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Respiratory function during simulated wet dives

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Lundgren CEG. Respiratory function during simulated wet dives. Undersea Biomed Res 1984; 11(2):139–147.—This presentation focuses on the effects of static lung loading (SLL) on diver performance. It is noted that SLL may arise from depth differences between the diver's chest and his breathing gear. Studies are reviewed in which subjects undergoing wet, simulated dives in a pressure chamber were exposed to SLL ranging from 14.7 to −14.7 mmHg (+20 to −20 cmH_2O) while breathing air at depths down to 58 m (190 ft). The subjects, assuming a prone or an upright position, performed leg exercise on an underwater bicycle ergometer. Various measurements of respiratory function were made. By applying a scoring scale for dyspnea it was found that in addition to being more pronounced as exercise and depth (gas density) increased, the dyspnea was most pronounced with negative SLL. Positive SLL alleviated the dyspnea. The dyspnea also tended to be more pronounced in the prone than in the upright posture. It was speculated that this may have been partly due to more of a compression effect on the extra thoracic airways by water pressure in the former than in the latter posture. There were no marked differences in gas exchange and end-tidal gas concentrations with different static lung loads, and it was hypothesized that differences in respiratory muscular strain may have accounted for the differences in dyspnea with different SLLs. That the dyspnea was inspiratory in nature would agree with the observation that positive SLL aiding inspiration would be perceived as beneficial. A breathing apparatus design that counteracts undesirable SLL is reviewed.

static lung loading
dyspnea
exercise
simulated wet dives

With regard to respiratory function, the diving environment is unique in two major aspects. The high environmental pressure may exert its effects via increased gas density and via pharmacological effects of various gases under pressure. The other important aspect of underwater breathing is that immersion or submersion may expose the diver to hydrostatic pressure differences between different parts of the body and between the chest and the breathing gear.

Figure 1 illustrates how immersion or submersion may put a strain on the respiratory system. It may induce either a situation akin to negative-pressure breathing on dry land—here exemplified by two situations that create the same amount of negative pressure (22.0 mmHg or 30 cmH_2O): a person treading water in an erect posture while immersed to the chin, or the submersed erect scuba diver breathing air from a scuba valve at the mouth. In these figures the × symbolizes the pressure centroid of the chest—a point on the chest at which one vector

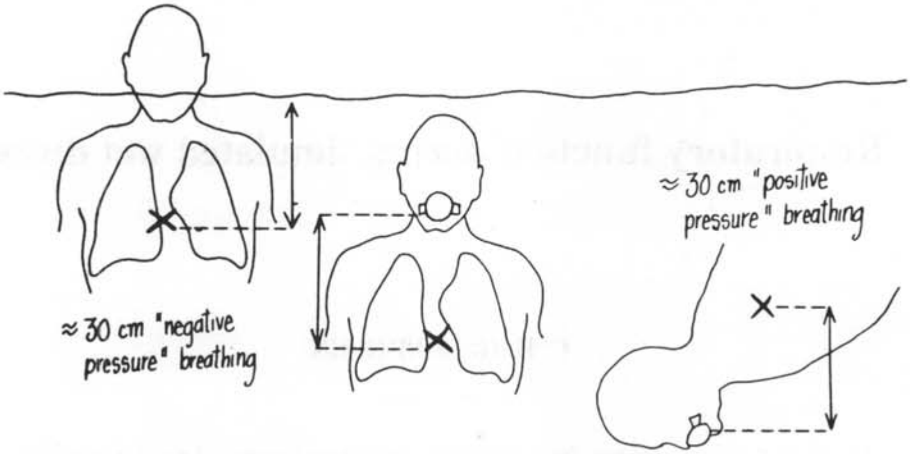

Fig. 1. Pressure difference between breathing gas at mouth/nose and pressure centroid of chest (marked by ×) may induce positive or negative pressure breathing (static lung loads) depending on posture and type of breathing gear. For further comments see text.

can represent the variety of pressures acting on the chest during submersion. The valve provides air at exactly the same pressure as the water pressure at the depth of the valve. In this case it means that the diver inhales air at less pressure than the pressure resting on his chest, which is located more deeply than the valve. By contrast, when he assumes the head-down position, the valve being at a greater depth than the chest creates a situation of positive-pressure breathing. Clearly, there is a situation in which inside pressure and outside pressure on the chest are equal and balance each other. That is when the pressure centroid and the breathing valve are at the same depth. It follows that the magnitude and direction of the static pressure load or static lung load that the diver is exposed to depend both on the body posture and the type of breathing gear he is wearing.

Though the effects of immersion and increased gas density have been studied separately earlier, studies of immersion and gas density acting together have been sparse. That the combination of these effects may profoundly influence the diver was demonstrated by Spaur et al. (1), whose diver subjects experienced severe work-limiting dyspnea exercising at oxygen consumptions of 2.0 liters/min and breathing helium-oxygen at 50 ATA. No reason for the dyspnea was apparent from the data; the arterial blood gases showed no evidence of hypoxia or hypercapnia.

Because of the lack of systematic studies of the combined effects of gas density, static loads, and exercise, we have involved ourselves in a series of studies of these factors in subjects breathing air at pressures up to 6.76 ATA (190 fsw).

In these studies the subject is positioned behind the so-called Lanphier-Morin barrier separating air and water in the hyperbaric chamber (Fig. 2) and breathes into a bag-in-box system (not shown) for respiratory measurements. Exercise loads are imposed by an underwater bicycle ergometer. The subject is fixed to a harness in the prone position or to a seat in the sitting position. It is possible to precisely control the subject's static lung load by adjusting his position relative to the water surface. With this arrangement, a series of submaximal and maximal exercise runs have been made in 3 subjects in the prone position (2) and in 3 to 5

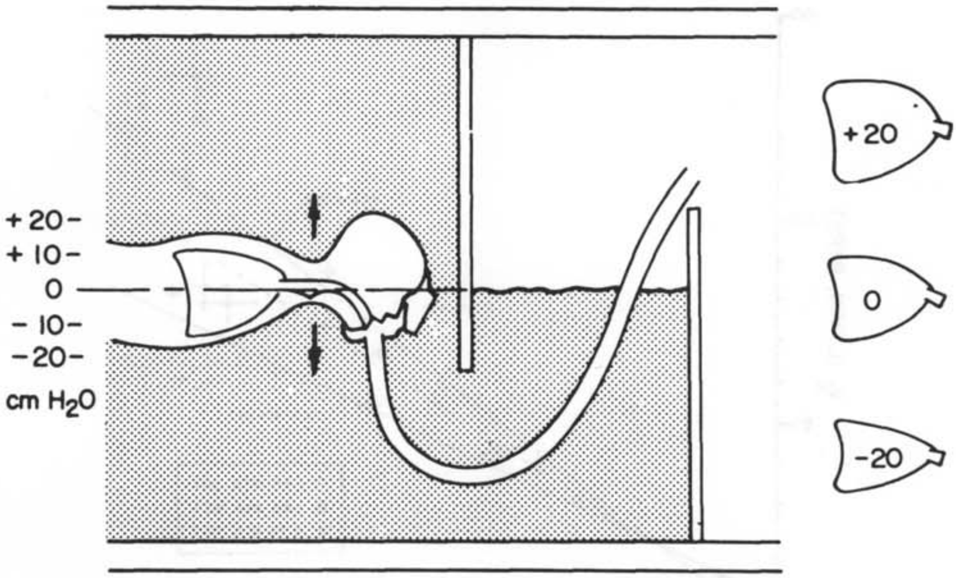

Fig. 2. Subject behind Lanphier-Morin barrier separating water and air in hyperbaric chamber. Adjustment of subjects' position relative to interface imposes negative or positive static lung loads with a tendency for changes in functional residual capacity as indicated by lung symbols to the right. [Adapted from Thalmann et al. (2)]

subjects in the upright sitting position (D. D. Hickey, C. E. G. Lundgren, A. J. Påsche, unpublished observations) at several stages of depth from 4.6 m down to 58 m (15 ft–190 ft).

In the prone position the ventilation in response to submaximal exercise was linear over the entire range of oxygen uptake. Static load did not affect the ventilation, and therefore data from runs at +14.7, +7.4, 0, −7.4, and −14.7 mmHg (+20, +10, 0, −10, and −20 cm H_2O, respectively) were pooled in Fig. 3. Both immersion and increasing pressure depressed the ventilatory response to exercise. The ventilation in response to maximal exercise was a depressed at 6.76 ATA. End-tidal CO_2 tensions were unaffected by static loads and immersion. Basically, the CO_2 tensions at the 1.45-ATA level showed the pattern well known from 1.0 ATA studies—i.e., high oxygen consumptions being connected with a tendency for a slight hypocapnia. The maximal runs yielded mostly normocapnic readings. At 6.76 ATA the resting values were slightly hypocapnic but showed steady increases indicative of hypercapnia as oxygen consumptions of about 1.5 liters/min were exceeded. At maximal exercise the end-tidal CO_2 levels were markedly hypercapnic.

The observations in the erect subjects were substantially similar to those in the prone subjects. Thus, ventilation at the 175-W workload at 4.6 m was significantly higher than at 58 m. Again, there were no systematic effects of static lung loads. The end-tidal carbon dioxide tensions showed the same pattern as in the prone subjects: no differences were induced by static loads. However, the level of hypercapnia at 2.5 liters $\dot{V}O_2$/min was more modest, at around 45 Torr, than in the prone subjects in whom it was 50 Torr on the average.

As far as the lung mechanics are concerned, the expiratory reserve volumes of prone subjects did not change as the subjects were exposed to increasing depths and air densities. Therefore, data from all depths have been pooled in Fig. 4. It shows the distribution of the tidal volumes on the vital capacity span. The expiratory reserve volume did change with static loads. The

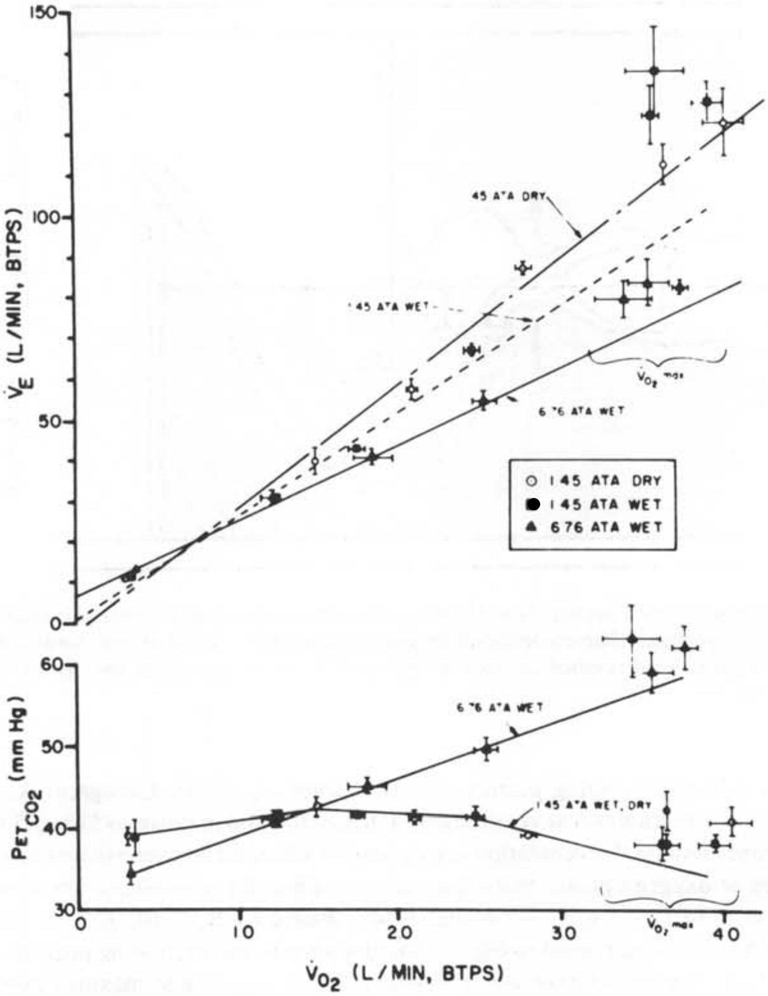

Fig. 3. Lung ventilation ($\dot{V}_E$) and end-tidal CO_2 pressure (means ± SD) vs. oxygen uptake ($\dot{V}_{O_2}$) in 3 subjects performing exercise at depth. $\dot{V}_{O_{2max}}$, means for each subject at a given depth. Data from all static lung loads were pooled. [From Thalmann et al. (2).]

more negative the static load, the smaller the expiratory reserve volume—and as static load increased, the subjects breathed on top of larger and larger expiratory reserve volumes.

It is interesting that there was no difference between rest and submaximal exercise—the increases in tidal volume were all achieved by deeper inspirations. Measurements of expiratory reserve volumes could not be obtained at maximal exercise because the subjects could not control their breathing then.

It appears that the respiratory system adapts to the static loads in such a way as to place the respiratory muscles (which have to overcome the static load) at a mechanical advantage without much consideration of the flow resistance during inspiration. Thus the low lung volumes at negative static loads will benefit inspiratory muscles while flow resistance in all likelihood is high; the larger volumes at positive loads will place expiratory muscles at an advantageous point on their length-tension curve and at the same time flow resistance will be low. It is

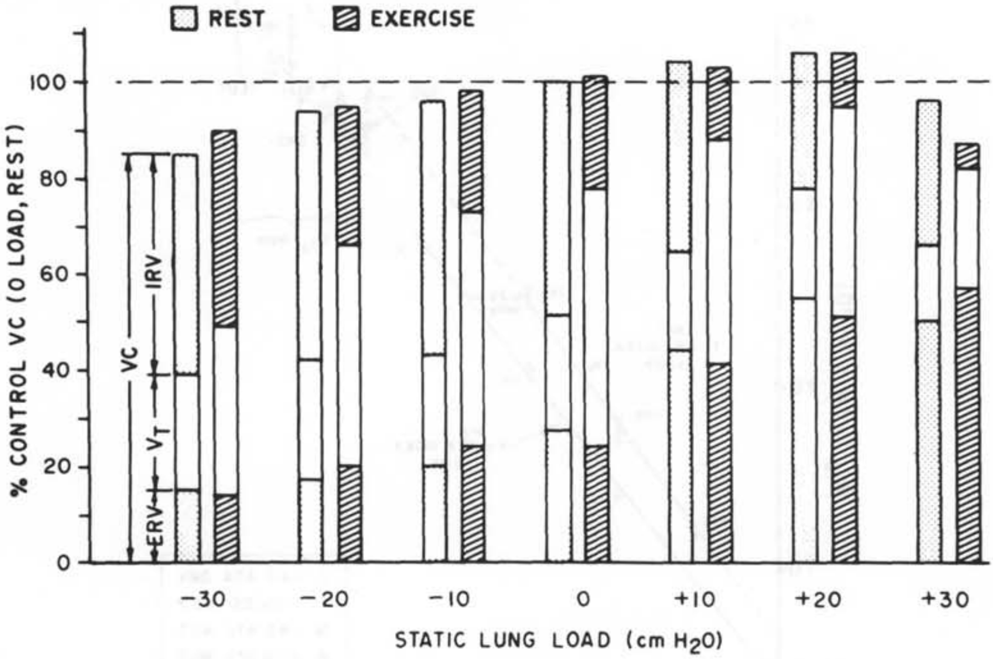

Fig. 4. Influence of static lung loading between −30 and +30 cmH_2O on spirogram of 3 subjects (means ± SD) resting and exercising at 141 W while submerged in the prone position. VC, vital capacity; IRV, inspiratory reserve volume; V_T, tidal volume; ERV, expiratory reserve volume. [From Lundgren (3).]

remarkable that the strong effect of high gas densities on flow resistance did not modify this scheme.

With regard to oxygen uptake, static lung load had no effect on the relation between oxygen uptake and exercise in the prone subjects. Therefore all static load data have been pooled in Fig. 5. The horizontal difference between the regression line for the dry control experiments and the line for the immersion experiments—about 25 W—is explained by the fact that in the water the subjects' legs had to move water as well as work on the ergometer. The slope of the line of the immersion data is slightly but significantly steeper than the line representing control experiments, by 50 ml/min at 100 W, and by 100 ml/min at 200 W. This means that a given increase in work load in water costs more oxygen than the same work load increase in the nonimmersed situation.

The individual mean values of the $\dot{V}O_{2\,max}$ measurements in the 3 subjects are also shown in Fig. 5. The 6.76-ATA or 58-m values are quite impressive—in the 3.0-to-3.5-liter range. Going from 1.15 ATA to 6.76 ATA caused only a slight reduction in $\dot{V}O_{2\,max}$ of 150–170 ml, and only in 2 subjects. Immersion in itself—comparing dry and wet data at 1.15 ATA—had no discernible effects on the maximal oxygen uptake. The measurements of $\dot{V}O_2$ in the upright position (a study in which we have not yet completed all data treatment) show basically the same picture as for the prone subjects.

Applying the objective physiological criteria that we have used, there were no striking differences in the performance of the respiratory system when the static lung loads were varied, and the same holds for some other parameters, such as carbon dioxide elimination and alveolar

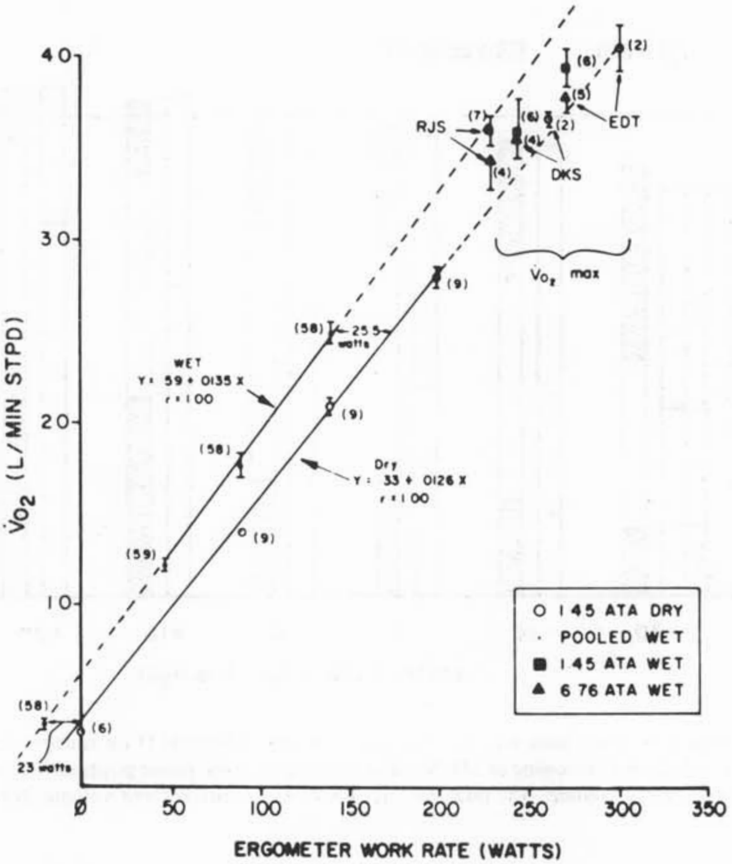

Fig. 5. Oxygen uptake ($\dot{V}O_2$) against work rate measurements at 1.45 ATA dry (nonimmersed) and wet (submersed) dives and at 6.76 ATA wet dives. Data at different static lung loads were pooled. Values are means ± SD. Data from $\dot{V}O_{2\ max}$ runs represent means in each of 3 subjects (identified by initials). For further comments see text. [From Thalmann et al. (2).]

ventilation. By contrast, the effects of static loading on a subjective criterion of respiratory performance were striking—that criterion being dyspnea.

Dyspnea was quantitated by the subjects in our experiments according to a scoring scale and the results obtained in subjects assuming the prone position are summarized in Fig. 6.

Dyspnea was considerably more common with negative static loads than with neutral or slightly positive static loads. This was particularly striking in the experiments with maximal exercise in which −7.36 mmHg (−10 cmH_2O) and 0 mmHg static loads were connected with premature termination of the run in 9 out of 15 experiments because of intolerable dyspnea, while with +7.36 mmHg (+10 cmH_2O) static load, only 5 out of 15 were terminated prematurely. Why is +7.36 mmHg of static load preferable to more negative pressure loads? There are not many hard physiological data to explain it. It is striking, though, that all subjects who experienced dyspnea stated that it was inspiratory in nature. This was also the case in studies by Dwyer et al. (4) and Spaur et al. (1). From both these studies it can be inferred that the subjects probably were exposed to negative static loads. If the dyspnea was at least partly due to overexertion of inspiratory muscles, one could see why a positive static load would be preferable because it would help inspiration by adding an element of insufflation.

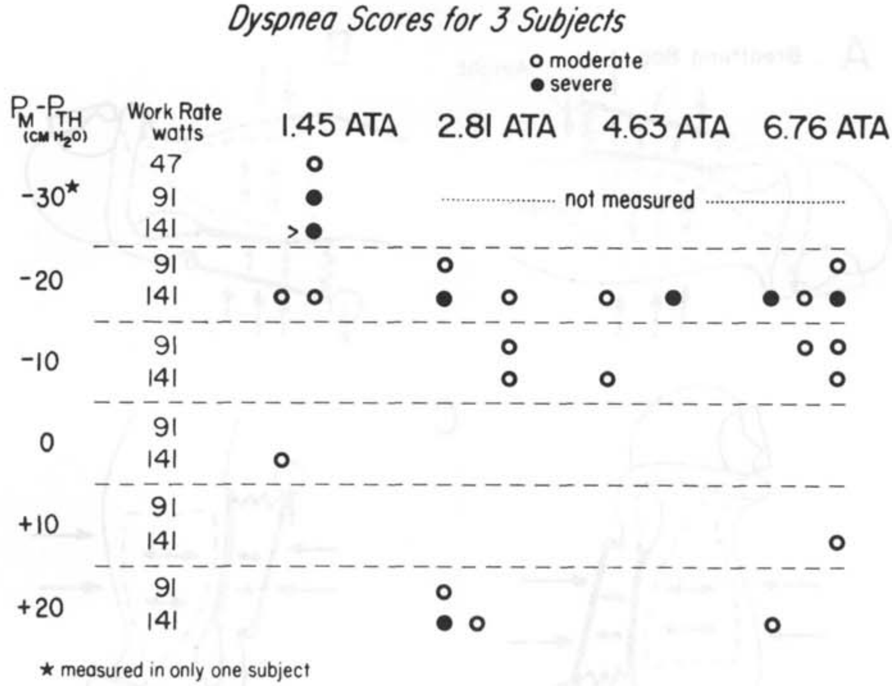

Fig. 6. Dyspnea scores in 3 subjects during submaximal exercise at different pressures (1.45–6.76 ATA) and static lung loads at mouth and midthoracic region ($PM - P_{th}$) of −30 to +20 cmH_2O). [From Thalmann et al. (2).]

Dyspnea was generally more common in the prone position than in the upright position. Although there is no clear-cut physiological explanation for that, it is worth noting that the pressures acting on the extrathoracic airways are quite different in the two body postures. For any given static load, relative to the pressure centroid of the chest, the extrathoracic airways (in the neck) will be at a lesser depth in the upright subject than in the prone and, therefore, exposed to lesser compressive forces from the surrounding water. Thus, to the extent that flow resistance in the extrathoracic airways contributed to dyspnea, "dilating" the airways by assuming an upright posture should help.

Only to be expected, dyspnea was more common with heavy work loads than with light work loads. Furthermore, the greater depth, i.e. 58 m, was generally also more conducive to dyspnea than the shallow depth (4.6 m).

To summarize what has been said so far: When no static load is imposed, immersion in itself does not limit exercise performance compared to what can be achieved in the nonimmersed situation. By contrast, when immersion is allowed to express itself as a negative static load on the respiratory organs, it limits the maximal exercise capacity by inducing dyspnea, while a moderate positive static load enhances the tolerance to maximal exercise. The same effects of negative static loads making dyspnea more of a problem and positive static load alleviating dyspnea was observed at submaximal exercise levels. While there were no clear-cut correlates between our measurements of pulmonary function and dyspnea, it is noteworthy that dyspnea tended to be inspiratory in nature, and this fits together with the beneficial effects of positive static loads aiding inspiration.

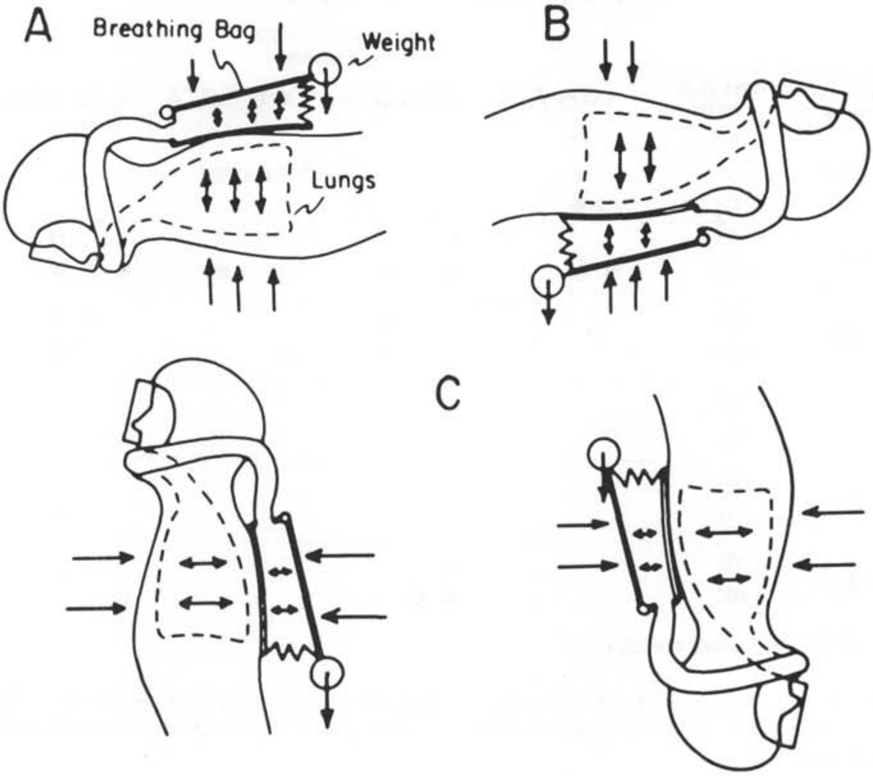

Fig. 7. Principle for weight compensation of hydrostatic pressure differences between rebreathing bag and chest. For further explanation see text. [From Lundgren (5).]

As for application of these observations in diving, it follows that whenever practical, a diver who is exercising should assume a position that minimizes his exposure to negative static lung loads (or negative pressure breathing)—or, better yet, breathing gear should be designed so as to provide breathing gas at a pressure that is somewhat higher (up to 7.36 mmHg) than the mean water pressure on the chest regardless of the diver's position.

A schematic is shown in Fig. 7 of how such a design can be made for a breathing apparatus of the type providing breathing gas from a bag (6). In this solution, the bag has the shape of a bellows placed on the back at the level of the lungs. In the prone position, the bellows is at a lesser depth, i.e., at lesser pressure than the chest, potentially exposing the diver to negative static lung loading. However, a weight on the hinged, stiff side of the bellows adds pressure to the gas in the bellows so as to match the pressure on the chest. In the supine position, *B*, the bellows is exposed to higher water pressure than the lungs, which tends to generate a positive static lung load, but the weight pulls on the bellows and reduces the inside gas pressure so as to match the pressure on the chest. In the erect position, whether head-up or head-down, *C*, the bellows is at the same water depth as the chest and the weight should not exert any effect on gas pressure. This function is achieved due to the weight either hanging down from or balancing on the hinge. This principle has been employed in the breathing apparatus currently used by the Swedish Navy for mine clearance diving.

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Lundgren CEG. Fonction respiratoire au cours de plongées simulées dans l'eau. Undersea Biomed Res 1984; 11(2):139–147.—Cette présentation est concentrée sur les effets de la charge pulmonaire statique (CPS) sur la performance du plongeur. Il est noté que la CPS peut provenir des différences de profondeurs entre la poitrine du plongeur et son équipement respiratoire. Les études sont revues dans lesquelles les sujets, effectuant des plongées simulées en eau dans un caisson, furent soumis à une charge pulmonaire statique variant de +14.7 à −14.7 mmHg (de +20 à −20 cmH_2O) tout en respirant de l'air à des pressions jusqu'à 58 m. Les sujets, en position couchée ventrale ou debout, effectuèrent un exercice avec les jambes sur une bicyclette ergométrique adaptée pour le travail sous l'eau. Grâce à l'application d'une échelle de pointage pour la dyspnée, il fut trouvé qu'en plus de devenir plus prononcée avec l'augmentation de l'exercice et de la profondeur (densité des gaz), la dyspnée était beaucoup plus ample avec la charge pulmonaire statique négative. La charge pulmonaire statique positive soulageait la dyspnée. La dyspnée avait également tendance à être plus prononcée en position couchée ventrale que debout. Il fut spéculé que ceci pouvait avoir été causé en partie par un effet de compression sur les voies respiratoires extra-thoraciques par une pression d'eau plus grande dans la première que la dernière position. Il n'y eut pas de différence marquée dans les échanges gazeux et les concentrations gazeuses en fin d'expiration avec les diverses charges pulmonaires statiques. L'hypothèse fut émise que des différences dans l'effort musculaire respiratoire pouvaient rendre compte des différences dans la dyspnée avec les diverses CPSs. Le fait que la dyspnée était de nature inspiratoire s'accorderait avec l'observation que la CPS positive aidant l'inspiration serait perçue comme bénifique. Un modèle d'appareil respiratoire qui contrecarre les CPSs indésirables est revu.

performance du plongeur
charge pulmonire statique
dyspnée

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