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Influence of increased gas density and external resistance on maximum expiratory flow

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Vorosmarti, J., Jr. 1979. Influence of increased gas density and external resistance on maximum expiratory flow. Undersea Biomed. Res. 6(4): 339–346.—The effect of external resistance on the relationship of expiratory air flow and intrathoracic and mouth pressure on subjects breathing gas of increased density was investigated. Five subjects breathing air performed multiple maximum forced expiratory maneuvers through orifices of various sizes at 1, 4, and 7 ATA in a standard double-lock compression chamber. Measurements of flow and pleural, mouthpiece, and transpulmonary pressures were made, and flow-volume and pressure-volume curves were constructed and analyzed at 75, 50, 35, and 25% of vital capacity. At each lung volume, maximum flow could be maintained until a certain orifice size was reached. This "limiting orifice" was 7.5–10 mm in diameter and did not change with lung volume or density. Under the conditions studied, this finding leads to the conclusion that the flow-limiting segment of the lungs behaved as a rigid orifice less than 10 mm in diameter. Orifices slightly larger than the limiting orifice increased pleural pressure, as expected, but transpulmonary pressure decreased while the flow remained stable, which indicates that airway compression may be lessened by increased intra-airway pressure.

expiratory flow
gas density
external resistance
flow limitation
respiration
diving
humans

The amount of work that a diver can do at increased pressure and in the water appears to be governed by his maximum ventilatory capability. Three environmental factors influence maximum ventilation: gas density, external resistance from the underwater breathing apparatus, and the degree of negative or positive pressure breathing the diver must perform to overcome the effects of immersion. However, maximum expiratory flow and ventilation are normally limited by collapse of intrathoracic airways, and this mechanism may also play a role at depth.

The effects of increased gas density on pulmonary ventilation and exercise functions have been studied extensively, and it appears that the decreasing flow rates achievable as gas density increases may limit the depth at which divers can work effectively. Studies have shown that divers may be able to perform moderate work at 60 ATA, but there are severe ventilatory limitations (Anthonisen, Bradley, Vorosmarti, and Linaweaver 1971; Miller, Lanphier, and Wangensteen 1971; Varene, Vieillefond, Lemaire, and Saumon 1974). All of these studies were done in dry chambers, with subjects using very low-resistance apparatus; their results therefore may not provide an accurate estimate of the ventilatory and exercise limits (Bradley, Vorosmarti, Merz, Heckert, and Kleckner 1970; Sterk 1973) in conditions in which external resistance and immersion effects interact with dense gas breathing.

The present study investigated the effect of external resistance on the relationship of intrathoracic expiratory air flow and intrathoracic and mouth pressure on subjects breathing gas of increased density.

MATERIALS AND METHODS

Measurement procedures

The measurements made during the experiment were expiratory flow and volume, esophageal pressure, mouthpiece pressure, and transpulmonary pressure. Because during most of this study a resistance to airflow was added distal to the mouthpiece and the tap for measuring mouthpiece pressure, airway outlet pressure was not measured in the usual sense. For want of a better term, transpulmonary pressure is used in this paper to designate the difference between pleural pressure and mouthpiece pressure, but the abbreviation P_{tp} is used rather than the usual P_L.

Required maneuvers were done through a 27-mm mouthpiece and a large-bore tubing into a low-resistance wedge spirometer (Medscience Electronics Model 170). Volume and flow signals from the spirometer were recorded simultaneously on a multichannel oscillograph (Grass Model 7B) and on magnetic tape, using a Honeywell Model 7600 recorder. The spirometer volume signal was calibrated before each experiment, using both the electronic calibration and the introduction of air via a 1-liter calibrated syringe. The flow signal was checked electronically before each experiment, after having been calibrated previously with air at an accurately known flow. Pleural pressure was estimated by measuring esophageal pressure, using an 80-cm length of 1.7-mm i.d. polyethylene tubing, the distal end of which was pierced by several holes and covered with a 12 cm × 1 cm latex balloon containing 1 cc of air. The balloon was positioned in the lower end of the esophagus, in a region free of cardiac artifacts, and the tubing was connected to a Statham-P23 AC pressure transducer modified for use at high pressures. Mouthpiece pressure (P_{mp}) was obtained through a tap proximal to the orifice in the mouthpiece assembly, which was also connected to a modified Statham transducer. Transpulmonary pressure (P_{tp}) was obtained with the same type of transducer, modified to measure differential pressure ($P_{pl}-P_{mp}$), and connected through T-connections to the esophageal balloon tubing and mouthpiece tubing (Fig. 1). Esophageal and mouthpiece pressures were referenced to ambient pressure. The space between the transducer cap and diaphragm in all transducers was filled with distilled water to obviate any errors that might be introduced by compression of this volume. Signals for P_{pl}, P_{mp}, and P_{tp} were recorded in the same manner as the flow-volume signals. Before each experiment a water manometer was used for calibrating the transducers.

External resistance was provided by a series of orifices consisting of 12-mm thick plastic discs with holes of the following diameters located in their centers; 15, 10, 7.5, 5, and 3.5 mm. When required, these discs could be securely placed in the mouthpiece.

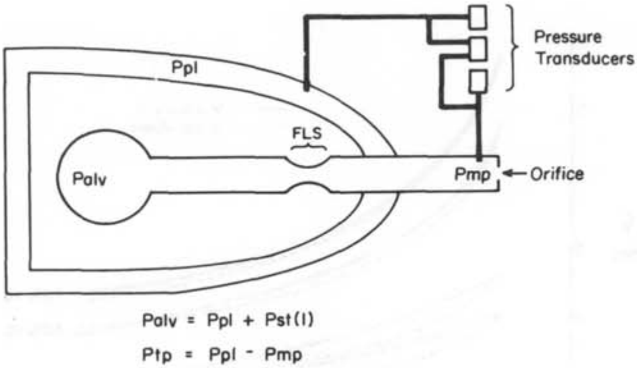

Fig. 1. Diagram of chest wall and lung with single airway; also shown are connections of transducers used in experiment. P_{pl} = pleural pressure, P_{alv} = alveolar pressure, $P_{st(l)}$ = recoil pressure of the lung, P_{tp} = transpulmonary pressure. Flow-limiting segment is indicated by curved sections of airway wall.

Subjects

Five subjects, whose physical characteristics are shown in Table 1, participated in the study. All subjects were nonsmokers; none had any evidence of lung disease.

The study was conducted in a standard double-lock compression chamber with the subjects breathing air. Measurements were made on the same day at the surface, then at 7 ATA, and, finally, at 4 ATA. To ensure that a maneuver was being done properly, the subjects, who were seated comfortably in the erect position, performed slow and forced vital capacity (VC) measurements through the unobstructed mouthpiece at each pressure. They then performed at least three forced VC maneuvers through the unobstructed mouthpiece and each of the orifices while the measurements (previously described) were made and recorded. The subjects were coached during the experiments by an investigator who accompanied them during the simulated dive.

TABLE 1

PHYSICAL CHARACTERISTICS OF THE SUBJECTS

Subject	Sex	Age, yr	Hgt, cm	Wgt, kg	Predicted VC, cc	Measured VC, cc BTPS
A	M	30	183	78.3	5300	4900
B	M	29	179	86.5	5700	6400
C	M	36	188	91.0	5450	6400
D	F	25	180	66.0	4100	4500
E	F	30	157	50.0	3050	3030

BTPS = body temperature and pressure, saturated with water vapor.

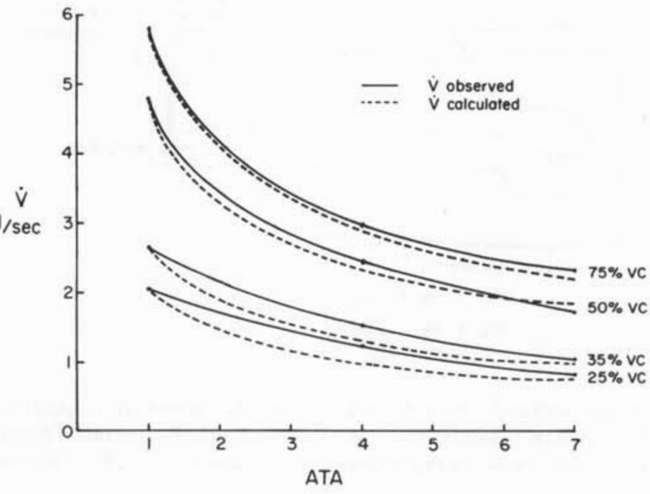

Fig. 2. Observed values of average $\dot{V}_{max\ u}$ at 25, 35, 50, and 75% of VC at 1, 4, and 7 ATA compared to expected calculated flows ($\dot{V} = l/\sqrt{D}$).

Analytical techniques

Flow, P_{pl}, P_{tp}, and P_{mp} volume curves were constructed for each experimental situation by reproducing the taped signals through an XY recorder (Honeywell Model 530) at 1/8th the recording speed. Flows and pressures at 75, 50, 35, and 25% of the VC were determined from these curves.

RESULTS

Figure 2 compares the mean maximum unresisted flow rates observed in this experiment to the flow rates that would be expected if calculated on the basis that flow decreases proportionally by a factor of $1/\sqrt{D}$. Calculated values at 2, 4, and 7 ATA were derived from the mean observed values at 1 ATA. The observed and calculated values are very close, especially at the two higher lung volumes.

Figure 3 illustrates the relationships of flows and pressures at 75, 50, 35, and 25% of the VC, and orifice size at 1, 4, and 7 ATA. Each point is the average for the five subjects.

These results show that at a given lung volume the maximum unresisted flow ($\dot{V}_{max\ u}$) attainable can be maintained until an orifice of a certain size is reached. The limiting orifice is defined as the largest orifice that caused a decrement in $\dot{V}_{max}$ at a given lung volume. Figure 2 shows that at all lung volumes studied, the limiting orifice was approximately 7.5 mm in diameter. Increasing gas density did not change these limiting orifices. The changes in P_{pl}, P_{mp}, and P_{tp} in relation to orifice size and flow also were unaffected by increased gas density.

DISCUSSION

From the results of this experiment it is concluded that at any specific lung volume between 25 and 75% of the VC, the flow-limiting segment (FLS) of the lung responds to increased gas

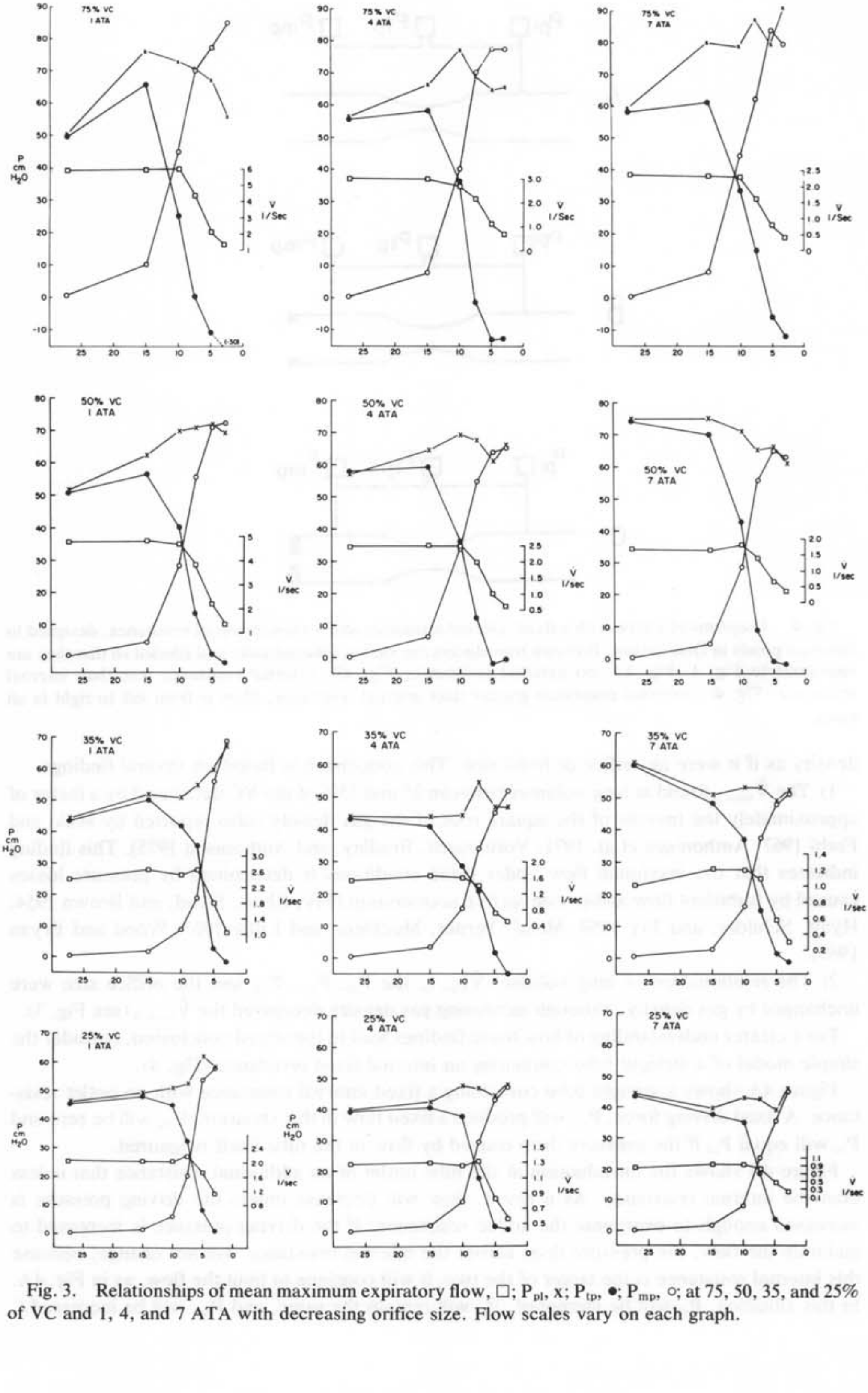

Fig. 3. Relationships of mean maximum expiratory flow, □; P_{pl}, x; P_{tp}, ●; P_{mp}, ○; at 75, 50, 35, and 25% of VC and 1, 4, and 7 ATA with decreasing orifice size. Flow scales vary on each graph.

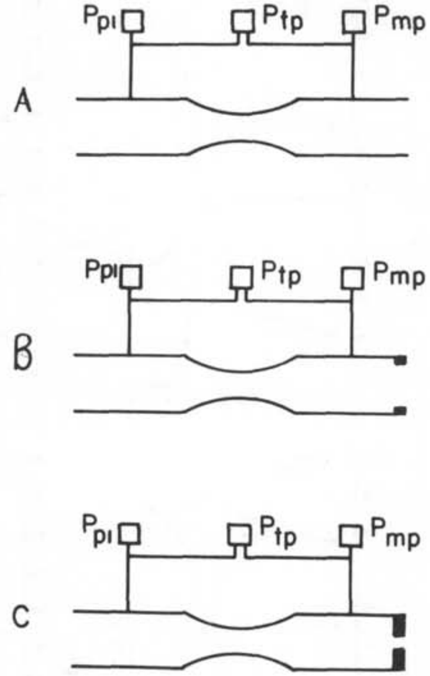

Fig. 4. Diagrams of a tube with a fixed internal resistance and a variable outlet resistance, designed to illustrate points in DISCUSSION. Pressure transducers are shown schematically and labeled so that they are analogous to Fig. 1. Fig. 4A, no external resistance; Fig. 4B, external resistance less than internal resistance; Fig. 4C, external resistance greater than internal resistance. Flow is from left to right in all cases.

density as if it were an orifice of fixed size. This conclusion is based on several findings.

1) The $\dot{V}_{max\ u}$ found at lung volumes between 25 and 75% of the VC decreased by a factor of approximately the inverse of the square root of the gas density (also reported by Maio and Farhi 1967; Anthonisen et al. 1971; Vorosmarti, Bradley, and Anthonisen 1975). This finding indicates that the maximum flow under these conditions is determined by pressure losses caused by turbulent flow and/or convective acceleration (Fry, Ebert, Stead, and Brown 1954; Hyatt, Schilder, and Fry 1958; Mead, Turner, Macklem, and Little 1967; Wood and Bryan 1969).

2) The relationships of lung volume, $\dot{V}_{max\ u}$, the P_{pl}, P_{mp}, P_{tp}, and the orifice size were unchanged by gas density, although increasing gas density decreased the $\dot{V}_{max\ u}$ (see Fig. 3).

For a clearer understanding of how these findings lead to the stated conclusion, consider the simple model of a straight tube containing an internal fixed resistance (Fig. 4).

Figure 4A shows a straight tube containing a fixed interval resistance with no outlet resistance. A fixed driving force, P_{pl}, will produce a fixed flow in this situation; P_{mp} will be zero and P_{tp} will equal P_{pl} if the pressure drop caused by flow in the tube itself is ignored.

Figure 4B shows the introduction at the tube outlet of an additional resistance that is less than the internal resistance. As a result, flow will decrease unless the driving pressure is increased enough to overcome the added resistance. If the driving pressure is increased to maintain the flow, the pressure drop across the internal resistance will not change; because this internal resistance is the larger of the two, it will continue to limit the flow, as in Fig. 4A. In this situation, P_{pl} will be increased, P_{tp} will remain the same, and P_{mp} will be increased.

Figure 4C shows an outlet resistance that is higher than the internal resistance and is therefore limiting to flow. If the driving pressure cannot be increased (if P_{pl} is already maximum) the flow will be decreased, the P_{tp} will be decreased as a result of the decreased flow, and the P_{mp} will be increased. If these simple models are placed in an environment of high gas density and the driving pressure remains the same as in the above situations, the flow will be reduced as a result of the increased gas density but the pressures will not be changed.

The data shown in Fig. 3 are the same as would be expected from the model discussed above and lead to the conclusion that the FLS of the lung acts as a fixed orifice of less than 10 mm in diameter which does not change at lung volumes between 25 and 75% of the VC nor with the gas densities studied.

One can logically argue further that because the FLS acts as a fixed orifice it does not change its position in the lung with either lung volume or with gas density. If the position of the FLS were to change with density, one would expect the limiting orifice to change also. In addition, the P_{tp} at which the expiratory flow becomes independent of the expiratory effort (P_{max}) would be expected to change. Miller (1976) showed that the P_{max} did not change in subjects breathing air at pressures up to 6 ATA.

The results of the present investigation also confirm an analysis of the mechanics of expiratory flow at depth made by Lanphier (1975), who concluded that external resistance would not simply reduce the effort-independent maximum expiratory flow by adding to the total resistance. Instead,

> addition of external resistance would require greater effort and an increase in P_{pl} to maintain a greater flow. However, pressure in the intrathoracic airways would rise to the same extent as P_{pl}, and the net tendency of airways to collapse should not be altered. Maximum expiratory flow should remain unchanged provided that the individual can perform the extra respiratory work imposed by added external resistance. (Lanphier 1975)

Another and somewhat more complicated point needs to be discussed. It was stated that at some point maximum P_{pl} is reached and that flow cannot be maintained because added external resistance cannot be overcome as P_{mp} continues to rise. The data in Fig. 3 show that the addition of the 10-mm orifice into the system caused an increase in P_{mp}, but the associated P_{pl} did not increase by the same magnitude; however, the $\dot{V}_{max\ u}$ was still maintained and the P_{tp} decreased. This finding suggests that there must be a decrease in the upstream resistance, since the pressure drop across it (P_{tp}) decreased. In other words, although the FLS is still limiting flow, it has a larger diameter, i.e., a larger orifice, than when the downstream resistance is smaller. Evidently, the increased pressure required to maintain flow across the 10-mm orifice is transmitted upstream to the FLS, where it does not affect flow but does influence the pressure drop across the resistor and, therefore, changes its resistance. This change indicates that the FLS and external resistance, when the latter is close to becoming flow limiting, are analogous to the well-known Starling resistor, in which the downstream pressure does not influence flow but does influence the pressure drop across the upstream resistor and, therefore, its resistance.

We have determined that an orifice that does not interfere with maximum effort-independent flow at 1 ATA will not interfere with this flow at increased pressure. If a breathing apparatus could be characterized as having an orifice of a certain size, no testing would be required at depth to determine whether the apparatus would allow the diver to achieve maximum flow; thus, testing procedures would be simplified. Such a simplified approach would ignore important factors such as hydrostatic imbalance and changes in breathing bag compliance, but it would be a starting point for the design and testing of apparatus.

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J. Vorosmarti, Jr. L'influence de la densité accrue du gaz et la résistance externe sur le flux réspiratoire maximum. Undersea Biomed. Res. 6: 339–346, 1979. L'effet de la résistance externe sur la relation du flux expiratoire intrathoracique de l'air et la pression intrathoracique de la bouche sur des sujets respirant du gaz de densité accrue a été enquêté. Cinq sujets respirant de l'air ont fait des manoeuvres multiples maximum de l'expiration forcée par des orifices des tailles variées, à 1, 4, et 7 ATA dans une chambre standarde de compression fermée à double tour. Des mesurages du flux et des pressions pleurales, embouchures, et transpulmonaires ont été faites, et les courbes du volume de flux et de volume de pression ont été construites et analysées à 75, 50, 35, et 25% du VC. A chaque volume specifique du poumon, le flux maximum pourrait être maintenu jusque l'atteinte d'une certaine taille d'orifice. Cet orifice limitatif a été 7.5–10 mm de diamètre et n'a pas changé avec le volume du poumon ou la densité. Dans les conditions étudiées, ce resultat mène au conclusion que le segment flux-limitatif des poumons s'est comporté comme un orifice rigide de moins de 10 mm de diamètre. Les orifices un peu plus grands que "l'orifice limitatif" ont produit la pression pleurale accrue, comme prèvu, mais la pression transpulmonaire a été décrue pendant que le flux a resté stable, qui indique que la compression de la conduite d'air peut être diminuer comme resultat de la pression intra-conduite accrue.

flux expiratoire
densité du gaz
résistance externe
limitation du flux
respiration
plongée
humains

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