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Inspiratory flow limitation in divers

V. FLOOK and I. M. FRASER

Department of Physiology, University of Aberdeen and The National Hyperbaric Centre, Aberdeen, Scotland

Flook V, Fraser IM. Inspiratory flow limitation in divers. Undersea Biomed Res 1989; 16(4):305–311.—Inspiratory dyspnea becomes an important factor in reducing a diver's ability to carry out physical work at depths in excess of 300 m. It is possible that dynamic compression of the trachea occurs when the intratracheal pressure drops below environmental pressure, thereby causing transient reduction in inspiratory flow. Vocal cords form an orifice of variable diameter, and orifice flow is predicted to occur at flow rates as low as 22 liter/min when gas density is 5 kg/m³ or more. Pressure drop across the vocal cords is calculated to range from 70 N/m² at flow rate 1 liter/sec to 2.8 kN/m² flow rate 4 liter/sec, aperture of the vocal cords 1.2×10^{-2} m, gas density range 5–10 kg/m³. A smaller aperture, 0.6×10^{-2} m, results in a pressure drop range 1.29–41.15 kN/m² for the same flow rates and density range. Thus the transmural pressures that can occur are high enough to cause tracheal compression. At 300 m, gas density 5.9 kg/m³, 3 of 4 divers showed evidence of sudden inspiratory flow limitation.

orifice flow
flow limitation
dense gases
transmural pressures

Over recent years, as divers have been asked to work at higher levels of physical activity at greater depths, it has become apparent that the diver's capacity for performing work is limited by the respiratory system (1). There is increasing evidence that dyspnea is a fairly common occurrence during work at depths greater than about 160 m (2, 3). Salzano et al. (3) suggest that inspiratory dyspnea was the work-limiting factor for their subjects during a simulated dive to 650 and 460 m (66 and 47 bar) and reported that some divers had felt "sudden momentary airway obstruction during rapid inspirations." This paper attempts to give a theoretical explanation of the phenomenon of dyspnea in divers.

The extrathoracic trachea, unlike the lower airways, is not shielded from environmental pressure by pleural pressure. Pressure on the outside of the trachea is environmental pressure modified by the neck tissue and muscular activity in the neck. It is possible that with some combinations of gas density and inspiratory flow rates, the pressure within the trachea is sufficiently below environmental to allow dynamic compression of the trachea. Olsen et al. (4) have reported human tracheal lumen reduction, brought about by the inward movement of one end of the incomplete cartilage rings, at transmural pressures as low as -10 kN/m². Gibson et al. (5) reported dynamic narrowing of the extrathoracic airways in subjects breathing air through a large resistance that caused the intra-airway pressure to drop at least 3 kN/m^2 below environmental pressure.

The pressure gradient between mouth and trachea is not easily estimated because of the complex pathway that the gas follows during inspiration (6). Eddies form in the narrow cavity behind the nose and can form at the teeth; formation of eddies, i.e., flow separation, results in large energy losses. However, most upper airway resistance lies in the larynx at the vocal cords (7); thus, this is where most of the pressure drop occurs. The vocal cords represent a variable orifice in the trachea. The opening through the cords increases with flow rate and lung volume (8, 9), varying from a very narrow slit at low flow and low volume to an aperture of 15–18 mm when fully abducted (7). The aperture of the vocal cords is also under nervous control and therefore may be influenced by pressure through the phenomenon of high pressure neurologic syndrome (HPNS) and its effect on muscular activity. It is interesting to note that divers taking part in the simulated dives of Salzano et al. (3) reported airway obstruction less frequently when the gas mixture used contained 10% nitrogen than when it contained 5% nitrogen, even though the higher nitrogen level results in approximately 20% greater density.

The effect of varying muscular activity and the possible influence of HPNS on this, together with the influence of flow rate and lung volume, mean that it is not possible to know the size of the aperture with any certainty at any time during the course of a breath. However, in the theoretical analysis which follows, we suggest that in the high gas densities of the hyperbaric environment, Reynolds' number, for the highest densities or flow rates or both, is sufficiently high to indicate orifice flow with flow separation. Jaeger and Matthys (10) suggested, on the basis of measurements made in human trachea, that at a gas density 4.2 kg/m^3 flow through the vocal cords is venturi flow, as would be expected from the lower values for Reynolds' number. Our hypothesis can be regarded as an extension of this analysis for higher gas densities.

THEORY

Flow through an orifice within a tube requires that the stream lines or flow lines of the fluid contract to pass through the orifice before spreading out to occupy the whole width of the tube downstream from the orifice (Fig. 1 *A*). The momentum of the gas molecules causes the contraction to continue for a short distance beyond the orifice so that the point of minimum cross-sectional area, the vena contracta, is not within the orifice but is a short distance beyond it. Thus, the increase in velocity resulting from the reduction in area continues to the vena contracta and therefore, according to the Bernouilli theorem, the point of minimum pressure on the walls of the tube is in the plane of the vena contracta. As the flow lines diverge to fill the downstream tube, the velocity decreases and therefore pressure increases; however, between the vena contracta and the tube walls eddies develop and flow separation occurs. The formation of eddies causes net loss of energy in the form of heat, and the maximum downstream pressure, P_3, is never as great as P_1. In this way an orifice differs from a venturi in that the tube immediately following the constriction in a venturi is shaped

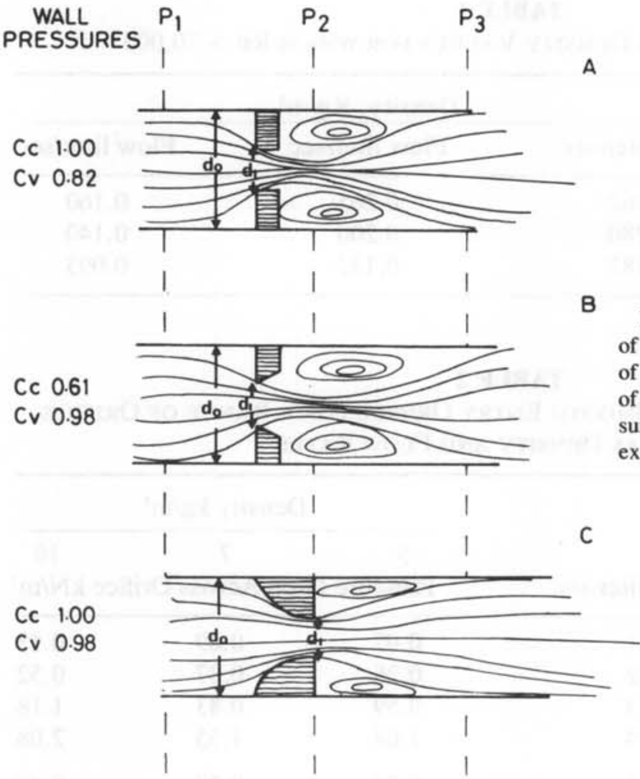

Fig. 1. Characteristics of three types of orifice: Cc the contraction coefficient of the orifice; Cv the velocity coefficient of the orifice; P_1, P_2, and P_3 wall pressures. *See* text for a more complete explanation.

as a truncated cone, eddies do not form, and the maximum downstream pressure can be equal or close to the pressure just before the constriction (11).

The precise shape of the orifice entry influences both the area of the vena contracta and the velocity of the gas molecules. This influence is quantified by two coefficients; the contraction coefficient, Cc, is the ratio of the area of the vena contracta to the area of the orifice. The actual velocity of the gas molecules at the vena contracta is less than the ideal velocity due to the effect of friction within the orifice, and this ratio is quantified as the velocity coefficient, Cv.

The product of Cc and Cv is called the discharge coefficient, Cd, which expresses the ratio between the actual and ideal flow through the orifice. Flow lines and coefficient values are shown in Fig. 1 for three orifice shapes. The values of the coefficients depend on the shape of the entry. From Fig. 1 it can be seen that the bell-shaped entry into orifice *C* reduces the effect of friction and momentum in that all coefficients are close to 1. The change of direction of the flow-lines is completed within the mouthpiece of the orifice and there is no vena contracta (12). For any shape of orifice the value of the discharge coefficient, Cd, is contant for values of Reynolds' number above about 10,000 (11). Table 1 shows values of combinations of density and flow for which this value of Reynolds' number would be exceeded. At the densities of interest in deep diving, Re exceeds 10,000 at flow rates that would occur in fairly quiet breathing. We can therefore regard the discharge coefficient as a constant value for present purposes and hence treat the flow as orifice flow.

TABLE 1
FLOW RATE AND GAS DENSITY VALUES FOR WHICH RE > 10,000

Orifice Size, m	Density, Kg/m³		
	Flow liter/sec	Flow liter/sec	Flow liter/sec
1.2×10^{-2}	0.367	0.265	0.160
0.9×10^{-2}	0.280	0.200	0.140
0.6×10^{-2}	0.183	0.132	0.093

TABLE 2
PRESSURE DROP ACROSS A SMOOTH ENTRY ORIFICE FOR A RANGE OF ORIFICE SIZES, GAS DENSITY AND FLOW RATES

		Density kg/m³		
		5	7	10
Orifice Size, m	Flow liter/sec	Pressure Drop Across Orifice kN/m³		
1.2×10^{-2}	1	0.07	0.09	0.13
	2	0.26	0.37	0.52
	3	0.59	0.83	1.18
	4	1.04	1.55	2.08
0.9×10^{-2}	1	0.24	0.34	0.48
	2	0.97	1.36	1.94
	3	2.18	3.05	4.36
	4	3.87	5.42	7.75
0.6×10^{-2}	1	1.29	1.80	2.57
	2	5.15	7.21	10.30
	3	11.59	16.22	23.20
	4	20.59	28.80	41.15

The pressure drop across an orifice is described by the equation (13);

$$P_1 - P_2 = \frac{8 \times \dot{Q}^2 \times \rho \left[1 - \frac{d_1^4}{d_0^4}\right]}{\pi^2 \times d_1^4 \times Cd^2}$$

Where $\dot{Q}$ is the flow rate, d_0 is the tube diameter, d_1 the entrance diameter of the orifice, ρ the gas density, and Cd the coefficient of discharge of the orifice.

Table 2 shows calculated pressure drop across three sizes of orifice for a range of values of density and flow. These values have been calculated for smooth entry orifice as shown in Fig. 1 *C*, this being the shape of entry with minimum energy loss for any orifice size. It seems unlikely that the vocal cords represent a sharp-edged orifice, although the precise shape is unknown.

The relationship between the pressure drops given here and those for any other shape of orifice with the same ideal flow and diameter characteristics is in the ratio of the square of the coefficients of discharge. For the extreme case of an orifice of the shape of that in Fig. 1 *B*, the pressures given in Table 2 would be increased by a factor of 2.67. From these estimates it can be seen that the pressure drop across the vocal cords exceeds 3 kN/m^2 [the pressure drop at which Gibson et al. (5) demonstrated dynamic narrowing of the extrathoracic airways] at relatively low flows at gas densities above about 7 kg/m^3. The size of the orifice remains unknown and changes with lung volume and gas flow rate, but the values used in Table 2 cover the range of openings likely to occur during a maximum inspiration. It is therefore possible that the pressure immediately downstream of the vocal cords drops far enough below extratracheal pressure to allow dynamic compression of the trachea.

EXPERIMENTAL EVIDENCE

We have some preliminary experimental evidence that inspiratory flow limitation does occur during dense gas breathing. Maximum inspiratory flow volume (MIFV) curves have been recorded on 4 divers taking part in a simulated dive at the National Hyperbaric Centre, Aberdeen. The maximum depth of the dive was 300 m, pressure 31 bar. MIFV curves were recorded at sea level before the dive and at three depths during the dive. Flow was recorded using a pneumotachograph and the flow signal was integrated to give a volume signal. Compression was achieved by adding an oxygen-helium mixture to 1 bar of air, which was already in the chamber when the doors were closed. Thus, at the beginning of the dive the chamber contained 0.79 bar nitrogen which was then gradually reduced as the dive proceeded and no more nitrogen was added. We have therefore allowed for this nitrogen during Day 1, at 31 bar, in our calculations of the gas density, which was 5.9 kg/m^3. The environmental gas on the day when MIFV curves were recorded at 270 m contained an unknown amount of nitrogen and we can only estimate gas density to be between 5.0 and 5.4 kg/m^3 during those recordings. Our concern with the nitrogen level is only with regard to gas density because it is not sufficient to have any effect on HPNS.

Three of the 4 divers showed a sudden reduction of flow at the mouth during the course of the maximum inspirations at depth. Figure 2 shows curves for 2 divers. The curves have been superimposed to the same maximum volume for all depths because vital capacity is known not to change greatly with depth (14). The point of sudden flow reduction is marked on each curve. The curves chosen illustrate several points that were noted in the course of the measurements. The sudden reduction in flow was not seen in all breaths in any one diver at one depth, it did not always occur at the same lung volume in any one diver, although in diver A (Fig. 2) the reduction in flow did happen at the same lung volume and this diver showed some evidence of a reduction in flow at sea level. In all divers who showed reduction in flow at depth the reduction in flow became less marked as the pressure decreased.

DISCUSSION

This evidence of transient flow reduction has implications for the selection of divers for deeper dives. The theory predicts that the higher the gas density the lower the

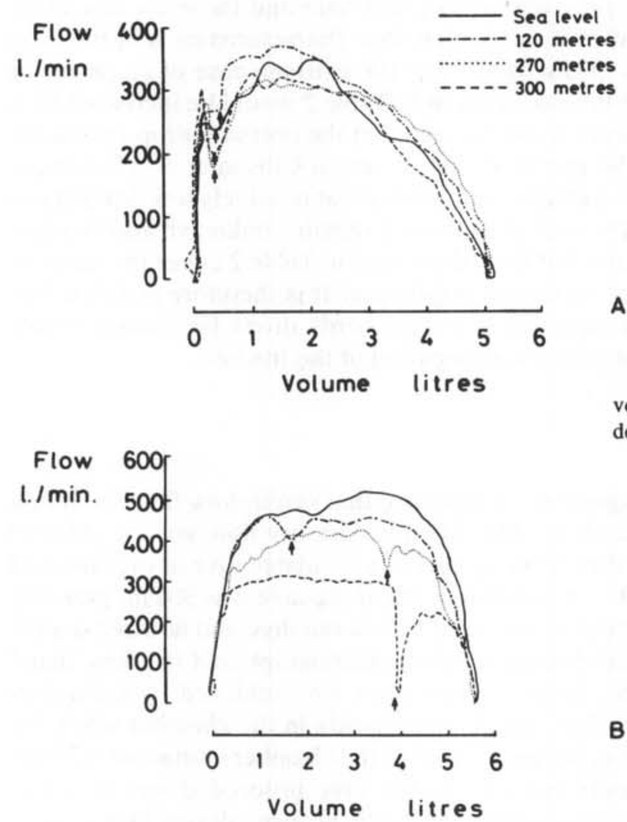

Fig. 2. Maximum inspiratory flow-volume curves as recorded for 2 divers at depth and at sea level.

flow rate at which transient tracheal narrowing may occur. From the evidence of 1 diver it may be possible to predict tracheal narrowing at depth from sea-level measurements, in that a diver who shows signs of flow reduction at sea level is more likely to show it to a greater extent at depth than one who does not show it at sea level.

One aspect of the individual variability of inspiratory flow limitation is the pressure differential that the tracheal wall can stand before narrowing occurs. A diver who shows evidence of flow limitation at sea level may be experiencing airway narrowing at lower transmural pressures than one who does not show it at sea level. The effect of HPNS on the orifice size is an additional factor that may vary with the susceptibility of the individual.

It should, in theory, be possible to prevent flow restriction by providing breathing gas at a pressure above environmental pressure and so splinting the trachea. It is difficult to estimate at this stage the pressures required to splint the trachea. A simplistic approach would suggest that the breathing gas pressure should exceed environmental pressure by the estimated pressure drops given in Table 2, some of which are perhaps higher than it would be possible to produce in breathing apparatus. We do not know with any certainty the size of the glottis opening at any moment during inspiration, although it seems likely that during maximum inspiratory effort the opening will be maximum and therefore the pressure required to splint the airway would be less than those given for the largest orifice in Table 2. Preliminary experiments using excised trachea indicate that under these conditions, i.e., without the support of the surrounding tissues, the airway can be splinted by pressures less than approximately 1 kN/m^2. This raises the possibility that breathing apparatus could be designed to reduce inspiratory flow limitation.

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