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The effects of increased gas density on pulmonary mechanics

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Vorosmarti, J., M. E. Bradley, and N. R. Anthonisen. 1975. The effects of increased gas density on pulmonary mechanics. Undersea Biomed. Res. 2(1):1-10.–Pulmonary function was studied in seven U.S. Navy divers on two helium-oxygen saturation dives to 19.1 and 26 ATA. Volume, flow, and transpulmonary pressure were measured during quiet breathing, hyperventilation, and forced expiratory vital capacity maneuvers. The measurements were made at different depths using $He\text{-}O_2$, $N_2\text{-}O_2$, and $Ne\text{-}O_2$ mixtures to provide a range of relative gas densities between 0.43 and 15. The changes in forced expiratory volume and average peak expiratory flow rate confirmed previous investigators' results. Maximum midexpiratory flow rate did not decrease when relative gas density was higher than 5. Inspiratory airway resistance increased with gas density but was closely similar during quiet breathing and hyperventilation. Expiratory airway resistance also increased with gas density and was significantly higher during hyperventilation than during quiet breathing. At 26 ATA the subjects respired 50 liters/min without undue stress but flow-resistive work of breathing was greatly increased. The problems of using this type of study to predict the depth to which divers will be able to do useful work are discussed.

pulmonary function
density
saturation diving
work
resistance

When man breathes a gas mixture more dense than air at sea level, his pulmonary flow resistance and work of breathing are increased. The resulting changes in pulmonary ventilation could be so drastic as to limit the depth to which man can effectively dive (Miles 1966; Miller, Wangensteen, and Lanphier 1971). The results reported here are from a larger study conducted during helium-oxygen saturation dives in the U.S. Navy SEALAB III program; they provide further insight into the effects of breathing dense gas (Bradley, Anthonisen, Vorosmarti, and Linaweaver 1971; Anthonisen, Bradley, Vorosmarti, and Linaweaver 1971).

MATERIALS AND METHODS

The following measurements were made during two saturation dives to depths of 600 and 825 fsw equivalent (19.1 ATA and 26 ATA) in the compression chambers of the U.S. Navy Experimental Diving Unit, Washington, D.C. Volume and flow were measured using a low-resistance wedge spirometer[1]. Esophageal pressure was measured using a 10-cm long, 1.2-cm wide latex esophageal balloon, affixed to one end of a 80-cm polyethylene catheter with an internal diameter of 1.3 mm; the end of the catheter covered by the balloon had been pierced with multiple small holes. The balloon was positioned in the lower third of the esophagus and 0.5 cc of helium was introduced into it. The correct position was ascertained for each subject prior to the dive and kept constant for subsequent experiments. The free end of the catheter was connected to one side of a Sanborn 267B differential pressure transducer; mouthpiece pressure was measured through a tap in the mouthpiece connected by catheter to the opposite arm of the transducer. The electrical signals for volume, flow, and transpulmonary pressure were recorded simultaneously on a multichannel oscillographic recorder. The spirometer was calibrated for volume prior to each use by injecting and withdrawing 7000 cc of gas in 1000-cc increments with a calibrated syringe and by the built-in electrical calibration circuit. Flow was calibrated by using the electric calibration signal which had been previously checked against the slope of a volume change. The pressure transducer was calibrated with a water manometer prior to each experiment.

The subjects were seven male U.S. Navy divers in excellent health who were trained in the required maneuvers. Two participated on the 19.1-ATA dive and the remaining five on the 26-ATA dive. During all measurements the subjects were seated comfortably and breathed from the spirometer through a large bore mouthpiece and 5-cm diameter smooth bore tubing. The measurements described previously were obtained on the subjects during quiet breathing, during voluntary hyperventilation for 10-15 seconds, and during at least three forced expiratory vital capacity maneuvers. At the completion of these maneuvers the subject continued breathing from the spirometer for a short period of time while a gas sample was taken for later analysis by gas chromatography.

TABLE 1

Pressure, gas mixtures, and relative gas densities at which measurements were made

Depth		Inspired mixture*	RGD†
ATA	METERS		
1	*surface*	$He-O_2$	0.43
		N_2-O_2	1
		SF_6-O_2	3.75
5.7	47	$Ne-O_2$	3.2
10.1	91	$Ne-O_2$	5.1
19.2	183	$He-O_2$	3.2
		$Ne-O_2$	9.5
23.7	228	$He-O_2$	3.9
26	250	$He-O_2$	4.25
		$Ne-O_2$	15

*P_{O_2} constant at 0.3 ATA

†Based on analysis of spirometer gas samples.
Air at 1 ATA = RGD1.

[1] Med. Science Electronics, Inc., Model 270.

To provide a greater range of gas densities than those obtainable from the chamber atmosphere alone, N_2-O_2, SF_6-O_2, and Ne-O_2 mixtures were used. Table 1 lists the combinations of pressures, gas mixtures, and their relative gas densities (RGDs) relative to air at 1 ATA. All mixtures contained 0.3 ATA of oxygen as did the chamber atmosphere. The RGD values listed were calculated from the results of the gas chromatographic analysis of the spirometer samples. To change from one gas mixture to another the spirometer was filled with 10 liters of the gas to be used. The subject then performed at least three expiratory vital capacities to the atmosphere and inspiratory vital capacities from the gas-filled spirometer to wash out the lungs. After the final washout breath, the spirometer was filled with 7½ liters of the gas mixture; the subject then performed the experimental maneuvers.

Three consecutive breaths that were considered representative in volume and flow pattern were chosen from the data obtained during quiet breathing and hyperventilation. At each 100 cc volume level during quiet breathing and at each 250 cc volume level during hyperventilation, the appropriate transpulmonary pressure was noted and the average values for the three breaths were calculated. Pressure-volume loops were constructed using these values. The flow-resistive work per average breath was determined by measurement of the appropriate areas of the pressure-volume loop with a planimeter (Otis 1964). An estimated minute volume was calculated using the average tidal volume and frequency of the breaths analyzed. Airway resistances were calculated at flow rates of 0.5 liters/sec during quiet respiration and 1 liter/sec during hyperventilation. Values of flow at specific lung volumes during forced vital capacity maneuvers were used to construct flow volume curves fitted by eye. All gas volumes reported in this paper are at ATPS conditions.

TABLE 2

Mean vital capacity and expired gas volume at peak flow at the various relative gas densities

RGD	Vital capacity (ATPS) cc	Volume of gas expired at PEFR (ATPS) cc	% Vital Capacity at which PEFR occurs
0.43	5510	890	84
1.0	5780	750	87
3.2	5560	600	89
3.9	5410	550	90
4.25	5280	440	92
5.1	5490	550	90
9.5	5390	470	91
15.0	5580	380	93

RESULTS

Table 2 lists the average vital capacities at the various RGDs. The values listed for RGD 0.43 and RGD 1 are the combined pre- and postdive data. There was little variation in vital capacity throughout these dives.

The relationships of the average forced expiratory volume in one second (FEV_1), average

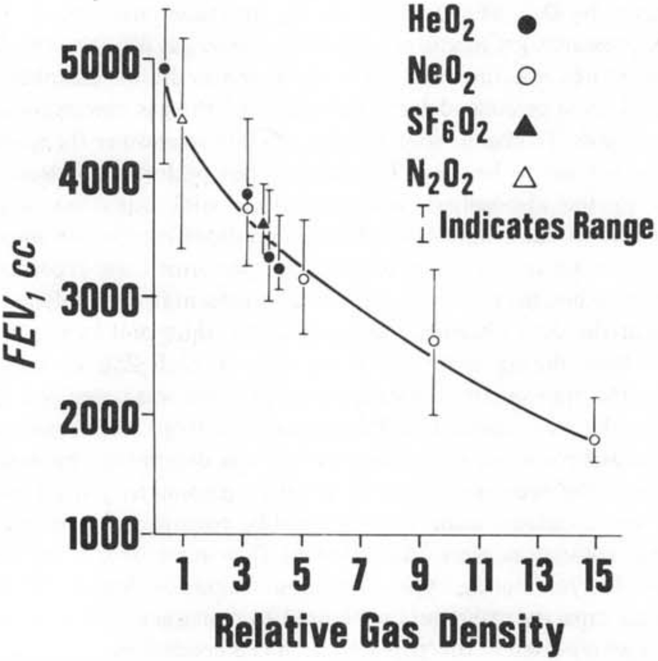

Fig. 1. Mean values of FEV_1 at various relative gas densities.

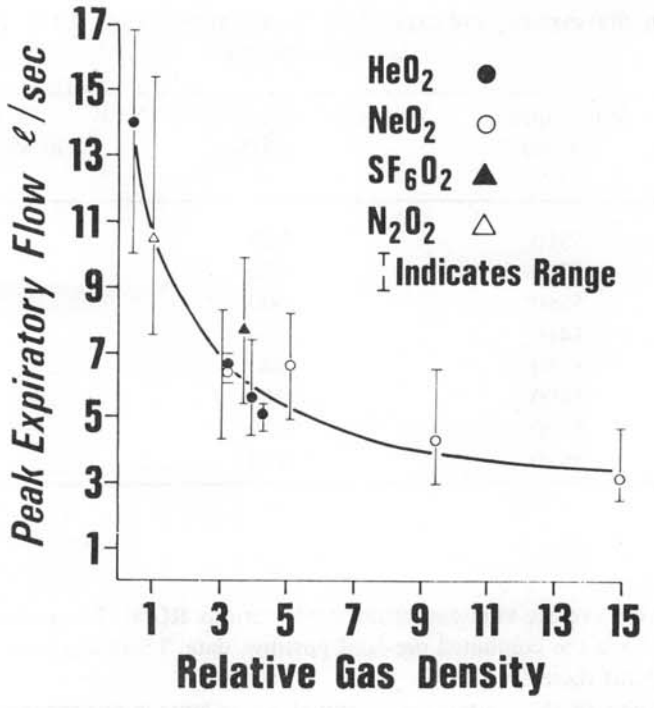

Fig. 2. Mean values of peak expiratory flow at various relative gas densities.

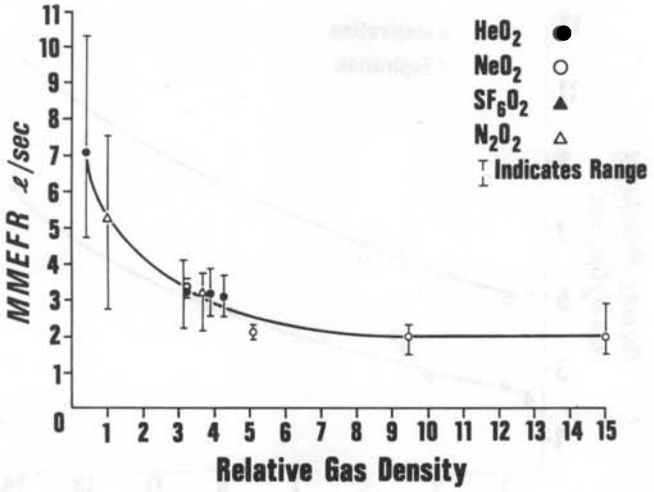

Fig. 3. Mean values of midmaximum expiratory flow at various relative gas densities.

peak expiratory flow rate (PEFR), and average maximum midexpiratory flow rate (MMEFR at 50% VC) with gas density are shown in Figs. 1-3. The largest decreases in these occurred between RGDs of 0.43 and 5. Comparing the values obtained at RGD 15 with those at RGD 1, the FEV_1 decreased 60%, PEFR 70%, and MMEFR 63%. It is of interest that between RGD 5 and RGD 15 there was almost no change in MMEFR and that PEFR occurred at

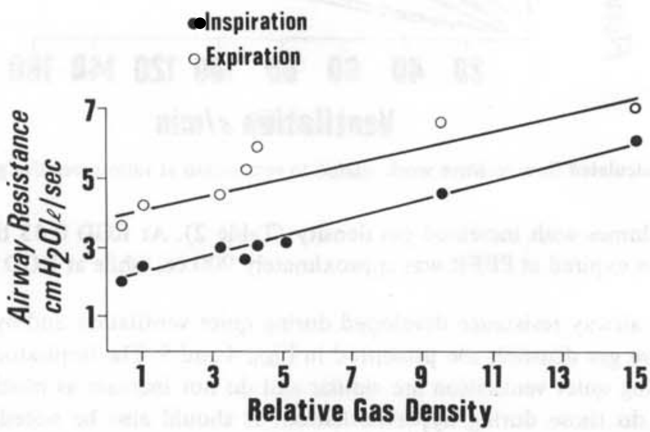

Fig. 4. Mean values of inspiratory and expiratory airway resistance at various relative gas densities during quiet breathing.

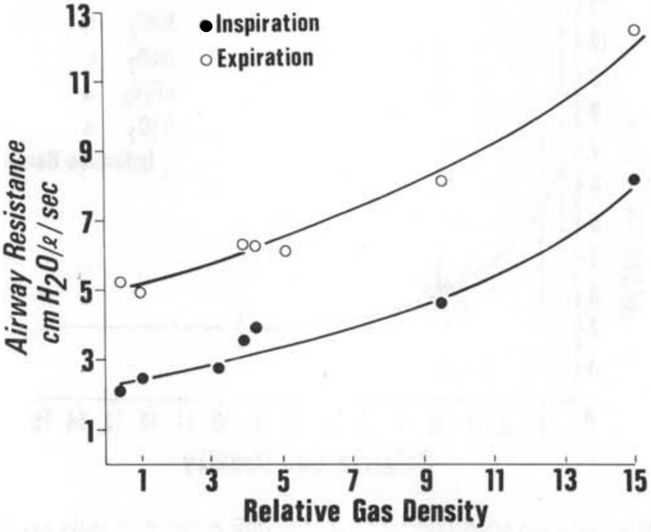

Fig. 5. Mean values of inspiratory and expiratory airway resistance at various relative gas densities during voluntary hyperventilation.

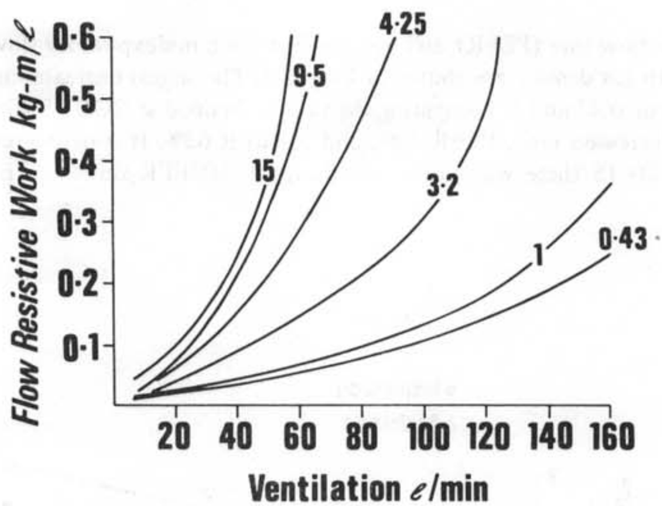

Fig. 6. Calculated flow-resistive work related to ventilation at various relative gas densities.

higher lung volumes with increased gas density (Table 2). At RGD 0.43 the amount of gas which had been expired at PEFR was approximately 900 cc, while at RGD 15 it was close to 400 cc.

The average airway resistance developed during quiet ventilation and hyperventilation at different relative gas densities are presented in Figs. 4 and 5. The inspiratory and expiratory resistances during quiet ventilation are similar and do not increase as much with increasing gas density as do those during hyperventilation. It should also be noted that inspiratory resistances during quiet breathing and hyperventilation are essentially equal up to RGD 9.5. The resistances shown in Fig. 4 were calculated from the resistances measured at a flow of

0.5 liters/sec and then doubled, while those in Fig. 5 were measured at a flow of 1 liter/sec; therefore these results also point up the flow dependence of resistance.

The average work done to overcome airway resistance at various minute ventilations and gas densities is shown in Fig. 6. At resting ventilations gas density had little effect on the work required to overcome airway resistance. At higher ventilations the general effect of increasing gas density was to increase the work done against airway resistance. Although these subjects were not attempting to perform maximum voluntary ventilation during hyperventilation and no definite endpoint was established at each relative gas density, the calculated minute volume decreased with increasing gas density to 50 liters/min at RGD 15.

DISCUSSION

Lord, Bond, and Schaefer (1966) reported a decrease in the vital capacities of three subjects during the first 4 days of a saturation dive to 4 ATA, but were unable to offer an explanation for these changes. Hamilton, MacInnis, Noble, and Schreiner (1966) reported a slight increase in the vital capacities of two divers during a 48-hour exposure to 20.6 ATA, which they attributed to a training effect. The results of this study indicate there is little or no effect on the vital capacity of men breathing helium-oxygen at high pressure. This agrees with the recent findings of Varene, Vieillefond, Lemaire, and Saumon (1974).

Additional findings in this study are similar to those of other investigators. For example, the effect of increasing gas density on FEV_1 was similar to that of Hamilton et al. (1966) and Wood and Bryan (1969). PEFR and MMEFR correlate extremely well with the results of others when flow rates are compared at the same relative gas densities (Lord et al. 1966; Maio and Farhi 1967; Marshal, Lanphier, and DuBois 1956; Wood and Bryan 1969). In addition, this study indicates that the viscosity of the gas breathed is of little significance compared to the effect of density. The two gas mixtures used to produce a RGD of 3.2 were $Ne\text{-}O_2$ at 5.7 ATA and $He\text{-}O_2$ at 19.1 ATA. Although neon has a viscosity 1.6 times that of helium the flows recorded at this gas density were extremely close (Fig. 2).

Agostoni and Fenn (1960) showed that maximum gas flow at high lung volumes is limited by the rate of muscle contraction. At such lung volumes the maximum flow rates achieved were less than theoretically possible if the subjects had generated greater pleural pressure and reached their effort-independent maximum flow. Wood and Bryan's findings (1969) show, as do the findings of this study, that PEFR occurred at higher lung volumes as gas density increased. They assumed that the velocity of muscle contraction is unchanged at increased ambient pressure; they explained this finding on the basis of a fixation of the equal pressure point (EPP) and the downstream flow-limiting segment earlier in expiration as density increases. In other words, as gas density increases the pressure drop between the alveoli and airways downstream increases for equal flows. This means that the EPP will be fixed at a lower flow rate (i.e. earlier in time) and peak flow will occur at a higher lung volume and become effort-independent as gas density increases.

Maio and Farhi (1967) noted that at relative gas densities above 5 the effect of density on peak flow rates (measured during maximum voluntary ventilation) decreases. This is also true of the peak flow rates measured in this study during single forced expirations. Maio and Farhi (1967) suggested that their finding was due to the increased inertia of the dense gas and the velocity of muscle contraction (i.e. because of the delay in gas flow the decrease in lung volume is slowed and the muscles can operate at a position of greater mechanical advantage, thus producing higher alveolar pressures and thereby maintaining flow). In addition, in the present study this phenomenon was more apparent with the MMEFR, which showed no appreciable difference between RGD 5 and 15. Since these flow rates were measured at 50% vital capacity, lung volume was a constant, flow was effort-independent, and inertial influences were no longer present; therefore, the above hypotheses do not adequately explain these results. A possible reason for this finding is that the decreases in MMEFR at RGDs greater than 5 may be so slight that a larger number of observations are needed to demonstrate them. Unfortunately, the pleural and mouthpiece pressures were not recorded along with the transpulmonary pressure. Knowing such actual pressures could help provide an explanation for this phenomenon.

The increased expiratory airway resistance during hyperventilation as compared to expiratory airway resistance during quiet breathing is the result of airway collapse, which does not occur when expiration is passive. This phenomenon also does not occur during inspiration and, indeed, closely similar inspiratory resistances were observed in this study during quiet respiration and hyperventilation. Expiratory resistance during hyperventilation is very effort-dependent, so the results presented here are to illustrate the above point only and should not be regarded as absolute values of airway resistance.

That increased resistance to flow caused by increased gas density requires more respiratory work has been previously demonstrated by Bühlmann (1963); Glauser, Glauser, and Rusy (1967); Bradley, Vorosmarti, Merz, Heckert, and Kleckner (1970). Investigation of this phenomenon is extended in the present study. The work of breathing during quiet respiration is small even at markedly increased gas densities because the flow rates and therefore the flow-resistive pressure losses are only slightly increased. Higher flow rates are achieved with larger minute volumes and resistance is increased dramatically with increasing gas density, causing the work of breathing to increase significantly.

One purpose of this and other studies (Anthonisen et al. 1971; Bradley et al. 1971; Miller et al. 1971; Morrison and Florio 1971; Salzano, Overfield, Rausch, Saltzman, Kylstra, Kelley, and Summitt 1971) has been to predict the depth at which the work of breathing will limit the useful work a diver can perform. Varene et al. (1974) have used the data from several of these studies along with their own data to depths of 61 ATA to formulate a linear regression to calculate maximum ventilation and maximum muscular exercise as a function of pressure. When the minute ventilations calculated from the data in this study were compared with the minute ventilations calculated from the regression formula, the data in this study gave consistently higher minute ventilations at all pressures. A possible explanation is that the 10- to 15-sec hyperventilation of the subjects in this study is an entirely different situation than that of sustained ventilation resulting from exercise, which was the basis of the calculations in the studies made by Varene et al.

At relative gas densities greater than 5, our subjects showed very little decrease in PEFR, no change in MMEFR, and were able to respire 50 liters/min at RGD 15, which can also explain the higher calculated minute ventilations. Extrapolations of this finding using the densities encountered with appropriate $He\text{-}O_2$ mixtures would indicate that divers should not be unduly limited by pulmonary mechanics in doing moderate work (125 watts) at pressures in the range of 100 ATA.

There are, however, several reasons why this extrapolation may not be valid. As noted above, the level of voluntary hyperventilation a man can reach for 10-15 sec cannot be used to predict the sustained ventilatory capability during exercise over much longer time periods. In the same vein, data obtained during forced respiratory maneuvers are also not predictive of respiratory function during more physiologic respiration. A more obvious reason is that this study was done using equipment with very low flow resistance in a dry environment. It is known that the addition of external resistance in the form of breathing apparatus will cause a decrement in man's ventilatory capability (Bradley et al. 1970). Immersion in water will, depending on the diver's position, cause him to breathe against negative or positive pressure, which increases his work of breathing and reduces his ventilatory capability (Sterk 1973). Finally, it has been shown that using the conventional method of estimating the total work of breathing (Campbell 1958) underestimates this amount by as much as 25% at high ventilations, since it ignores work done overcoming distortion of the chest wall (Goldman, Grimby, and Mead 1972). In the immersed state both the chest and abdominal walls will be distorted from the normal relaxation configuration even during quiet respiration, and this will increase the total work of breathing.

To predict the practical depth to which a man may dive and still be capable of useful work requires a great deal more study in each of these specific areas.

The opinions or assertions contained herein are solely those of the authors and are not to be construed as official or reflecting the views of the Navy Department or tha Naval Service at large.

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Vorosmarti, J., M. E. Bradley, and N. R. Anthonisen. 1975. Effets de densité accrue des gaz sur la méchanique pulmonaire. Undersea Biomed. Res. 2(1):1-10.–La fonction pulmonaire a été étudiée chez sept plongeurs de la Marine americaine au cours de deux plongées à saturation en hélium-oxygène à 19.1 et 26 ATA. Volume pulmonaire, débit respiratoire, et pression transpulmonaire ont été étudiés lors de la respiration tranquille, de l'hyperventilation, et des manoeuvres de capacité vitale expiratoire forcée. Les dosages ont été faits à des profondeurs variées en mélanges de $He-O_2$, N_2-O_2, et $Ne-O_2$ pour donner une gamme de densités des gaz entre 0.43 et 15. Les changements de volume expiratoire forcé ont confirmé les resultats obtenus par des auteurs antérieurs. Le débit maximum mi-expiratoire n'a pas diminué quand la densité gazeuse relative excedait 5. La résistance inspiratoire des voies aeriennes a augmentée avec la densité des gaz, mais ne différait pas beaucoup pendant la respiration tranquille et l'hyperventilation. La résistance expiratoire des voies aeriennes a aussi augmenté avec la densité des gaz, et se trouvait augmentée d'une facon significative pendant l'hyperventilation par comparaison avec la respiration traquille. A 26 ATA les sujets ont respiré 50 litres/min sans stress important, mais le travail de respiration resistant au débit se trouvait augmenté. L'emploi possible de ce genre d'étude pour prédire la profondeur à laquelle les plongeurs seront capables de travailler est discuté.

fonction pulmonaire travail
densité résistance
plongée à saturation

REFERENCES

Agostoni, E., and W. D. Fenn. 1960. Velocity of muscle shortening as a limiting factor in respiratory air flow. J. Appl. Physiol. 15:349-353.

Anthonisen, N. R., M. E. Bradley, J. Vorosmarti, and P. G. Linaweaver. 1971. Mechanics of breathing with helium-oxygen and neon-oxygen mixtures in deep diving. Pages 339-345 *in* C. J. Lambertsen, ed. Underwater physiology. Proceedings of the fourth symposium on underwater physiology. Academic Press, New York.

Bradley, M. E., N. R. Anthonisen, J. Vorosmarti, and P. G. Linaweaver. 1971. Respiratory and cardiac responses to exercise in subjects breathing helium-oxygen mixtures at pressures from sea level to 19.2 atmospheres. Pages 325-337 *in* C. J. Lambertsen, ed. Underwater physiology. Proceedings of the fourth symposium on underwater physiology. Academic Press, New York.

Bradley, M. E., J. Vorosmarti, J. Merz, P. J. Heckert, and J. C. Kleckner. 1970. Breathing impedance of the Mark VIII and Mark IX semi-closed underwater breathing apparatus. Research Report 1-70, Submarine Development Group One, San Diego, California.

Bühlmann, A. A. 1963. Respiratory resistance with hyperbaric gas mixtures. Pages 98-107 *in* C. J. Lambertsen, ed. Proceedings second symposium on underwater physiology. Publ. 1181, Nat. Acad. Sci.–Nat. Res. Counc., Washington, D.C.

Campbell, E. J. M. 1958. The respiratory muscles and the mechanics of breathing. Year Book Publ., Chicago, Ill., p. 93.

Glauser, S. C., E. M. Glauser, and B. F. Rusy. 1967. Gas density and the work of breathing. Respir. Physiol. 2:344-350.

Goldman, M., G. Grimby, and J. Mead. 1972. An improved measurement of the mechanical work of breathing. Physiologist 15:148.

Hamilton, R. W. Jr., J. B. MacInnis, A. D. Noble, and H. R. Schreiner. 1966. Saturation diving to 650 feet. Tech. Memo. B-411, Ocean Systems Inc., Tonawanda, N.Y.

Lord, G. P., G. F. Bond, and K. E. Schaefer. 1966. Breathing under high ambient pressure. J. Appl. Physiol. 21:1833-1838.

Maio, D. A., and L. E. Farhi. 1967. Effect of gas density on mechanics of breathing. J. Appl. Physiol. 23:687-693.

Marshall, R., E. H. Lanphier, and A. B. Dubois. 1956. Resistance to breathing in normal subjects during simulated dives. J. Appl. Physiol. 9:5-10.

Miles S. 1966. Underwater medicine. J. B. Lippincott Co., Philadelphia, Pa., pp. 93-95.

Miller, J. N., O. D. Wangensteen, and E. H. Lanphier. 1971. Ventilatory limitations on exertion at depth. Pages 317-323 *in* C. J. Lambertsen, ed. Underwater physiology. Proceedings of the fourth symposium on underwater physiology. Academic Press, New York.

Morrison, J. B., and J. T. Florio. 1971. Respiratory function during a simulated saturation dive to 1500 feet. J. Appl. Physiol. 30:724-732.

Otis, A. B. 1964. The work of breathing. Page 466 *in* W. O. Fenn and H. Rahn, eds. Handbook of physiology. Sect. 3: Respiration. 1. American Physiological Society, Washington, D.C.

Salzano, J. E., M. Overfield, D. C. Rausch, H. A. Saltzman, J. A. Kylstra, J. S. Kelley, and J. K. Summitt. 1971. Arterial blood gas, heart rate, and gas exchange during rest and exercise in men saturated at a simulated seawater depth of 1000 feet. Pages 347-356 *in* C. J. Lambertsen, ed. Underwater physiology. Proceedings of the fourth symposium on underwater physiology. Academic Press, New York.

Sterk, W. 1973. Respiratory mechanics of diver and diving apparatus. Drukkerij Elinkwijk, Utrect.

Varene, P., H. Vieillefond, C. Lemaire, and G. Saumon. 1974. Expiratory flow volume curves and ventilatory limitation of muscular exercises at depth. Aerosp. Med. 45:161-166.

Wood, L. D. H., and A. C. Bryan, 1969. Effect of increased ambient pressure in flow volume curve of lung. J. Appl. Physiol. 27:2-8.