was calculated for at least five breaths per period. The exercise was divided into four 5-min periods starting at Minute 5. The results for exercise are averages of these four periods. Each experimental resistance combination was performed in duplicate and the results presented are averages of these two experiments. The order of resistance level, placement and depth was randomized with the exception that all combinations in the first set were completed before the second repetition was started. The subjects were not informed of the placement and level of resistance. A total of 100 experiments were performed.

*Parameters used to judge acceptability*: The criteria used to decide whether a breathing resistance was acceptable were the same as employed in an earlier study (5). They pertain to the risk of hypercapnia and dyspnea as reflected by end-tidal $CO_2$ and dyspnea scores. The reasons for these two criteria and the levels chosen are elaborated on in (5). Briefly, for each criterion, neither of two levels should be exceeded: one for the group mean and one for the individual subject. For the end-tidal $CO_2$ the group mean should not exceed 55 mmHg (7.3 kPa) and nobody should maintain levels above 60 mmHg (8.0 kPa). These levels were chosen to allow the subjects' to retain their performance by avoiding $CO_2$ narcosis and levels of end-tidal $CO_2$ that are known to be too high (10). As for the dyspnea scores, the group mean should not exceed 0.5 and everybody should report a score less than 2. Thus, the subjects should, despite the dyspnea, be confident about continuing exercise for at least 5 min more.

*Statistical methods*: Differences between inspiratory and expiratory resistances were analyzed with paired *t* tests. Wilcoxon's signed rank test was used to determine differences for dyspnea scores. Statistical significance was noted at $P < 0.05$.

## RESULTS

Tables 2–5 provide compilations of results for all parameters, sorted by exercise level and depth. The values are averages for all subjects and, for Tables 4 and 5, over all exercise periods.

The resistance placement did not cause any changes in the end-tidal $CO_2$ pressure when the subjects were at rest. However, during exercise (Fig 1) at the shallow depth it was influenced by the resistance placement ($P < 0.01$), the inspiratory resistance producing higher values, on the average by 1.8 mmHg (0.25 kPa). At the greater depth the difference did not reach statistical difference ($P$ = 0.07). Subject B maintained $CO_2$ levels of 61–62 mmHg (8.1–8.3 kPa) with the two high resistances at the greater depth. In the same situation, subject C maintained 59 mmHg (7.9 kPa) while the other subjects' levels were considerably lower. It is worth noting that the $CO_2$ levels were sometimes higher, sometimes lower, when the subject was exposed to the depth-load combination the second time.

The dyspnea scores were higher with moderate inspiratory resistance than with expiratory resistance at the shallow depth and with the high inspiratory resistance at the greater depth (Fig. 2). At the great depth and the moderate inspiratory resistance the dyspnea scores were only marginally higher ($P$ = 0.07). The inspiratory resistance caused a subject to quit an experiment because of overwhelming dyspnea in three instances. In no case was an experiment terminated because of the expiratory resistance. One subject quit an experiment after 20 min with the control resistance at the greater depth.

Neither $\dot{V}_E$, $V_t$, $\dot{V}o_2$ nor f was influenced by the placement of the resistance. The R was slightly higher with inspiratory resistance than with expiratory resistance during resting conditions at the shallow depth.

The MVV (Fig. 3) at the greater depth was reduced by about 9% when the high resistance was on the inspiratory side compared to the expiratory side ($P$ = 0.009). The $FEV_{1.0\%}$ was not changed by the resistance placement.

As could be expected, the VC was not influenced by the resistance loads. The high inspiratory resistance caused a greater change in the ERV during exercise at the shallow depth compared to the expiratory resistance ($P$ = 0.01).

Both resistance placements caused changes in the $T_i/T_{tot}$ during exercise at the shallow depth ($P < 0.01$), Fig. 4. The inspiratory resistance caused increases while the expiratory resistance caused decreases. The changes were greater with the inspiratory resistance. At the greater depth, statistically significant differences were only seen with the moderate resistance ($P < 0.01$). At this depth the data for the high resistance were not normally distributed and a paired *t* test could therefore not be performed. Wilcoxon's Signed Rank

**Table 2: Respiratory Parameters and Heart Rate During Rest at the Shallow Depth (4.5 msw, 15 fsw, 147 kPa, 1.45 atm abs)[a]**

| | | | | Resistance Placement and Level | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | control | | moderate resistance | | | | high resistance | | | |
| | | | | expiratory | | inspiratory | | expiratory | | inspiratory | |
| Parameter | Units | mean | SE | mean | SE | mean | SE | mean | SE | mean | SE |
| $P_{et}CO_2$ | kPa | 5.33 | 0.10 | 5.28 | 0.13 | 5.43 | 0.14 | 5.53 | 0.19 | 5.48 | 0.18 |
| dyspnea | (mean) | – | – | – | – | – | – | – | – | – | – |
| | (median) | – | – | – | – | – | – | – | – | – | – |
| | (75th percentile) | – | – | – | – | – | – | – | – | – | – |
| | (maximum) | – | – | – | – | – | – | – | – | – | – |
| $\dot{V}_E$ | liter•min$^{-1}$ | 13.9 | 1.2 | 12.7 | 0.8 | 13.4 | 0.7 | 14.5 | 0.7 | 12.7 | 0.7 |
| $V_t$ | liter | 1.09 | 0.10 | 1.12 | 0.09 | 1.17 | 0.12 | 1.30 | 0.09 | 1.13 | 0.11 |
| f | liter•min$^{-1}$ | 13.2 | 1.8 | 11.7 | 1.3 | 12.1 | 1.6 | 11.4 | 0.5 | 11.7 | 1.2 |
| MVV | liter•min$^{-1}$ | 160.7 | 11.9 | 142.8 | 7.7 | 131.0 | 13.5 | 127.7 | 10.4 | 119.8 | 9.8 |
| $FEV_{1.0\%}$ | | 0.76 | 0.03 | 0.75 | 0.03 | 0.77 | 0.02 | 0.76 | 0.02 | 0.78 | 0.03 |
| VC | liter | 5.13 | 0.27 | 5.19 | 0.25 | 5.13 | 0.30 | 5.21 | 0.30 | 5.10 | 0.33 |
| ERV | liter | 1.57 | 0.14 | 1.40 | 0.13 | 1.37 | 0.11 | 1.46 | 0.11 | 1.51 | 0.13 |
| $T_i/T_{tot}$ | | 0.399 | 0.018 | 0.396 | 0.015 | 0.402 | 0.019 | 0.392 | 0.016 | 0.407 | 0.015 |
| $\dot{V}O_2$ | liter•min$^{-1}$ | 0.39 | 0.02 | 0.39 | 0.03 | 0.38 | 0.02 | 0.39 | 0.02 | 0.39 | 0.02 |
| R | | 0.97 | 0.04 | 0.91 | 0.04 | 0.97 | 0.02 | 1.00 | 0.03* | 0.93 | 0.05 |
| WOB/V | kPa | 0.40 | 0.04 | 0.44 | 0.01 | 0.46 | 0.05 | 0.46 | 0.02 | 0.53 | 0.04 |
| $Pm_{,in}$ | kPa | −0.41 | 0.06 | −0.48 | 0.10 | −0.46 | 0.06 | −0.39 | 0.03 | −0.52 | 0.07 |
| $Pm_{,ex}$ | kPa | 0.17 | 0.04 | 0.21 | 0.04 | 0.15 | 0.02 | 0.31 | 0.05 | 0.19 | 0.04 |
| HR | liter•min$^{-1}$ | 67.4 | 5.8 | 64.7 | 4.6 | 65.4 | 2.8 | 68.5 | 3.8 | 68.5 | 3.5 |

[a]Volumes are in BTPS except $\dot{V}O_2$ which is in STPD. Unless indicated, the values are averages from all subjects with experiments in duplicate. Statistically significant changes between inspiratory and expiratory resistances at the same level is indicated by * if $P < 0.5$ and by ** if $P < 0.01$.

**Table 3: Respiratory Parameters and Heart Rate During Rest at the Great Depth (57 msw, 190 fsw, 690 kPa, 6.8 atm abs)[a]**

| | | | | Resistance Placement and Level | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | control | | moderate resistance | | | | high resistance | | | |
| | | | | expiratory | | inspiratory | | expiratory | | inspiratory | |
| Parameter | Units | mean | SE | mean | SE | mean | SE | mean | SE | mean | SE |
| $P_{et}CO_2$ | kPa | 4.82 | 0.19 | 4.71 | 0.15 | 4.84 | 0.20 | 4.81 | 0.13 | 4.94 | 0.17 |
| dyspnea | (mean) | – | – | – | – | – | – | – | – | – | – |
| | (median) | – | – | – | – | – | – | – | – | – | – |
| | (75th percentile) | – | – | – | – | – | – | – | – | – | – |
| | (maximum) | – | – | – | – | – | – | – | – | – | – |
| $\dot{V}_E$ | liter•min$^{-1}$ | 17.0 | 0.6 | 19.3 | 1.3 | 18.5 | 1.5 | 18.4 | 1.0 | 17.0 | 0.5 |
| $V_t$ | liter | 1.25 | 0.12 | 1.34 | 0.08 | 1.33 | 0.14 | 1.29 | 0.08 | 1.25 | 0.09 |
| f | liter•min$^{-1}$ | 14.0 | 1.0 | 14.5 | 1.0 | 14.4 | 1.4 | 14.4 | 0.9 | 14.0 | 1.2 |
| MVV | liter•min$^{-1}$ | 80.6 | 4.1 | 89.1 | 7.6 | 78.7 | 2.6 | 80.1 | 6.2** | 73.2 | 5.1 |
| $FEV_{1.0\%}$ | | 0.58 | 0.03 | 0.58 | 0.04 | 0.59 | 0.03 | 0.59 | 0.03 | 0.60 | 0.03 |
| VC | liter | 5.12 | 0.25 | 5.15 | 0.22 | 5.16 | 0.20 | 5.21 | 0.26 | 5.18 | 0.22 |
| ERV | liter | 1.45 | 0.16 | 1.62 | 0.08 | 1.48 | 0.10 | 1.65 | 0.19 | 1.63 | 0.08 |
| $T_i/T_{tot}$ | | 0.423 | 0.011 | 0.424 | 0.009* | 0.449 | 0.012 | 0.430 | 0.010 | 0.437 | 0.015 |
| $\dot{V}O_2$ | liter•min$^{-1}$ | 0.41 | 0.03 | 0.42 | 0.02 | 0.42 | 0.04 | 0.40 | 0.02 | 0.40 | 0.02 |
| R | | 1.00 | 0.03 | 1.08 | 0.04 | 1.05 | 0.04 | 1.08 | 0.06 | 1.02 | 0.06 |
| WOB/V | kPa | 0.37 | 0.09 | 0.55 | 0.08 | 0.55 | 0.03 | 0.57 | 0.04 | 0.74 | 0.06 |
| $Pm_{,in}$ | kPa | −0.55 | 0.06 | −0.49 | 0.04 | −0.51 | 0.05 | −0.47 | 0.04* | −0.70 | 0.05 |
| $Pm_{,ex}$ | kPa | 0.27 | 0.11 | 0.36 | 0.03 | 0.31 | 0.06 | 0.31 | 0.05 | 0.30 | 0.05 |
| HR | liter•min$^{-1}$ | 65.5 | 2.1 | 65.1 | 3.2 | 66.7 | 3.5 | 62.4 | 3.7 | 64.9 | 3.0 |

[a]Volumes are in BTPS except $\dot{V}O_2$ which is in STPD. Unless indicated, the values are averages from all subjects with experiments in duplicate. Statistically significant changes between inspiratory and expiratory resistances at the same level is indicated by * if $P < 0.5$ and by ** if $P < 0.01$.

**Table 4: Respiratory Parameters and Heart Rate During Exercise at the Shallow Depth (4.5 msw, 15 fsw, 147 kPa, 1.45 atm abs)[a]**

| | | | | Resistance Placement and Level | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | control | | moderate resistance | | | | high resistance | | | |
| | | | | expiratory | | inspiratory | | expiratory | | inspiratory | |
| Parameter | Units | mean | SE | mean | SE | mean | SE | mean | SE | mean | SE |
| $P_{et}CO_2$ | kPa | 6.00 | 0.25 | 5.99 | 0.18** | 5.79 | 0.21 | 6.28 | 0.29 | 5.76 | 0.21 |
| dyspnea | (mean) | 0.23 | 0.17 | 0.23 | 0.14 | 0.50 | 0.16 | 0.43 | 0.18 | 0.73 | 0.37 |
| | (median) | 0 | | 0** | | 0 | | 0 | | 0 | |
| | (75th percentile) | 0 | | 0 | | 1 | | 1 | | 1 | |
| | (maximum) | 2 | | 1 | | 2 | | 1 | | 2 | |
| $\dot{V}_E$ | liter•min$^{-1}$ | 62.3 | 5.4 | 62.1 | 7.4 | 60.7 | 8.1 | 61.8 | 9.0 | 60.5 | 7.4 |
| $V_t$ | liter | 2.43 | 0.14 | 2.47 | 0.13 | 2.49 | 0.13 | 2.61 | 0.14 | 2.54 | 0.14 |
| f | liter•min$^{-1}$ | 25.8 | 2.1 | 25.3 | 3.0 | 24.5 | 3.3 | 23.7 | 3.1 | 23.7 | 2.5 |
| MVV | liter•min$^{-1}$ | – | – | – | – | – | – | – | – | – | – |
| $FEV_{1.0\%}$ | | – | – | – | – | – | – | – | – | – | – |
| VC | liter | 5.28 | 0.19 | 5.12 | 0.25 | 5.12 | 0.27 | 5.21 | 0.28 | 5.16 | 0.27 |
| ERV | liter | 1.50 | 0.17 | 1.47 | 0.17 | 1.34 | 0.14 | 1.57 | 0.16* | 1.34 | 0.13 |
| $T_i/T_{tot}$ | | 0.474 | 0.008 | 0.458 | 0.011** | 0.526 | 0.003 | 0.437 | 0.013** | 0.541 | 0.007 |
| $\dot{V}O_2$ | liter•min$^{-1}$ | 2.11 | 0.16 | 2.22 | 0.21 | 2.15 | 0.24 | 2.17 | 0.25 | 2.26 | 0.25 |
| R | | 0.99 | 0.01 | 0.97 | 0.01 | 0.99 | 0.01 | 0.99 | 0.01 | 0.99 | 0.01 |
| WOB/V | kPa | 0.61 | 0.05 | 1.60 | 0.18 | 1.48 | 0.19 | 1.91 | 0.31 | 1.91 | 0.21 |
| $Pm_{,in}$ | kPa | −0.62 | 0.03 | −0.53 | 0.05** | −1.48 | 0.16 | −0.52 | 0.06** | −1.99 | 0.23 |
| $Pm_{,ex}$ | kPa | 0.25 | 0.02 | 1.65 | 0.24** | 0.44 | 0.09 | 2.16 | 0.34** | 0.46 | 0.05 |
| HR | liter•min$^{-1}$ | 133.2 | 6.1 | 139.1 | 4.6 | 138.0 | 4.7 | 139.4 | 7.3 | 140.9 | 5.0 |

[a]Volumes are in BTPS except $\dot{V}O_2$ which is in STPD. Unless indicated, the values are averages from all subjects with experiments in duplicate. Statistically significant changes between inspiratory and expiratory resistances at the same level is indicated by * if $P < 0.5$ and by ** if $P < 0.01$.

**Table 5: Respiratory Parameters and Heart Rate During Exercise at the Great Depth (57 msw, 190 fsw, 690 kPa, 6.8 atm abs)[a]**

| | | | | Resistance Placement and Level | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | control | | moderate resistance | | | | high resistance | | | |
| | | | | expiratory | | inspiratory | | expiratory | | inspiratory | |
| Parameter | Units | mean | SE | mean | SE | mean | SE | mean | SE | mean | SE |
| $P_{et}CO_2$ | kPa | 6.97 | 0.37 | 7.04 | 0.41 | 6.88 | 0.38 | 7.06 | 0.43 | 6.73 | 0.39 |
| dyspnea | (mean) | 0.60 | 0.25 | 0.28 | 0.13 | 0.63 | 0.11 | 0.45 | 0.15 | 0.75 | 0.12 |
| | (median) | 0 | | 0 | | 0 | | 0** | | 1 | |
| | (75th percentile) | 1 | | 1 | | 1 | | 1 | | 1 | |
| | (maximum) | 3 | | 0 | | 3 | | 1 | | 3 | |
| $\dot{V}_E$ | liter•min$^{-1}$ | 56.9 | 4.4 | 55.6 | 6.8 | 54.5 | 6.1 | 54.9 | 6.0 | 53.6 | 6.4 |
| $V_t$ | liter | 2.35 | 0.17 | 2.35 | 0.17 | 2.38 | 0.17 | 2.29 | 0.16 | 2.27 | 0.15 |
| f | liter•min$^{-1}$ | 24.7 | 2.6 | 24.0 | 3.2 | 23.2 | 2.6 | 24.2 | 2.8 | 23.9 | 3.0 |
| MVV | liter•min$^{-1}$ | – | – | – | – | – | – | – | – | – | – |
| $FEV_{1.0\%}$ | | – | – | – | – | – | – | – | – | – | – |
| VC | liter | 5.15 | 0.18 | 5.07 | 0.25 | 4.97 | 0.21 | 5.06 | 0.19 | 4.98 | 0.22 |
| ERV | liter | 1.79 | 0.20 | 1.71 | 0.20 | 1.59 | 0.13 | 1.77 | 0.17 | 1.62 | 0.17 |
| $T_i/T_{tot}$ | | 0.490 | 0.010 | 0.468 | 0.011** | 0.499 | 0.010 | 0.462 | 0.010 | 0.514 | 0.007 |
| $\dot{V}O_2$ | liter•min$^{-1}$ | 2.08 | 0.16 | 2.02 | 0.19 | 2.03 | 0.17 | 2.07 | 0.21 | 2.06 | 0.22 |
| R | | 0.94 | 0.01 | 0.95 | 0.01 | 0.94 | 0.01 | 0.93 | 0.01 | 0.93 | 0.00 |
| WOB/V | kPa | 1.14 | 0.08 | 1.76 | 0.18 | 1.72 | 0.18 | 2.00 | 0.25 | 1.87 | 0.16 |
| $Pm_{,in}$ | kPa | −1.04 | 0.08 | −0.91 | 0.09 | −1.65 | 0.18 | −0.96 | 0.12** | −1.89 | 0.16 |
| $Pm_{,ex}$ | kPa | 0.66 | 0.10 | 1.47 | 0.18** | 0.72 | 0.12 | 1.75 | 0.23** | 0.75 | 0.13 |
| HR | liter•min$^{-1}$ | 127.8 | 3.9 | 126.3 | 3.5* | 131.0 | 3.5 | 124.7 | 4.2 | 128.1 | 3.5 |

[a]Volumes are in BTPS except $\dot{V}O_2$ which is in STPD. Unless indicated, the values are averages from all subjects with experiments in duplicate. Statistically significant changes between inspiratory and expiratory resistances at the same level is indicated by * if $P < 0.5$ and by ** if $P < 0.01$.

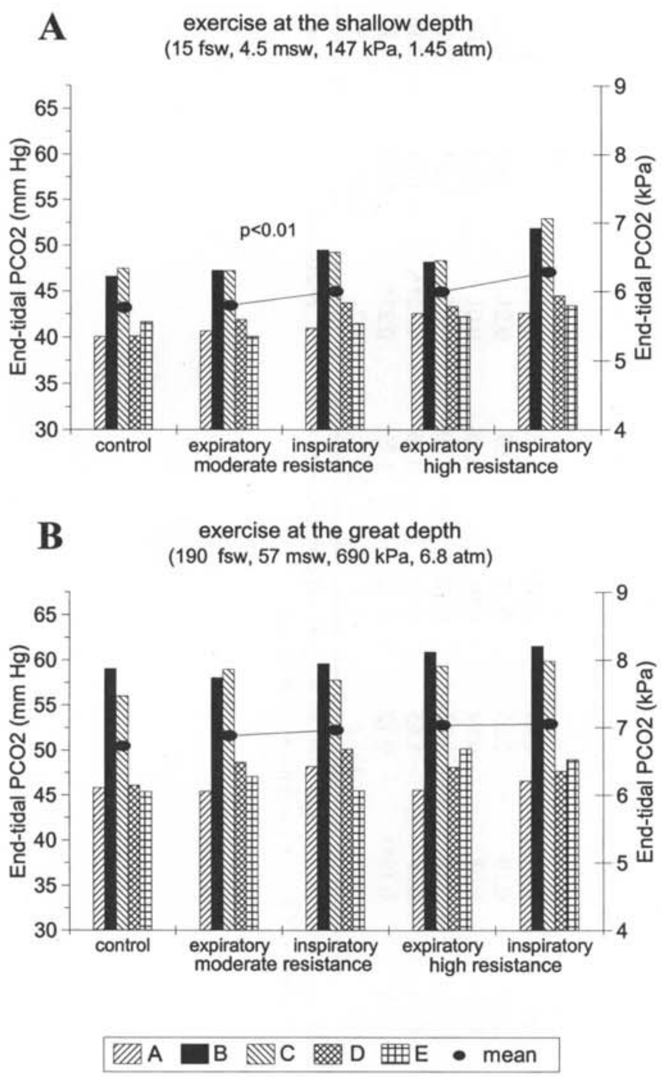


FIG. 1—End-tidal $CO_2$ values plotted vs. the resistance level and placement. *A*, results from the shallow depth; *B*, results from the great depth. *Each bar* represents a subject and the *filled circle* represents the group mean.

Test did not show a statistical difference. During resting conditions, the moderate inspiratory resistance caused a greater change than the moderate expiratory resistance at the great depth ($P = 0.04$).

During exercise, the pressures in the mask were affected by the placement of the resistance as intended, i.e., the pressures were higher on the side that the resistance was placed. The only statistically significant change during resting conditions was at the greater depth where the inspiratory resistance caused greater pressures than the expiratory resistance. The volume averaged pressure was not influenced by the different resistance placements.

During exercise at the greater depth the inspiratory resistance caused a small increase of 4 beats $\cdot$ min$^{-1}$ in the HR ($P = 0.02$) compared to the expiratory resistance.

## DISCUSSION

The goal of imposing the same total resistive load with the different resistance placements was achieved since the volume-averaged pressure (work of breathing per volume) was the same. Thus, the changes seen were not due to the total breathing resistance but to its distribution.

Based on the changes in $T_i/T_{tot}$, the strategy used by the subjects to handle the resistive load was to spend a greater part of each breath during the loaded phase, e.g., an inspiratory resistance caused an increase in $T_i/T_{tot}$. This lowers the mean flow during the loaded phase and, consequently, the pressure required to overcome the

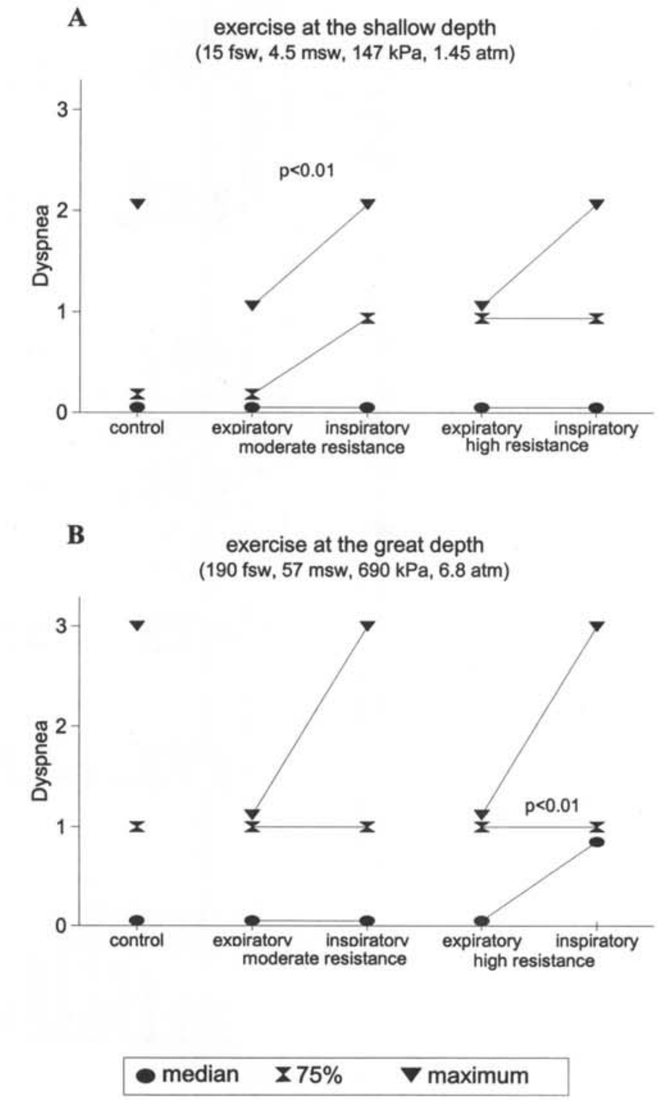


FIG. 2—Dyspnea scores plotted vs. the resistance level and placement. *A*, results from the shallow depth; *B*, results from the great depth. *Three symbols* represent the median value, the 75th percentile, and the maximum values reported.

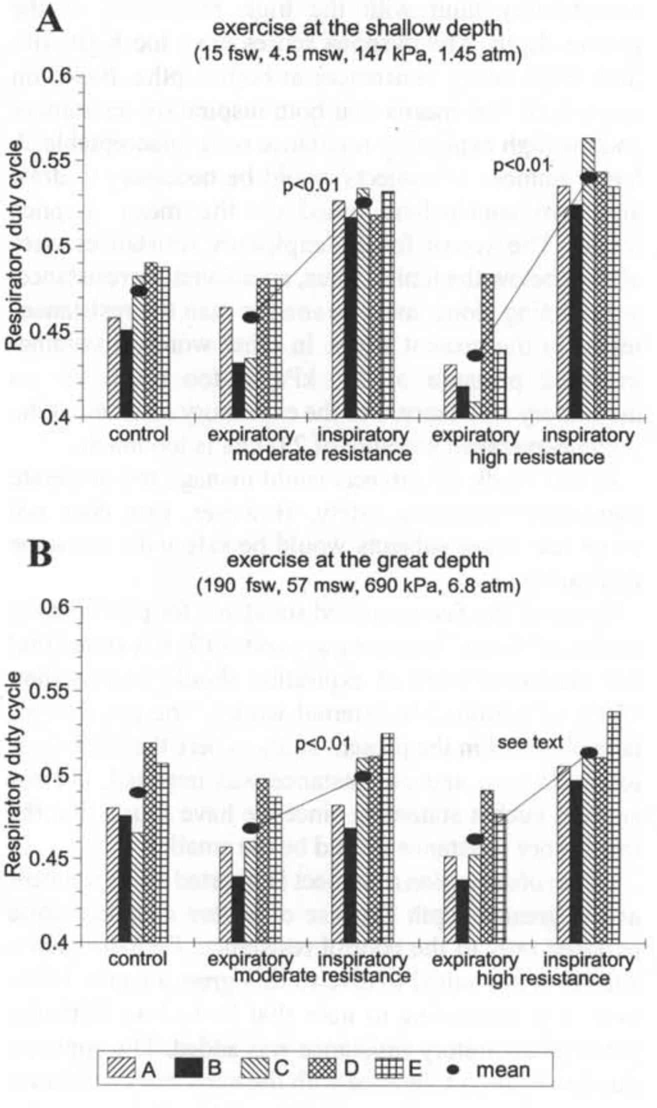


FIG. 3—$T_i/T_{tot}$ values plotted vs. the resistance level and placement. *A*, results from the shallow depth; *B*, results from the great depth. *Each bar* represents a subject and the *filled circle* represents the group mean.

resistance. This strategy has been reported in other studies (3,4) as well. The reduction in ERV that was seen with the high inspiratory resistance compared to expiratory resistance at the shallow depth would tend to assist the inspiration by placing the inspiratory muscles at a mechanical advantage. This response was not seen at the great depth probably because of the increased gas density, which increased the airway resistance which in turn tends to even out the differences between the externally applied resistances.

During rest at the great depth the ventilation appears to have been higher and the end-tidal $CO_2$ lower than during rest at the shallow depth. This confirms previously reported observations (5,8).

*Differences between inspiratory and expiratory resistances*: Several parameters indicated that inspiratory breathing resistance causes greater changes than expiratory breathing resistance. For instance, at the great depth the MVV was 9% lower with the high inspiratory resistance than with the high expiratory resistance. To determine if this was a systematic effect, the changes in the different parameters were compared. These parameters are the ones that would reflect physiologic changes (e.g., dyspnea, end-tidal $CO_2$, $T_i/T_{tot}$, etc.) but not the ones that would be directly caused by the resistance placement, i.e., mouth pressures. The inspiratory resistance induced higher values or greater changes from control in 10 out of the 11 statistically significant changes ($P < 0.006$, one-sample proportion test).

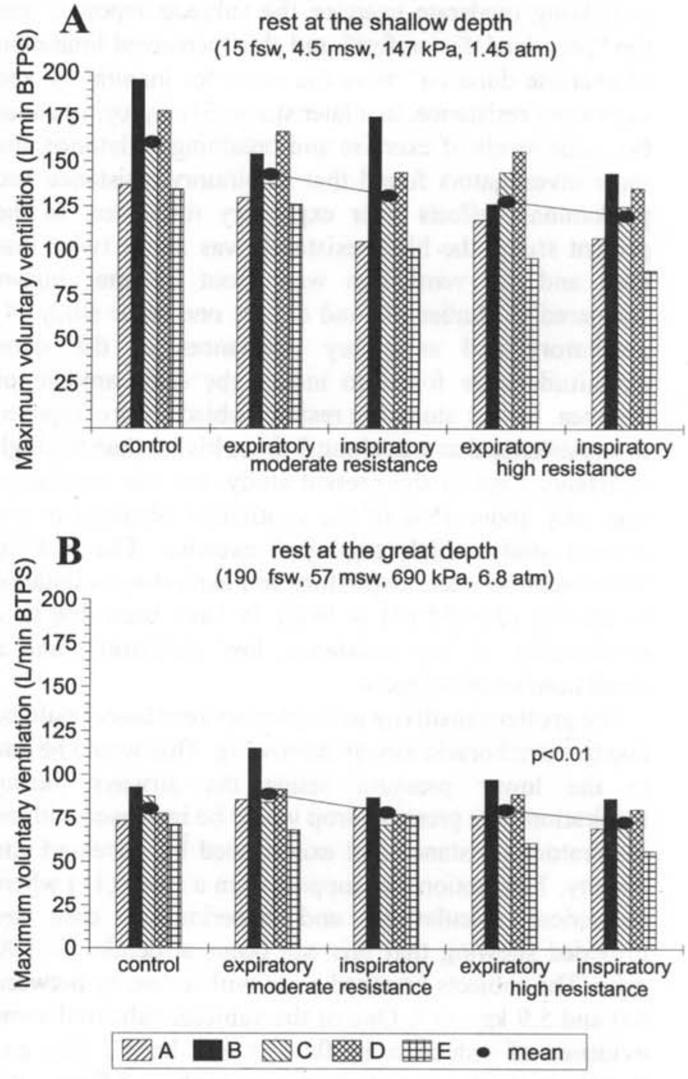


FIG. 4—Maximum voluntary ventilation values plotted vs. the resistance level and placement. *A*, results from the shallow depth; *B*, results from the great depth. *Each bar* represents a subject and the *filled circle* represents the group mean.

Most important was the difference in the dyspnea scores. At both depths there were statistically significant changes between inspiratory and expiratory resistances, the inspiratory resistance inducing the higher dyspnea scores. Even more telling is the fact that three different subjects actually had to quit because of overwhelming dyspnea caused by the inspiratory resistance.

Relatively fewer differences between the expiratory and inspiratory resistances were seen at the greater depth compared to the shallow depth. This can be explained by the fact that at the greater depth the increased gas density causes greater internal resistance which tends to even out the difference between external inspiratory and expiratory loading.

Other studies have shown less clear changes between inspiratory and expiratory resistance. In one study (2) employing moderate exercise the subjects reported that the "perceived discomfort" and the "perceived limitation of exercise duration" were the same for inspiratory and expiratory resistance. In a later study (3) employing about the same levels of exercise and breathing resistance, the same investigators found that inspiratory resistance had predominant effects over expiratory resistance. In the present study, the high resistance was about twice that used and the ventilation was about 3 times higher compared to studies (3) and (2). In one other study (4) inspiratory and expiratory resistances of the same magnitude were found to induce the same amount of dyspnea. In that study the resting subjects were exposed to a resistance that was about 3 times higher than the high resistance used in the present study, but the ventilation was only about 15% of the ventilation obtained in the present study which employed exercise. The lack of differences between inspiratory and expiratory resistance in studies (2) and (4) is likely to have been due to a combination of low resistance, low ventilation, and a small number of subjects.

The greater sensitivity to inspiratory resistance could be due to extrathoracic airway narrowing. This would be due to the lower pressure inside the airways during inspiration. The pressure drop would be increased with an inspiratory resistance and exacerbated by increased gas density. This notion has support from a study (11) where theoretical calculations and experimental data are provided showing that this can occur at depths of 300 msw. The subjects breathed a gas with a density between 5.0 and 5.9 $kg \cdot m^{-3}$. One of the subjects "showed some evidence of reduction in flow at sea level". The gas density in the present study was as high as 8.8 $kg \cdot m^{-3}$ making this phenomenon likely.

*Acceptable levels of asymmetrical resistance*: One subject maintained $CO_2$ levels that were just above the acceptability limit with the high resistances at the greater depth. The dyspnea scores were too high with both inspi-ratory resistances at both depths. Based on our criteria this means that both inspiratory resistances and the high expiratory resistance were unacceptable. A larger number of subjects would be necessary to draw any firm conclusions based on the mean dyspnea scores. The scores for the expiratory resistances were always below the limits. Thus, an inspiratory resistance, when acting alone, must be smaller than the resistances tested in the present study. In other words, a volume-averaged pressure of 1.5 kPa is too much for an inspiratory resistance. For the expiratory resistances the volume-averaged pressure of 2.0 kPa is too much.

In this study all subjects could manage the moderate expiratory resistance safely. However, this does not mean that other subjects would be safe with the same resistances.

In one of the few proposed standards for performance testing of divers' breathing apparatus (9) it is stated that the maximum work of expiration should be less than "50% of permissible external work". The physiologic data obtained in the present study, where the static lung load was zero and no elastance was imposed, did not support such a statement since we have found that the inspiratory resistance should be the smaller.

*Other observations*: Subject D aborted an experiment at the greater depth because of severe dyspnea while exposed only to the control resistance. Perhaps such a subject is not suited to dive to this great a depth. However, it is interesting to note that he had no difficulty when an expiratory resistance was added. The apparent improvement in tolerance with the expiratory resistance was not due to a change in the ERV. However, one might speculate that it relates to the changes in respiratory duty cycle. The expiratory resistances increased the time spent during expiration, thereby lowering the average expiratory flow. A lower expiratory flow would give a greater margin to the flow at which dynamic airway collapse would occur. This subject was the one who had the highest workload and, consequently, the highest $\dot{V}_E$. With the control load at the greater depth, his $\dot{V}_E$ was 86% of his MVV. It seems likely that this high ratio of $\dot{V}_E$ to MVV may induce some dynamic airway collapse or at least be fatiguing. With the moderate expiratory resistance the $\dot{V}_E$ was 81% of the MVV and with the high expiratory resistance it was 79% of the MVV. This improvement was caused by concomitant decreases in the $\dot{V}_E$ and increases in the MVV. The decreases in $\dot{V}_E$ were most likely due to the imposed resistance. The improvement in the MVV was not paralleled by changes in the

$FEV_{1.0}$% but may perhaps have been due to a lower mean expiratory flow induced by the expiratory resistance.

*Conclusions*: The external breathing resistance should be as small as possible. An inspiratory breathing resistance, of a magnitude likely to apply to divers' breathing apparatus, should be the same or smaller than the expiratory breathing resistance. Unavoidable resistances, such as those caused by $CO_2$ absorbers in closed or semi-closed circuit breathing gear, should be placed on the expiratory side. The volume-averaged pressure for inspiratory resistance, when acting alone, should be less than 1.5 kPa. An expiratory resistance, acting alone, should not induce a volume-averaged pressure higher than 2.0 kPa.

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