PEAK AIRWAY PRESSURE DURING HIGH FREQUENCY JET VENTILATION: THEORY AND MEASUREMENT

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During high frequency jet ventilation, accurate measurement of arterial carbon dioxide tension using end-tidal carbon dioxide concentrations is not possible because of the small tidal volumes delivered [1] and the slow response of carbon dioxide analysers [2]. Interrupting jet ventilation with a "conventional" positive pressure breath overcomes this problem, but requires a second ventilator [3, 4]. If the jet ventilator is designed to deliver intermittent deep breaths using a high driving pressure and long inspiratory and expiratory times, the need for a second ventilator is removed [5]. The volume delivered to the lungs during a prolonged breath delivered by a jet depends on respiratory system compliance, jet geometry, jet driving pressure and the duration of inspiratory time. If inspiration is sufficiently long, equilibrium is reached where the flow of gas leaving the jet is the same as the flow leaving the breathing circuit. At this equilibrium, the pressure within the airways balances the pressure generated by the jet and there is no net movement of gas into or out of the lungs. We term this condition "stalled flow" and the airway pressure at which it occurs the "stalling pressure". Thus, during those jet breaths which are large and slow enough to produce a good end-tidal carbon dioxide estimation, the jet ventilator acts as a pressure generator.

The same situation occurs in circumstances other than high frequency jet ventilation. A Sanders [6] injector system used during rigid bronchoscopy acts as a pressure generator. Air entrainment (fixed performance) masks stall and cease to entrain if the pressure downstream from the jet approaches the stalling pressure [7, 8]. Anaesthetic equipment which relies on entrainment ceases to function correctly as the back pressure increases [9].

We have investigated the interrelationships of injector size, airway size and jet velocity on the stalling pressure in a simple blocked tube model and a model which simulates the use of a purpose-made tracheal tube for jet ventilation. We have produced also a mathematical model based on fluid dynamic theory which allows accurate prediction of stalling pressure and we have compared the results of a published study with those predicted by our equations.

SUMMARY

A mathematical model has been developed to predict the peak airway pressure attainable during jet ventilation. The theory assumes inviscid and incompressible flow and agrees closely with experimental results using bench models of simple jet systems and systems using a tracheal tube designed for jet ventilation. The results of a previous published study also show good agreement with the predicted results.

MATERIALS AND METHODS

Theoretical Analysis

We have modelled jet entrainment using the classical application of Newton’s second law of motion to a homogeneous fluid [10, 11]. Figure 1 depicts our assumptions. A stationary open control volume is defined which extends from the point of entry of the gas jet into the entrainment duct to some section downstream from the jet approaches the stalling pressure [7, 8]. Anaesthetic equipment which relies on

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Let the velocity of entrained gas at this section be uniform, of magnitude \( U_1 \) and issuing from an area \( A_1 - a \) with a density \( \rho_1 \). We consider the general case depicted in figure 1. An abrupt change of cross section takes the area from \( A_1 \) at the point of entry of the jet to a greater area \( A_2 \) downstream from this point. Steady flow is assumed throughout.

We assume that pressures across the inflow and outflow sections of the control volume are uniform and denote them \( P_1 \) and \( P_2 \). Assuming further that frictional shear forces at the flow boundary are insignificant in comparison with pressure forces in the direction of flow (i.e. flow is inviscid), the equation of motion (force = rate of change of momentum) may be described:

\[
(P_1 - P_2) A_2 = \rho_2 U_2^2 A_2 - \rho_0 U_0^2 a - \rho_1 U_1^2 (A_1 - a)
\]

(1)

where \( \rho_2 \) is the density of gas at the downstream section. This form of the law of motion is sometimes termed the momentum equation.

Continuity of mass flow is required:

\[
\rho_0 U_0 a + \rho_1 U_1 (A_1 - a) = \rho_2 U_2 A_2
\]

(2)

As Mach numbers in the control volume are likely to be low and pressures vary only by a few percent, the flow may be regarded as incompressible, giving continuity of volume flow:

\[
U_0 a + U_1 (A_1 - a) = U_2 A_2
\]

(3)

Finally, we refer \( P_1 \) to atmospheric pressure \( P_{\text{atm}} \) by the use of Bernoulli's equation for steady flow in an inviscid incompressible fluid (loss of pressure energy = gain of kinetic energy). Assuming that the entrained gas flows unimpeded from a static reservoir at pressure \( P_{\text{atm}} \), we get

\[
P_{\text{atm}} - P_1 = \frac{\rho_1 U_1^2}{2}
\]

(4)

Equations (1)–(4) represent a complete model of one-dimensional entrainment flow. For the specific case \( A_1 = A_2 \) the model has been shown previously [7] to predict the performance of oxygen entrainment masks [12] and the effects of back pressure on an anaesthetic machine which was designed for use in the Antarctic [9].

In this paper we consider the specific case of stalling of the device. We define stalling here as the condition of zero flow from the entrainment duct (\( U_2 = 0 \)). In this case, all gas entering via the jet leaves via the duct through which it is normally entrained. The solution for equations (1)–(4) in this case is:

\[
P_2 - P_{\text{atm}} = \rho_0 U_0^2 \left[ \frac{a}{A_1 - a} \right] \left[ \frac{A_1}{A_2} - \frac{a}{2(A_1 - a)} \right]
\]

(5)

For one group of experiments reported here, the entrainment duct had a constant diameter along its length (\( A_1 = A_2 = A \)). For this situation, equation (5) reduces to the form:

\[
P_2 - P_{\text{atm}} = \rho_0 U_0^2 \left[ \frac{a}{A - a} \right] \left[ \frac{2A - 3a}{2(A - a)} \right]
\]

(6)

Experimental Methods

Simple injector system (fig. 2).

Three 1-m lengths of plastic tubing, with internal diameters of 9.5, 19 and 25.4 mm were used. Each was suspended vertically, and the bottom end sealed with a rubber bung. A plastic
Fig. 2. Schematic diagram of the apparatus used. A high pressure oxygen supply was passed through a regulator and control valve to the jet. The driving pressure was measured with a solid state transducer. The stalling pressure was measured at the end of the outer tube and recorded on a strip chart recorder. The reservoir helped to stabilize the driving pressure.

Fig. 3. Diagram of the end of an 8-mm "Hi-Lo-Jet" tracheal tube, showing the termination of the jet and sample lumens and the cross section of the lumens. The cuff lumen is omitted on the lateral view for clarity.

tube passed through the bung to a Gould T150 AD pressure transducer. The pressure was displayed on a Lectromed strip chart recorder. The transducer had been calibrated previously against a mercury column.

Two i.v. cannulae (Venflon 17- and 14-gauge) were used as injectors, with internal diameters of 1.0 and 1.5 mm. The tips of the injectors were 3.5 cm inside the outer tube in the mid line. The injectors were fed with 100 % oxygen. The driving pressure was controlled with a Norgren pressure regulator and stabilized with a 22-litre reservoir. A solenoid valve was used for on/off control. Driving pressure 2 cm upstream from the hub of the cannula was measured using a National Semiconductor LX16OD pressure transducer calibrated against a Bourdon gauge. The flow through the jet was measured by sealing the jet into the inlet of a 1-m length of hose connected to a Parkinson-Cowan dry gas meter. The time for one revolution (25 litre) was timed by a small microprocessor and the flow calculated. Figure 2 shows the experimental apparatus.

Tests using a "Hi-Lo-Jet" tracheal tube (fig. 3).

Three 1-m lengths of tubing were taken as in the previous experiments. For these experiments we used a Hi-Lo-Jet tracheal tube of 8 mm nominal internal diameter (i.d.) with a proximal (jet) lumen of cross sectional area 8.05 mm² and a distal (monitoring) lumen of cross sectional area 1.77 mm². The main lumen had a cross sectional area of 50 mm². This tube was inserted in the top of the 19- and 25-mm tubes and the cuff inflated. In the case of the 9.5-mm tube, the tracheal tube was connected to the top of the tube with a sleeve.
The top of the 9.5-mm tube had been bevelled to abut on the end of the tracheal tube. Two sets of tests were undertaken, using the proximal (jet) lumen as the jet injector, and using the distal (monitoring) lumen as an injector. Stalling pressure was measured again with a Gould transducer, and driving pressure with the National Semiconductor transducer. Jet flow was measured by inflating the cuff of the tracheal tube in the hose leading to the dry gas meter. The top of the tracheal tube was closed with a bung during measurement of jet flow, to prevent entrainment.

In both sets of experiments, measurements were performed at 35–175 kPa driving pressure at 35-kPa intervals. The internal diameters of the tubes were measured with vernier calipers, except the distal lumen of the tracheal tube and the lumens of the cannulae used for injectors, which were measured with probes of a known diameter. The main and proximal lumens of the tracheal tube are not circular in cross section, so the cross-sectional areas were calculated using simple geometry. The arrangement of the proximal and distal lumens of the tracheal tube are shown in figure 3. The density of oxygen was taken as 1.337 kg m⁻³ at a temperature of 15 °C. No correction was made for ambient pressure.

For the experiment using a tube of uniform bore and in the comparison with the work of Baer [13], a theoretical stalling pressure was calculated according to equation (6). For the experiments using a tracheal tube, a theoretical stalling pressure was calculated according to equation (5) or (6) to assess which of the two equations best represented the experimental situation.
The results are presented as stalling pressure–jet velocity graphs, as it is velocity that appears in the equation. In some circumstances, but not all, velocity is proportional to driving pressure [Young, unpublished observations].

RESULTS

Simple injector system

Figure 4 shows the stalling pressure plotted against the gas velocity out of the jet, for 1- and 1.5-mm i.d. jets. Each graph shows the measured and calculated stalling pressure for each of the three outer tube sizes. The calculations were performed using the equation describing an unstepped system (equation (6)). As can be seen, there is close agreement between the observed and expected results.

System using the jet tracheal tube

Figure 5 shows the observed and calculated stalling pressures obtained using the jet tracheal tube and the proximal (jet) lumen as the injector port. The calculated results are shown for both the stepped and unstepped equations. The measured pressures agreed with those calculated for the unstepped model (equation (5), \( A = 50 \text{ mm}^2 \)), but not with those for the stepped model (equation (6)).

Figure 6 shows the results of the experiments using the distal (monitoring) lumen of the tracheal tube as an injector port. Again, the measured result and the calculated result using both equations are shown; the measured pressures agreed better with the stepped model. This agreement was least precise when the 19- and 25-mm outer tubes were used. There is a very large discrepancy between the calculated values using the unstepped equations and the measured values.

Comparison with previous data

In figure 7 the values of stalling pressure for central and lateral jets for tracheal models of varying cross sectional area are shown for both the calculated values and the experimental values found by Baer [13]. The experimental data are the means of values observed for each tracheal cross sectional area. There is good agreement between the observed and expected results.
DISCUSSION

We have found it necessary to derive two sets of equations to describe a jet exiting into a tube of fixed bore and into a tube with a step change in bore at the point where the jet exits. The former situation corresponds to a jet positioned directly in the trachea or proximally within a tracheal tube, whilst the latter describes a jet leaving a tracheal tube at its tip.

In the case of a simple, unstepped injector system, with the jet entering a duct of constant cross sectional area, equation (6) should predict the stalling pressure. For the two different sizes of injector the predicted and experimental plots virtually coincide. In all cases except the 9.5-mm i.d. tube with the lowest jet velocity and the 1-mm injector, there is excellent agreement. The difference between observed and expected values at this point may be the result of a 1–2 cm H₂O pressure decrease produced by back flow up the tracheal tube.

When a jet tracheal tube is used with the proximal (jet) lumen utilized for the jet, there is good agreement between the measured values and those predicted using equation (6), the unstepped model, but not equation (5), the stepped model. These findings may be explained by the geometry of the jet tracheal tube (fig. 3). The proximal (jet) lumen terminates 7 cm from the tip of the tube, so the system behaves as an unstepped system with an outer tube bore the same as the tracheal tube bore; the increase in bore is sufficiently far downstream from the jet to have little or no effect on the stalling pressure.

A different situation occurs if the distal (monitoring) lumen is used as the jet lumen. This port terminates 1.7 cm from the tip of the tube. Here a stepped system (equation (5)) best predicted the stalling pressure. There was a difference between the predicted and measured values which decreased as the bore of the outer tube decreased. These findings may be explained if the situation is considered as transitional between stepped and unstepped. As the bore of the tracheal tube and the outer tube approach the same value (i.e. as the outer tube bore diminishes), the error decreases because the predicted values of stalling pressure for each system become identical.

To test our hypothesis further we applied our equations to the data of Baer [13] using an unstepped model. Baer had taken a series of different tracheal models of different shape and four cross sectional areas, and measured peak pressures using centrally and laterally placed jets. Although he had not left the jet open, but had ventilated the model, the low resistance (quoted as zero) and low compliance (20 ml kPa⁻¹) of the lung model used and the slow rate (24 b.p.m. with an I:E ratio of 1:1) at which the model was ventilated, suggested that the jet probably reached a stalled state on every breath. There is generally good agreement, although the mean values for the lateral jets are closer to the predicted values than those for central jets. This is the reverse of the expected difference: the lateral jets would be expected to have a lower mean velocity as the boundary layer at the tracheal wall would be stationary. However, Baer measured the airway pressures at 15 cm distal to the jet and may have included some element of dynamic (velocity) pressure in his measurements arising from the high velocity jet. This would account for the differences between observed and expected results.

In summary, we have derived a mathematical model of inviscid, incompressible flow to predict the pressure generated by a jet of gas entering a duct closed at one end and confirmed the theory with experiments related to jet ventilation. A comparison of the theory with published experimental results showed good agreement.

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