POSITIVE-NEGATIVE PRESSURE VENTILATION WITH A MODIFIED AYRE'S T-PIECE

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It has been repeatedly demonstrated (1, 2) that alterations in circulatory dynamics due to increase in mean airway pressure are harmful in some circumstances (for example, hypovolemia). Ventilation produced by intermittent positive pressure (IPP) results in increased mean airway pressure. This may be reduced by the addition of a negative (relative to ambient) phase between each positive phase. The insertion of this negative phase has been shown to lessen the undesirable circulatory effects of IPP ventilation (1, 2, 3).

One of the problems associated with conventional anesthetic systems (that is, circle, to-and-fro) is the inability to perform manually controlled or assisted ventilation without raising mean airway pressure. The following are observations made using a simple, compact, inexpensive device which will develop a controllable degree of negative pressure and may be used to produce a negative phase in ventilation in all conventional systems. A small metal tube (needle) bent 90 degrees is placed in an Ayre's T-piece (4) so as to be the only passageway between stem and bar (fig. 1). Gases flowing through the needle as they exit at point (C) entrain gas in the larger surrounding tube (bar) and create a negative pressure in the portion behind the jet of exiting gases (area D). This effect is based on the Bernoulli principle which states that the velocity of a gas through a tube is inversely re-

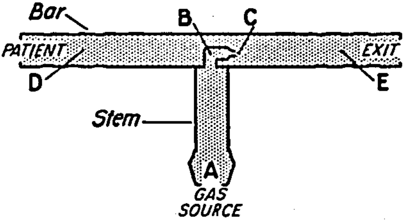

Fig. 1. A diagrammatic cross sectional representation of the Bernoulli T tube. Gas is delivered through (A). (B) is the area of 90 degree bend in the needle. (C) is the area of gas exit from the needle. (D) is the limb to be attached to the patient and is the area of negative pressure. (E) is the limb connected to circle or to-and-fro system.

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lated to the pressure of that gas against the side of that tube. We have named tubes so constructed Bernoulli T (BT) tubes.

Several BT tubes have been made, the construction varying in the cross-sectional area of the bar and in the cross sectional area of the needle at its exit point (C, fig. 1). A large bore needle (15 or 17 gauge) has been used to diminish the effect of resistance caused by constriction of the cross sectional area at the bend. A major constriction occurs then only at the end of the needle so that the gases flow for a minimum distance through a sharply constricted portion.

METHODS

The BT tubes were tested in the following manner. To determine the actual rate of flow through the needle, varying rates of gas flow of a mixture of nitrous oxide and oxygen were directed through the needle and measured after their exit with a dry gas meter. This measurement was necessary because of the inaccuracy of rotameters proximal to the stem when the pressure in this area rose due to the resistance of the needle. The error was always in the nature of a lower rotameter reading than actual gas flow. However, the rotameters were roughly (within 20 per cent in the clinically useful ranges) accurate if they were set at a desired flow prior to connecting the BT tube to the delivery tube. If the rotameters were preset, the rotameter readings dropped after connecting the BT tube, even though the actual gas flow remained relatively constant. However, the ratio of one gas to another in the mixture being forced through the BT tubes did not necessarily remain constant. The rotameters appeared to represent the true ratio of one gas to another, both before and after the addition of the BT tube. For example, a machine was set to deliver nitrous oxide at 4 l./minute and oxygen at 1½ l./minute, thus indicating 27.3 per cent oxygen in the mixture. A Pauling type oxygen meter sampling this mixture read 27.0 per cent oxygen. A BT tube was then connected to the gas source. The rotameters then decreased to 3.0 and 1.05 l./minute of nitrous oxide and oxygen, respectively. The concentration of oxygen leaving the BT tube measured 25.5 per cent compared to the 25.9 per cent calculated from the rotameter readings. The actual flow rate of gases after the addition of the BT tube was 5 l./minute as compared with the preset figure of 5.5 l./minute. After the flow rate at (E) in figure 1 had been measured (area D being blocked off), and the pressure at (A) for that particular rate and gas mixture had been determined on a mercury manometer, the amount of negative pressure generated at point (D) was measured with a water manometer. The rate at which gas was entrained was determined by connecting the negative limb of the BT tube to a dry gas meter.

Using the various BT tubes in a circle system (see fig. 2), the pressures developed in the endotracheal tubes of anesthetized patients were

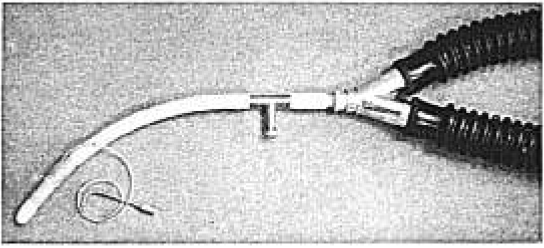

FIG. 2. The BT tube as it would be positioned for use in the circle system. Gases are delivered through the limb of the BT tube which appears free or open in the above picture.

determined with varying flow rates through the BT tubes. Anesthetic gases were delivered to the circle system through the BT tube rather than through the usual gas inlet on the circle. The latter was closed off to prevent the escape of anesthetic gases while the BT tube was in use. A pressure limited ventilator was used to provide a consistent source of intermittent positive pressure. For all measurements, the ventilator was set to produce a pressure of 20 cm. water positive pressure for inspiration, and zero pressure for expiration. The phasing was adjusted to allow an expiratory period approximately twice as long as inspiration. The rate was 15 cycles per minute. Endotracheal airway pressures were monitored using a Statham strain gauge and recorded on a direct writing oscillograph. Patients were made apneic with narcotic-barbiturate-curare-nitrous oxide-oxygen anesthesia before recording was begun.

RESULTS

The figures obtained from testing the BT tube alone are given in tables 1 and 2. From them it can be seen that the negative pressure attained is a function of three factors. First, it is an exponential function of the velocity of the gas exiting from the needle and this, in turn, is a direct function of the quantity of gas flowing per unit time and an inverse function of the cross sectional area of that needle. Secondly, the negative pressure varies directly with the density of the gas forced through the needle. This is shown in table 2 where the data indicate that although total gas flow remains the same, an increase in the percentage of nitrous oxide (density 1.88 g./l.) in a nitrous oxide-oxygen mixture (oxygen density 1.43 g./l.) results in increases in the negative pressure of as much as 22 per cent. (The results shown in table 1 were obtained with percentages of nitrous oxide varying from approximately 60–75 per cent, the remainder being oxygen.) Thirdly, the negative pressure appears to vary inversely with the cross-sectional area of the tube (the bar) surrounding the needle (see table 1).

TABLE 1

Physical Characteristics of 6 Bernoulli T Tubes

BT Numbers	Cross Sectional Area of Bar in Sq. Mm. (D) or (E) in Figure 1	Cross Sectional Area of Needle in Sq. Mm. at (C) in Figure 1	Liters Per Minute Flow Through Needle (B) in Figure 1	Centimeters Water Negative Pressure at (D) in Figure 1	Pressure at Point (A) in Figure 1 in Cm. of Mercury
1	33.3	1.09	1	0.0	0.1
1	33.3	1.09	3	2.2	2.3
1	33.3	1.09	5	4.1	5.5
1	33.3	1.09	7	7.0	10.8
1	33.3	1.09	10	14.6	24.2
2	33.3	0.59	1	0.1	1.1
2	33.3	0.59	3	2.2	9.6
2	33.3	0.59	5	6.0	21.0
2	33.3	0.59	7	10.6	33.5
2	33.3	0.59	10	20.6	70.0
3	33.3	0.32	1	0.2	1.6
3	33.3	0.32	3	3.8	17.6
3	33.3	0.32	5	10.0	50.0
3	33.3	0.32	7	16.7	93.0
3	33.3	0.32	10	27.2	156.0
4	17.3	0.79	1	0.1	1.0
4	17.3	0.79	3	3.5	5.4
4	17.3	0.79	5	8.7	13.6
4	17.3	0.79	7	16.4	25.8
4	17.3	0.79	10	29.5	55.0
5	17.3	0.39	1	0.3	1.2
5	17.3	0.39	3	4.6	12.2
5	17.3	0.39	5	12.3	30.4
5	17.3	0.39	7	22.6	50.4
5	17.3	0.39	10	42.0	90.0
6	17.3	0.26	1	0.8	3.4
6	17.3	0.26	3	9.0	29.5
6	17.3	0.26	5	19.4	69.0
6	17.3	0.26	7	32.8	125.5
6	17.3	0.26	8.4	40.0	158.0

The measurements were made using nitrous oxide-oxygen mixtures at room temperature with constant flow rates through the respective needles for each determination.

Data were obtained with the BT tube in a circle system under clinical conditions as described earlier. Figure 3 (A) represents control endotracheal pressures obtained with the ventilator (at + 20 cm. of water and at zero water pressure) providing the only source of ventilation. Figure 3 (B) shows the effect of the addition of BT tube 1 with gas flow through the needle at 5 l./minute and then in (C), at 10 l./minute. Similarly, (D) and (E) are representative of the endotracheal pressure tracings obtained using BT tube 3 with gas flows of 5 and 10 l./minute, respectively, through the needle. In figure 4, (F) is a control and (G) and (H) demonstrate the effect of BT tube 6 with gas glows

TABLE 2

EFFECT OF VARYING CONSTITUTION OF NITROUS OXIDE–OXYGEN MIXTURES FLOWING THROUGH THE NEEDLE OF THE BERNOULLI T TUBES ON NEGATIVE PRESSURE DEVELOPED AT POINT (D) IN FIGURE 1

Cross Sectional Area of Bar in Sq. Mm. (D) or (E) in Figure 1	Cross Sectional Area of Needle in Sq. Mm. (C) in Figure 1	Liters Per Minute Flow Through Needle (B) in Figure 1	Percentage of Nitrous Oxide Introduced at (A) in Figure 1	Centimeters Water Negative Pressure at (E) in Figure 1
33.3	0.56	10	48	20.0
33.3	0.56	10	75	20.6
33.3	0.56	10	100	21.0
33.3	0.39	5	0	6.8
33.3	0.39	5	50	7.3
33.3	0.39	5	79	7.5
33.3	0.39	5	100	8.2
17.3	0.79	5	12	7.6
17.3	0.79	5	34	7.6
17.3	0.79	5	67	8.6
17.3	0.79	5	100	8.9

through the needle of 3 and 5 l./minute, respectively. The negative pressures obtained in the airway approximate those obtained under static conditions (table 1) and appear to approximate a square wave in shape. It would appear from the tracings that the amount of positive pressure necessary to overcome the force of the jet from the needle numerically equals the negative pressure obtained at that particular flow rate from the needle. Thus, both the base line and the highest point in the graph move a similar amount in response to the addition of a BT tube. This amount is comparable to the amount of negative pressure shown to be developed by that particular BT tube at that particular flow rate through the needle.

This apparatus may be used satisfactorily without a mechanical ventilator. Figure 5 illustrates the effect of BT tube 3 at 5 l./minute on endotracheal pressures obtained during manually controlled ven-

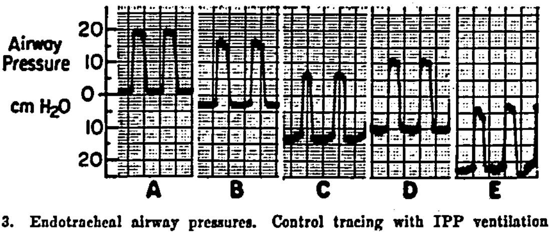

FIG. 3. Endotracheal airway pressures. Control tracing with IPP ventilation secured with a pressure limited ventilator set at + 20–0 cm. water with 15 cycles per minute (A). BT tube 1 in place with flow rates through the needle of 5 and 10 l./minute, respectively, (B) and (C). BT tube 3 in place with flow rates of 5 and 10, respectively, (D) and (E).

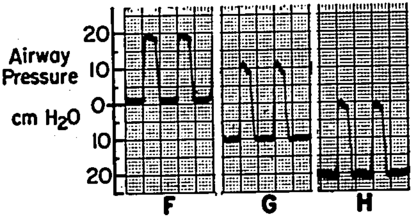

FIG. 4. Endotracheal airway pressures. (F) is the control tracing as in figure 3 (A). (G) and (H) show the effect of BT tube 6 at 3 and 5 l./minute, respectively.

tilation; the first portion represents airway pressures developed with controlled ventilation in a conventional circle system. The BT tube is added at the arrow.

Although this apparatus was designed for use with assisted or controlled ventilation, if the bar of the tube is large enough in cross sectional area, it does not impose an appreciable resistance to spontaneous ventilation if left in place *without* gas flow through the needle. Figure 6 (K) represents endotracheal pressures generated by the patient while breathing through the circle alone, (J) through the circle plus BT tube 2, and (I) through the circle plus BT tube 6. Although no evaluation of adequacy of respiration was made, it appears that the resistance of BT tube 6 as indicated by the airway pressure developed during spontaneous respiration is prohibitive, but that the resistance of BT tube 2 is not greatly different from that of the circle alone.

DISCUSSION

Clinically, the BT tube can be used to develop a fairly predictable negative phase in ventilation in which flow rates of anesthetic gases of three or more liters per minute are delivered. The BT tube is con-

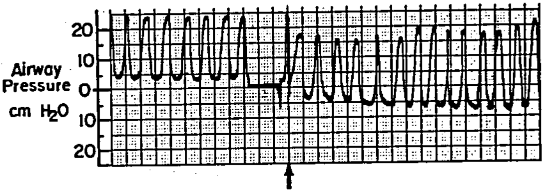

FIG. 5. The area preceding the arrow portrays the endotracheal airway pressures during manual controlled ventilation using a circle system; the area following the arrow represents manual controlled ventilation using a circle system with the addition of BT tube 3 at 5 l./minute through the needle.

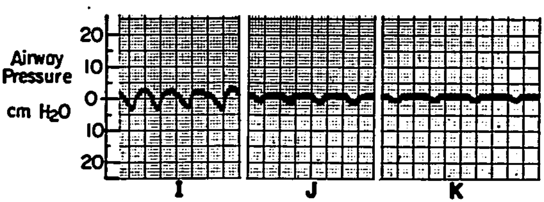

Fig. 6. Endotracheal airway pressure tracings. (I) patient spontaneously breathing through BT tube 6. (Cross sectional area slightly less than 17.3 sq. mm.) (J) patient breathing spontaneously through BT tube 3 (cross sectional area slightly less than 33.3 sq. mm.). (K) patient breathing spontaneously through the endotracheal tube alone (cross sectional area around 50 sq. mm.).

nected at its negative end to the end of a cuffed endotracheal tube. The other end of the BT tube is connected to a circle system (fig. 2) or to a to-and-fro system. The anesthetic gases are then delivered through the stem of the BT tube to produce the desired negative pressure and to supply anesthetic gases to the system. The usual inlet for gas is closed off to prevent the loss of the anesthetic gases. If it is desired to use the BT tube by itself, then respiration can be controlled by intermittent occlusion of the exit end of the tube, the other end being connected as above to the endotracheal catheter. The last method requires the delivery of higher flow rates in order to provide adequate inflationary volumes in a short period of time. However, the higher the flow rate through the needle of any particular BT tube, the greater the negative pressure developed. If the negative pressure becomes unduly high, it may be corrected by using a BT tube with a needle or bar of adequately increased cross-sectional area.

In no case should the patient be allowed to spontaneously ventilate while any BT tube is *functioning* because the negative pressure produced imposes an increase in resistance to the more active portion (inspiration) of respiration and may mildly or markedly increase the work of ventilation. In depressed or weakened patients, this resistance may make adequate spontaneous ventilation impossible.

It is important to carefully observe rotameter readings with the addition of a BT tube. First, they must fall at least 20–30 per cent from the readings taken before the addition. If this fall does not occur, then there are probably leaks in the system proximal to the BT tube, and the desired negative pressure will not be attained. Secondly, if after the addition of the BT tube the oxygen rotameter reading falls more than that of the nitrous oxide rotameter reading, so that the oxygen reading becomes less than 20–25 per cent of the snm, then the oxygen rotameter must be raised or the nitrous oxide rotameter lowered in order to maintain adequate oxygen tension.

SUMMARY

A device is presented which incorporates Bernoulli's principle into Ayre's T-piece so as to permit the development of negative pressure at one limb of the T when gases are driven through the stem. It is simple, compact, and inexpensive to make and operate. We have named this tube a Bernoulli T tube.

The simple physics of this device are presented and discussed. The negative pressure developed is a direct function of the jet velocity and of the density of the gas in the jet. It is an inverse function of the area surrounding the jet. Negative pressures of up to — 42 cm. of water are easily developed. Lesser pressures (— 5 to — 15 cm. water) are developed with greater efficiency, requiring a jet flow of only 3-5 l./minute. The gases used to develop the negative pressure are the same gases used to maintain anesthesia.

Clinically, the Bernoulli T tube may be used in any of the conventional systems (circle, to-and-fro) to produce a controllable negative phase in controlled or assisted ventilation. Tracings of endotracheal pressure changes due to its effect show that its action is rapid and sustained so that a square wave graph is approximated in the negative phase. If an appropriate size Bernoulli T tube is chosen, when not functioning it offers little resistance to spontaneous respiration.

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