THE SCIENTIFIC ASPECT OF ENDOTRACHEAL TUBES

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Introduction

Endotracheal anesthesia probably had its inception by Andreas Vesalius (1) in 1543, who showed that the lethal effects of pneumothorax could be avoided through inflating the lungs by "blowing air in the trachea with a tube." Through long stages of interrupted development, in which small tubes were used with the insufflation method, there was no general acceptance of endotracheal anesthesia until the discovery of the circle filter and the absorbent technic. This comparatively recent method of administering anesthetic agents with tubes of a larger size than used with the insufflation method permits adequate gas movement in both directions, more closely resembling normal respiration.

In recent years endotracheal intubation has been accomplished more frequently and for a greater variety of reasons than ever before which, undoubtedly, means that the technic of inducing this method of anesthesia is generally improving and is providing safer and more satisfactory anesthesia, thus strengthening the specialty of anesthesiology. The average anesthesiologist uses endotracheal tubes as he deems necessary. His indications and contraindications are based upon his experience, training, and judgment. However, nothing has been written to direct one in choosing scientifically the tube size in any given situation in which anthropometric, pathologic and pharmacologic modifying factors are present. The smaller nasotracheal tubes are less likely to produce trauma and are easier to introduce than are larger tubes; however, it has been held that the diameter of a smaller endotracheal tube may not provide the patient with adequate gaseous exchange. Trauma from larger tubes has been pointed out in the literature. We are concerned here with this question: What is the smallest tube which will support adequate respiratory exchanges under *anesthetic conditions.*

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Certain physics of gas flow are presented to show why calculated data would not allow us to predict satisfactorily and so explain the necessity for an experimental approach.

In laminar, or streamlined, flow the paths of the molecules lie parallel to the direction of the tube whereas, in turbulent flow, the paths of the molecules cease to be parallel to the long axis of the tube and become random. Poisseuille's law † applies to laminar flow and differs from the formula describing turbulent flow. The criterion for indicating whether the flow through a tube is laminar or turbulent is the Reynold's number formula. If this number is less than 2000, the flow will be laminar; if it is above 2600, it will be turbulent; between 2000 and 2600 it may be either or a mixture. In laminar flow, viscosity, but not density is a factor, while, in turbulent flow, density but not

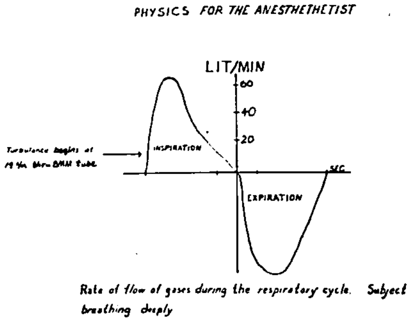

FIG. 1. Respiratory cycle of three seconds (2). In quiet breathing as would occur under anesthesia, the maximum flow would be about 25 liters per minute. The maximum amount of breathing is allowed for in our estimation of tube diameter. Since the inception of this work Dr. Leslie Silverman has shown that the maximum or instantaneous flow under various anesthetic agents has never been over 40 liters per minute. Turbulence begins at 14 liters a minute.

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† Formula for Turbulent Flow:

$$\text{Volume rate} = \text{Calibration factor}\sqrt{\frac{(\text{tube diameter})^5 \times (\text{pressure drop})}{(\text{tube length}) \times (\text{density of gas})}}$$

Formula for Poisseuille's Law:

$$\text{Volume rate} = \frac{3.14 \times (\text{pressure drop}) \times (\text{tube diameter})}{128 \times (\text{tube length}) \times (\text{viscosity of gas})}$$

Formula for Reynold's Number:

$$R = \frac{4 \times q}{3.14 \times d \times V}$$

where q = volume flow in cc./sec., d = diameter of tube in cm., V = viscosity (poise).

TABLE 1

FACTORS BY WHICH INITIAL PRESSURE MUST BE MULTIPLIED AS TUBE SIZE IS DECREASED FROM 10 MM.

Tube size mm.	With laminar flow	With turbulent flow	If flow is laminar part of the time and turbulent part of the time
10	1.000	1.000	1.0
9	1.524	1.694	1.6
8	2.441	3.052	2.7
7	4.165	5.950	5.0
6	7.716	12.860	10.3
5	16.000	32.000	24.0

In preparing this table (3), it was assumed that pressure required with a 10 mm. tube is unity. If the tube is decreased to 9 mm., the pressure required to pass the same amount of air or gas through the same length of tube will be between 1.5 and 1.7 times that required for the 10 mm. tube. From this table it will be seen that the effects of changing from an 8 mm. tube to a 7 mm. tube will be 4.16/2.44 = 1.70 for the "streamlined" flow and 5.95/3.05 = 1.95 for turbulent flow. Likewise, in changing from a 6 mm. tube to a 5 mm. tube it will be 16.00/7.72 = 2.07 for the "streamlined" and 32.00/12.86 = 2.49 for the turbulent flow. Thus, a millimeter difference in tube size is much more important in working with smaller tubes.

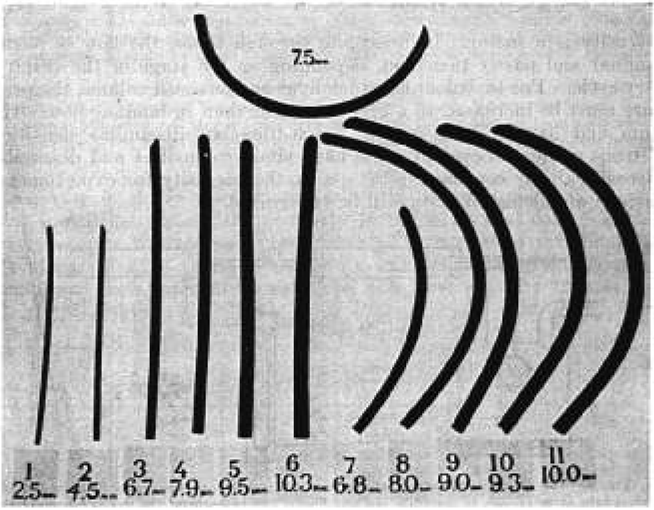

FIG. 2. The tubes here depicted are the same, with the exception of three which were mutilated, as those used to obtain our experimental data. On close examination of the tubes, the silver nitrate marking of the internal diameter can be seen. The internal diameter is below the tube number. The tube at top photograph is the choice of one of us (E. B. M.) as it is judged to supply adequate ventilation with a minimum of trauma.

TABLE 2

TABULATION OF THE PHYSICAL MEASUREMENTS OF THE TUBES SHOWN IN FIGURE 2 AND FROM WHICH OUR EXPERIMENTAL DATA WERE OBTAINED TO MAKE FIGURES 4 AND 5

Tube No.	Lumen Radius mm.	Length mm.	Cross Area mm.^{2}	Volume mm.^{3}	Circumference mm.	Total Inner Surface Area mm.^{2}
1 Woven	1.25	216	4.91	1,060	7.85	1,700
a straight	2.25	184	15.90	2,930	14.10	2,600
2 b curved*	2.25	184	15.90	2,930	14.10	2,600
c short	2.25	100	15.90	1,590	14.10	1,410
3 Woven Foregger 26	3.35	283	35.25	9,990	21.05	5,960
4 Woven Foregger 32	3.95	285	49.00	13,970	24.81	7,060
5 Woven Foregger 38	4.75	285	70.90	20,100	29.85	8,500
6 Woven Foregger 40	5.15	285	83.30	23,740	32.15	9,220
7 Rubber	3.40	215	36.30	7,800	21.36	4,590
8 Rubber Foregger 32	4.00	385	50.30	19,350	25.15	9,680
9 Rubber Foregger 35	4.50	390	63.60	24,800	28.28	11,050
10 Rubber Foregger 38	4.65	375	67.90	25,450	29.22	10,900
11 Rubber Foregger 40	5.00	375	78.60	2,947	31.4	11,800
12 Large Connell Airway	23×2.58	108	59.40	6,417	51.16	5,525

* Same tube, but bent at right angles as in throat. Radius of curvature—38 mm.

viscosity is a factor. In breathing through tubes, the flow is partly laminar and partly turbulent, depending on the stage of the respiratory cycle. For turbulent flow to deliver an increased volume, the pressure must be increased to a greater extent than in laminar flow. Helium and oxygen have similar viscosities but dissimilar densities. Nitrous oxide and cyclopropane have similar densities and dissimilar viscosities. By considering the above, the necessity for experimental, instead of calculated, data will be recognized.

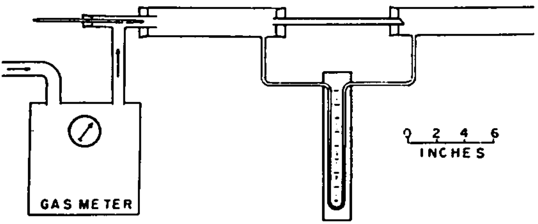

FIG. 3. The gas to be measured enters the meter and then passes over a thermometer into a glass tube large enough to maintain laminar flow. The pressure of the gas is measured just before it passes through the endotracheal catheter into a second large glass tube into which is connected the other side of the manometer. The pressure on the far side is essentially atmospheric. Another manometer, not shown, measures the pressure of the gas flowing into the meter. (We wish to acknowledge the courtesy of Mr. C. E. Martin of the Durham Gas Company of North Carolina through whose consideration these measurements were made possible.)

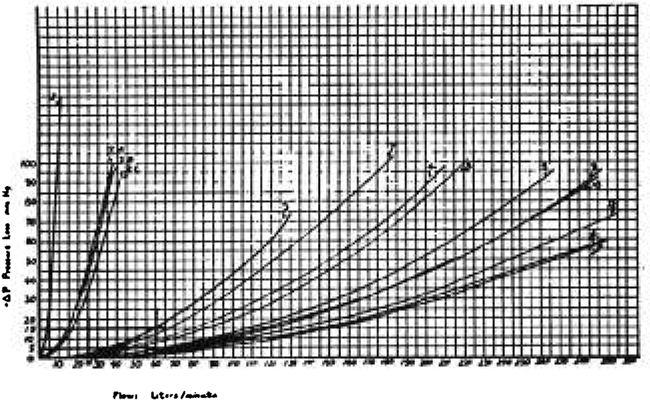

FIG. 4. Graph obtained by use of the apparatus diagrammed in Figure 3. Horizontal lines represent the pressure and vertical lines the flow rates. The lines indicating pressure of 5 and 15 mm. of mercury are heavy as are also the vertical lines indicating rates of flow of 25 liters per minute and 60 liters per minute. These intersections are important. The 5 mm. line represents a pressure which could be safely continuous, while the 15 mm. line represents a pressure which could be safely intermittent. The volume to be delivered is known from table 3.

All of the measurements were carried out at temperatures between 28 and 33 C. This simulates about the average temperature of the gas flows passing through the larynx, that is, the average temperature of the tidal air. The humidity of the air used for these measurements was between 30 and 35 per cent relative humidity instead of the average 90 per cent humidity in tidal air.

Figure 1 shows diagrammatically the intermittency of respiration and helps explain the necessity for experimental data. Table 1 demonstrates the necessity for increased pressure as turbulent flow develops. Figure 2 shows the tubes numbered as in the figures 4 and 5 and their internal diameters as noted below. The 7.5 mm. tube

TABLE 3*

Age, years	Rate (after Feer)	Tidal Volume (after Gregor) cc.	Computed Minute Volume, cc.	Weight, Kg.	Ventilation Volume per Kg., cc.
Birth	40–45	27	1080–1215	3.0	360–405
1	25	48–100	1200–2500	?	?
2	24	85–129	2040–3096	7.0	291–258
3–7	20	124–221	2480–4420	14.3–19.0	166–232
8–14	18	221–395	3978–7110	22–29	180–244
Adults	16	500	8000	70	144

From these anthropometric data approximate values in minute volume exchange can be found for certain ages and weights. In comparing these values with the delivery of gases (figs. 4 and 5) through the various size tubes, the size necessary can be estimated fairly accurately.

* Henry Laurens from Brennemann's Practice of Pediatrics (Chapter 38, Volume 2, Page 5)

was not used in the experiment. These tubes are Foreggers except for the 7.5 mm. tube which is a number 32 McKesson. The measurements of the tubes are listed in table 2 and correspond to those shown in figure 2.

METHOD

The means of obtaining the data for figures 4 and 5 are illustrated in figure 3.

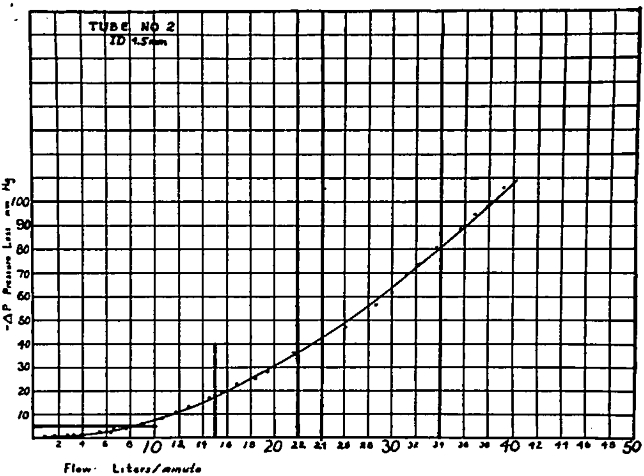

FIG. 5. Abscissa for the number 2 tube is shown in more detail than in figure 4. By referring to table 3 it can be seen that this size tube is adequate for respiratory exchange of the average child from 3 to 7 years of age with constant pressure maintained to 10 mm. of mercury.

RESULTS

The results obtained from the apparatus, as diagrammed in figure 3, are shown in figures 4 and 5 and the anthropometric data necessary for selection of a tube size to meet the requirement are listed in table 3.

DISCUSSION

Turbulent flow requires more pressure to deliver gas. As shown in the graphs, there is no abrupt change in the curves when it occurs. The transition must be smooth. The result of turbulent flow is shown in table 1. It is always noisy.

When additional pressure is required to supply the body needs, inspiration is prolonged and expiration becomes active, forceful and prolonged. This may slow the respiratory rate and increase the depth.

An interesting observation on figure 4 is that, although tube number 5 is slightly larger and considerably shorter than tube number 9, it takes 15 mm. more pressure to deliver 250 liters per minute. On examining the tubes the reason is apparent. The internal surface of tube number 5 is rougher, throwing the gas into turbulent flow more quickly than when tube number 9 is used. This is true of all similar tubes.

It is also interesting to note, in the medium-size tubes (6 to 8 mm. internal diameter), that the ratio of mm. in diameter to liter per minute is about 1 to 5.5 at 5 mm. pressure. A quick calculation is thus available. Length of tubes is a minor factor.

In the experimental data presented here, the gases have been considered to flow continuously but, actually, the flow is intermittent with the respiration. Although a patient breathes only a total of 8 liters a minute, at the peak of inspiration the flow rate is 25 liters a minute. In both instances, the flow is turbulent through a 7.5 mm. tube with a Reynold's number of 4000 and 10,000 respectively. From the experimental data (fig. 1), the necessity for increased pressure at the peaks of both types of breathing is shown. The exhalation valve on the Connell machine can be placed at 6 mm. of mercury and, as shown in figure 4, even with the number 3 tube of 6.7 mm. diameter, pressure of less than 5 mm. of mercury is needed to supply up to 35 liters a minute. In other gas machines, when the bag is moderately distended the pressure is approximately right. With tube number 3, the maximum flow that can be obtained under pressure of 15 mm. of mercury (which should only be applied during the inspiratory phase) is 60 liters a minute. This is considered adequate in resuscitating the apneic patient. Cournand and Collins (4), working at Bellevue on cardiac output during anesthesia, demonstrated that large amounts of pressure can be used, "up to 100 cm. of water even, and can be applied without harmful effects—provided that the pressure is exerted only for a short time and only during periods of inspiration and that the duration of expiration be longer and passive." H. L. Motley et al. (5) stated, "an endotracheal tube with an inflatable rubber cuff on the end definitely decreases the resistance to artificial respiration in the apneic subject." He also stated, in using respirators (passed by Council on Physical Medicine), "the regulator line pressure may be set much lower (for inspiration) with the endotracheal tube (10–15 cm. of water) and still maintain proper cycling."

We can consider these facts regarding the oxygen supply under anesthesia: (1) In most cases, when one is using 80 to 95 per cent oxygen, the oxygen content of the blood is raised at least 10 per cent as the nitrogen is displaced. (2) There is no muscular activity. (3) The metabolic rate is low owing to premedication and to the anesthetic. (4) Intubation decreases physiologic dead space by 50 cc. and mechanical dead space by 150 cc., which adds to the efficiency of respiration (6).

In order to carry out the recommendations as to tube size, made in this paper, it is necessary that the following be done: (1) All tubes should be labeled with the inside diameter; this can be done on all rubber tubes with a pen dipped in a 50 per cent solution of silver nitrate. (The outside diameter will be found to be 2 to 3 mm. larger.) One soon is able to recognize diameters at a glance. (2) The cuffs should not be inflated unless necessary. (They may constrict the tube and traumatize.) (3) By using table 3, the proper size for children can be easily estimated.

The practical clinical value of the knowledge contained herein occurred in cases such as these two: (1) a colleague was worried about tube size because of intermittent dyspnea in an intubated patient. When reassured on this point, further investigation showed the patient to have an attack of cardiac asthma. Treatment with aminophyllin and digitalis eliminated the condition. (2) Difficult inspiration occurred in another patient, a 9-year-old child, for whom an adequate tube size of 6 mm. was used. It was found that the expiratory valve of the machine was not closing and the gases were not circling. This was remedied immediately and there was no further difficulty.

SUMMARY

Intermittently, for the last year, we have been using a tube with an inside diameter of 7.5 mm., usually employing the nasotracheal technic. This tube is 0.8 mm. larger than tube number 3 (6.7 mm.). There has been no evidence of anoxia that could not be accounted for from other causes. We present these data with a reasonable assumption that this size tube is more than adequate and has a considerable margin of safety. It will not usually traumatize if ordinary care is practiced. We are not recommending the use of small tubes except as the facts of our studies indicate. Certainly, the size employed is modified by the nasotracheal route. By the visual oral technic, with a large glottic opening, nothing is to be gained by selecting a small tube. We do believe, however, that, when a tube is selected, we should know approximately how much gas it can deliver and how much pressure is necessary to deliver it. By study of the data here presented, this information is now available.

The tables, figures and graphs provide scientific means of selecting tubes applicable for use in anesthesia.

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