THE CLASSIFICATION AND PERFORMANCE OF RESPIRATORY VALVES

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Respiratory valves have been in use for over two centuries. Stephen Hales in his book, Vegetable Staticks, 1727, described a closed circuit respiratory apparatus which employed valves to effect unidirectional breathing,¹ and again in A Description of Ventilators, 1743, he also mentioned the use of leather respiratory valves for an open circuit apparatus. The idea of valves was apparently not new with Hales, because in the preface of the latter book he stated that he sent to London for a book from the library of the Royal Society printed in 1877 in which valves were discussed. Hales was also acquainted with the work of Robert Boyle who had used tight closing automatic valves in his pneumatical engine (1680) for studying the elastic properties of air.

Respiratory valves were employed by early workers in metabolism and anesthetic practice. A discussion of such use is contained in Tigerstedt's Handbuch der Physiologischen Methodik (1811). More recently a bibliography by Silverman lists references on valves up to 1943. In 1943 Silverman also published a comprehensive monograph on respiratory valves,² but because of wartime restrictions only 150 copies were printed. Kaye's paper on the respiratory valve has stimulated research on this subject by anesthetists and engineers.³

TERMINOLOGY

The following terms are used in connection with the design of valves:⁴

1. The valve body assembly is a housing with associated internal parts including a movable part which opens, shuts or partially obstructs one or more parts.
2. The valve body is a pressure vessel constituting the housing for the valve body assembly with inlet and outlet flow connections.
3. The valve seat or seating is the machined surface, usually but not always annular, with an opening which may be partially or completely ob-

structed by a movable part for the purpose of flow regulation.
4. The orifice is the respiratory channel which traverses the seating; it may have appreciable length and so depart from the strict definition of an orifice.
5. The diameter is the internal diameter of the narrowest channel within the valve assembly (the orifice).
6. The vents are the outlet channels through which gases escape after having passed through the valve.
7. The lift or stroke is the distance through which the movable part of the valve is free to move away from its seating so that gases may escape.
8. The valve disc, flap, or cover is a movable part which provides a variable restriction with its associated seating.
9. The locating pin, guide, or cage is a device employed in many valves to keep the disc aligned with the seating.
10. A positional valve must remain horizontal as it requires gravity or reversal of air flow to close it completely. A nonpositional valve is closed by elastic tension of rubber or by a spring and may be used in any position.

CLASSIFICATION OF RESPIRATORY VALVES USED IN ANESTHESIA PRACTICE

Respiratory valves although varying in performance, appearance and construction, may be classified under six types according to their principle of operation (fig. 1). The following classification is based upon that of Silverman.⁴ Under each type are listed examples of valves found in anesthesia practice with references for more complete descriptions. The list is not complete.

Type A. Rigid opening closed with a rubber flap fastened or suspended from its center. (1) Flap of molded rubber which is self seating. Air flow in these valves causes the center pivoted rubber flap to lift on the edge and flex or bend to allow gas flow. The valves have positive seating, as the seating is accomplished by the elastic tension of molded rubber. They are nonpositional so can be used in the Y piece of the breathing circuit attached to the mask or endotracheal tube adapter.
Fig. 1. Some types of respiratory valves used in anesthesia practice. A. Digby-Leigh with flexible rubber flap; B. Stephen-Slater; C. Caged disc valve; D. Disc on locating pin; E. Mushroom valve; F. Sadd valve.

(2) Flap of sheet rubber which seats mainly by reversal of air flow.

The rubber disc must have enough resilience (by adequate thickness and stiffness) to return to a position where the reversed flow can seal it completely.

Examples are Kirchhoff, Stephen-Slater (fig. 1B) Fink, Gutter, Edison unidirectional transparent mask valve, Sierra Y valve, Anesthesia Associates swivel Y valve.

Type B. Rigid opening closed with a rubber flap fastened at outer edge. (1) Flap of molded rubber, and (2) flap of sheet rubber.

Valves of type B permit air flow by lifting the flap as a plane surface off the seat. The escaping air flows to the side through the cylindrical area created. When gas flow ceases, these valves close by the elastic tension of the rubber. The Henderson-Haggard or mushroom valve (fig. 1E) is an example of this type of valve made from sheet rubber. Gas pressure separates the flaps' opening slits, allowing gas to flow. The valve is nonpositional and has been used for many years in anesthesia apparatus.

Type C. Rigid opening with a rubber flap, hinged to swing off seat. Valves of Type C have a rubber flap pivoted or fastened at the side, and open by flexing the rubber flap or by pivoting on a hinge (fig. 1A). These valves cause little change in the direction of air flow. Some valves of this type are positional requiring gravity or reversal of air flow to close them.

Type D. Rubber flutter type. Rubber flutter valves partially inflate with flow, thus opening slits or outlets. Closure is produced by collapse of the rubber tube, usually because of elastic tension, which allows the rubber surfaces to seat upon each other. The Sadd valve is an all rubber valve shaped like a spear head or duckbill (fig. 1F). It is nonpositional. Many modifications have been made. It is widely used in chest respirators, in industrial gas masks, and in metabolism and anesthesia apparatus. The design of gas mask valves was investigated by Sadd of the British Chemical
Defense Experimental Establishment in 1915 and the early Box respirators of the British Army and gas masks of the U. S. Army in World War I were equipped with these valves.\textsuperscript{11, 12} India rubber valves of the spearhead or flutter type had been employed in connection with breathing apparatus made as early as 1878.\textsuperscript{13} Synonyms are butterfly valve, lippenventile, molded rubber valve, calvole del tipo a mitra, soupape lancée.

**Type E. Rigid opening closed by a rigid flap.** (1) Gravity seating force, and (2) Spring seating force.

These valves open to permit flow either by lifting a flap or disc against gravity or the force of a light spring. Those seated by gravity are positional, whereas those employing a spring for seating are nonpositional. They are commonly used in anesthesia practice. In the first group are discs on a locating pin, caged disc valves and metallic hinged flap valves.

The disc on a locating pin (fig. 1D) consists of a metal or composition disc on a smooth frictionless pin to prevent the disc from tilting or moving laterally from the seat into the vents. The seat is knife-edged to reduce the area of contact and adhesion. The construction details have been enumerated by Kaye\textsuperscript{4} and Hunt.\textsuperscript{15} In the caged disc valve (fig. 1C) displacement of the disc from its seating into the vents is prevented by some form of cage. This eliminates the frictional resistance which occurs between a locating pin and its disc. It also obviates leakage around the pin. Attempts to use the valve housing to restrain the disc have met with failure; the disc adheres to the top of the housing if the breathing is unusually deep. The metallic hinged flap valve has been described by Bach in his valve assembly for anesthesia purposes.\textsuperscript{16}

In group 2 are expiratory pop-off valves and the metallic inspiratory valve flap or disc of the original Digby-Leigh assembly.\textsuperscript{14} In the spring loaded valve, an expiratory air vent valve (exhalation, relief, or pop-off valve) is placed in a continuous flow system to exhaust excess gases. These valves are spring loaded to increase the opening pressure slightly above that of the collapsing pressure of the reservoir bag else the bag will not act as a reservoir. The force exerted by the spring should be slightly greater than the weight of the disc, so that the expiratory valve will not leak when used in other than horizontal positions.

**Type F. Miscellaneous.** This group includes all valves that do not fall into the above classes and also those which utilize combinations of the above classes. Examples are Ruben spool and spring valve,\textsuperscript{17} Lewis-Leigh,\textsuperscript{18} Shuman,\textsuperscript{19} Piston,\textsuperscript{20} Flach-Voss,\textsuperscript{21} F. B. Martínez ball valve,\textsuperscript{22} Bach,\textsuperscript{16} and J. M. Martínez\textsuperscript{22} valves.

**Performance of Respiratory Valves**

The most important factors in the performance of respiratory valves are: (1) resistance to gas flow; (2) leakage, which may be dynamic or static; (3) opening pressure; and (4) location of the valve.

**Resistance to Gas Flow.** The flow of gas through a system depends upon the pressure difference across the system. Resistance is defined as the pressure gradient required to produce unit flow. If flow is laminar, the flow of gas will be in direct proportion to the magnitude of the pressure gradient.

\[
\Delta p = KQ
\]

where \(\Delta p\) is the applied pressure gradient, \(K\) is the resistance and \(Q\) is the flow. Therefore flow through the resistance at any moment will be proportional to the existing pressure drop.

Increasing the velocity of flow produces transitional followed by turbulent flow. Turbulence will be increased where flow changes direction or passes through orifices of varying cross sectional areas. The relationship between pressure drop and turbulent flow is not easily predictable. It is obviously not linear. In general for turbulent flow

\[
\Delta p = KQ^n
\]

where \(n\) is an exponent > 1 and approaching 2.

The definition of the factors comprising \(K\), the resistance, can be better understood by referring to the theoretical formula for pressure drop through an orifice: Pressure loss in orifice \(= \Delta p = \frac{\rho v^2}{2}\), where \(\rho\) = density and \(v\) = velocity.

If \(A\) is the area of the orifice and \(Q\) the rate of volume flow, \(V = Q/A\). Therefore,

\[
\Delta p = \rho \frac{Q^2}{2A^2} = KQ^2
\]

\(d\) being the diameter of the orifice if the latter
is round. Here the resistance \( K \) is \( \frac{8p}{\pi^2d^4} \). This assumes an orifice without length.\(^{24}\)

A continuous stream of gas can be used in the laboratory for testing resistance of a respiratory valve but this should approximate the maximum rate of gas flow encountered clinically during inspiration and expiration inasmuch as pressure drop will always be greater at higher flow rates. The apparatus for testing resistance of respiratory appliances have been described.\(^{4, 25, 26, 27}\)

Since the pressure drop bears a relationship to the volumetric flow rate, it is necessary to know what maximum instantaneous flow rates are encountered during the respiratory cycle. Instantaneous respiratory velocities can be visualized by pneumotachography and a number of such studies have been made. The pneumotachogram records the flow velocity of the gas stream as the subject breathes through a fine mesh screen. In such a tracing the height of the curve indicates the rate of flow at that instant while the volume moved is expressed by the area underneath the curve. Table 1 lists the maximum instantaneous flow rates observed at various levels of activity. The flow rates needed for investigating resistance through respiratory equipment have been established.\(^{27-21}\) For the quiet breathing encountered during anesthesia the maximum instantaneous respiratory flow rate in the adult will be about 30 L/min.

The resistance characteristics of some respiratory valves used in anesthesia practice are shown in figures 2 and 3. When respiratory minute volumes are low and maximum instantaneous flow rates do not exceed 30 L/min., some valves offer low resistance to breathing. Two mushroom valves and one of the flutter type (fig. 2) and the two disc valves on a pin (fig. 3) have resistances of less than 4 mm. of water within the range of flows from 0 to 30 L/min. The construction details of the disc valve on a locating pin, the pressure flow rate characteristics of which are shown in figure 3, have been described by Hunt.\(^{15}\) The resistance of this valve is less than that of the standard 8 x 13 cm. Waters canister filled with soda lime. The resistance of the disc valve on a locating pin \(^{27}\) recently discontinued in the Heidbrink anesthetic apparatus is as low as the optimum or the ideal valve of Hunt (fig. 3). The advantage of a graphic presentation is to give the anesthetist an objective method of comparing pressure flow rate characteristics of the various valves. Resistance studies are particularly important for pediatric anesthesia and for the patient with weakened respiratory musculature. Low resistance is not the only criterion for selection of a valve. Some valves although low in resistance, may leak considerably.

By inspection, the majority of curves in figures 2 and 3 are linear at the flow rates depicted, indicating laminar flow under these test conditions. The curves for the caged disc valve of Cara \(^{24}\) and the new Kirchhof flapper \(^{25}\) appear alinear indicating that the pressure drop is possibly proportional to \( Q^n \). To test this and if correct to determine the value of \( n \), the logarithms of the pressure drop \( \Delta p \)

### Table 1

<table>
<thead>
<tr>
<th>Reference</th>
<th>Activity</th>
<th>Minute Volume Respiration L/min.</th>
<th>Peak Flow Rate L/min.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gaensler(^{28})</td>
<td>Basal, sedentary</td>
<td>8</td>
<td>30</td>
</tr>
<tr>
<td>Silverman(^{29})</td>
<td>Sedentary</td>
<td>10.3</td>
<td>32-40</td>
</tr>
<tr>
<td>Silverman(^{29})</td>
<td>Working</td>
<td>14-113</td>
<td>43-322</td>
</tr>
<tr>
<td>Gaensler(^{28})</td>
<td>Maximum breathing capacity test</td>
<td>200</td>
<td>700</td>
</tr>
<tr>
<td>Ross(^{20})</td>
<td>Cough</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Whittemberger &amp; Mend(^{11})</td>
<td>Cough</td>
<td>200 (^{17})</td>
<td></td>
</tr>
<tr>
<td>Proctor(^{27})</td>
<td>Anesthesia (adult resting respiration)</td>
<td>250-260</td>
<td>700 (^{18})</td>
</tr>
<tr>
<td>Proctor(^{27})</td>
<td>Anesthesia (newborn)</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Proctor(^{27})</td>
<td>Anesthesia (age 1 year)</td>
<td>---</td>
<td>1-4 (^{19})</td>
</tr>
</tbody>
</table>

\(^{24}\) This assumes an orifice without length.
\(^{25}\) Waters canister filled with soda lime.
\(^{15}\) The resistance of this valve is less than that of the standard 8 x 13 cm. Waters canister filled with soda lime.
\(^{27}\) Recently discontinued in the Heidbrink anesthetic apparatus.
\(^{17}\) The advantage of a graphic presentation is to give the anesthetist an objective method of comparing pressure flow rate characteristics of the various valves.
\(^{21}\) Resistance studies are particularly important for pediatric anesthesia and for the patient with weakened respiratory musculature.
\(^{18}\) Low resistance is not the only criterion for selection of a valve. Some valves although low in resistance, may leak considerably.
\(^{29}\) The curves for the caged disc valve of Cara and the new Kirchhof flapper appear alinear indicating that the pressure drop is possibly proportional to \( Q^n \). To test this and if correct to determine the value of \( n \), the logarithms of the pressure drop \( \Delta p \).
and of the volumetric flow rate $Q$ were plotted. Then if

$$\Delta p = K Q^n$$

$$\log \Delta p = \log K + n \log Q$$

which would be the equation of a straight line inclined at a slope of $n$ and intercepting the axis of $\log \Delta p$ at $\log K$. By such calculation the value of the exponent $n$ was 1.3 for the new Kirchhoff flapper and 1.59 for the caged disc valve of Cama (fig. 3) at flow rates above 30 liters per minute. Pressure drop and flow rate are here related in exponential fashion indicating that transitional or turbulent flow exists. Visualization of flow through the valve by means of smoke and photography would provide useful information on this point.

Under experimental conditions the passage of gas is steady and uniform once the disc or flap has been lifted from its seat. This does not pertain to use of the valve in a respiratory appliance. Here the flow rate changes during the respiratory cycle from a peak of 25 to 30 liters per minute to zero, ten to twenty times each minute. The size and shape of the stream changes repeatedly as gas passes through a continuously enlarging and contracting orifice created by the alternating lifting and closing of the disc or flap. These factors produce turbulence at lower flow rates than in the test conditions and hence a higher resistance.

The total resistance of a respiratory valve at an air flow of 50 l./min. is arbitrarily rated as low, medium or high depending on the pressure difference through the valve.4 (Re-

### TABLE 2

<table>
<thead>
<tr>
<th>Reference</th>
<th>D cm.</th>
<th>L cm.</th>
</tr>
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<tbody>
<tr>
<td>1. Kaye†</td>
<td>2.2</td>
<td>.55</td>
</tr>
<tr>
<td>2. Hunt‡</td>
<td>2.2</td>
<td>.49</td>
</tr>
<tr>
<td>3. Ruben and Hesse‡</td>
<td>1.4</td>
<td>.35</td>
</tr>
<tr>
<td>4. Burns‡</td>
<td>1.58</td>
<td>—</td>
</tr>
</tbody>
</table>
Fig. 3. Pressure flow rate characteristics of respiratory valves used in anesthesia practice. The numbers on the curves refer to the source of data.

Resistance is classified as low, medium, or high at the pressure differences \( \Delta p \) cm. H\(_2\)O, at flow 50 L/min. of .7 cm. or less, 1.2 cm. or less, and greater than 1.2 cm., respectively.) Table 2, compiled from the literature,\(^4\)\(^8\),\(^9\)\(^{26}\),\(^{27}\) presents information on the optimum diameter and lift for the respiratory valve in relation to pressure drop. There is some disagreement here. In valves 1 and 2 with diameters of 2.2 cm. the discharge from the valve is almost perpendicular to the inflow direction. A larger diameter is needed to offset this factor producing pressure losses. In valves 3 and 4 with smaller diameter, flow proceeds in one direction with minimum deflection. Formulas and nomographs for determination of optimum valve diameters for fluid flow capacity ranges are available. These have been used for calculation of the optimum area of a cardiac valve orifice, but have not been applied to valve orifices in respiratory appliances.

Table 3 summarizes the physiological changes resulting from breathing 30 L/min. against a resistance of 20 cm. and 7.2 cm. of water.\(^{28}\) Resistance to breathing at the higher value produces an altered pattern of respiration, increased work of breathing, increased oxygen consumption, decreased cardiac output, increased alveolar pCO\(_2\) and increased functional residual capacity. The physiological effects in healthy adults were slight for resistance values below 7.2 cm. H\(_2\)O. Table 4 shows the results of four studies\(^{27},^{39},^{40},^{41}\) of resistance
TABLE 4
TOTAL RESISTANCE OF ANESTHESIA CIRCUITS

<table>
<thead>
<tr>
<th>Reference</th>
<th>Δp cm. H₂O at 30 L/min.</th>
<th>Type Apparatus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proctor</td>
<td>1.8</td>
<td>Heidbrink circle with endotracheal tube No. 40</td>
</tr>
<tr>
<td>Barth</td>
<td>2</td>
<td>Draeger model F with endotracheal tube No. 40</td>
</tr>
<tr>
<td>Wu</td>
<td>1.2</td>
<td>Heidbrink with endotracheal tube No. 37</td>
</tr>
<tr>
<td>Orkin</td>
<td>1</td>
<td>Universal McKesson Adriani Heidbrink To and fro</td>
</tr>
</tbody>
</table>

in anesthetic circuits. All of these values are below that amount of resistance probably required in the adult to produce appreciable physiological changes.

Valve Leakage. Valve leakage or backflow through a respiratory valve is an indication of the efficiency of a valve in performing the task for which it is designed, i.e., to check the flow of air at the proper time. When leakage or backflow occurs, there is an alternating movement of air where there should only be a unidirectional movement. There is therefore “rebreathing,” which is proportional to the back leakage of the valve.

A distinction is made between static leakage and dynamic leakage. Static leakage occurs under static conditions, i.e., the valve is closed but some air passes anyhow. If the valve were perfectly constructed, no air should pass. Thus the test for static leakage is a test of quality of manufacture. This provides a means of comparing valves during their production and of controlling their uniformity and acceptability. To test for static leakage (fig. 4), a specified negative pressure is applied to a closed valve. In actual practice, negative pressures of 4, 8, 12, 16, 20, 25, 40 mm. of water are applied for 1 minute. The amount of air escaping through the valve is the amount of static leakage at that negative pressure. In some valves, for instance with a rubber flap, increased negative pressure closes the seal more tightly and static leakage decreases with negative pressure. If the orifice causing the leakage were of fixed size as for instance a pin hole in the flap, the amount of air flowing through would obey the law for efflux of fluid through an orifice, \( Q = A \sqrt{\frac{2g}{h}} \) where \( Q \) = volumetric flow rate, \( A \) = area of orifice, \( g \) = constant of gravity acceleration, and \( h \) = pressure drop. Doubling the negative pressure (or \( h \)) would increase as \( \sqrt{2} \) times the quantity of air flowing through or about 41 per cent. Leakage around the disc or flap of a closed valve however obeys no such laws. Increasing the negative pressure may reduce the leak or cause a new one elsewhere.

A simple test for static leakage is to exert positive pressure on the outlet of a seated valve, the inlet of which is covered with a small lightweight balloon. If leakage occurs it will be detected by inflation of the balloon. Alternatively the valve inlet may be held under water in which case bubbles of air will be seen if leakage occurs. This latter modification is currently used by the U. S. Bureau of Mines in their tests for static valve leakage.

The pressure differences in respiration are rhythmic, smoothly varying ones roughly resembling a sine wave. When a sinusoidally varying pressure gradient is generated in a breathing system a flow will be established which also varies in a sinusoidal fashion. The

![Fig. 4. Apparatus for measurement of static leakage of respiratory valves.](image-url)
Fig. 5. Apparatus for the measurement of dynamic leakage. The discharge of the pump, A, passes through the valve, C, under test, which is placed in the small chamber, D. This chamber outlet passes through a slide valve E controlled by solenoids F and G. The other chamber connection passes through slide valve H to the small gasometer J. The solenoids for the slide valves are operated by the contacts K and L, which operate the relays M connected with the solenoids. The timer contacts are adjusted so that the moment the piston reaches the end of its discharge stroke, the solenoid valves reverse and allow the back leakage caused by closing and pulsating negative pressure on the valve to flow out from the gasometer. When the piston reaches the bottom of its stroke, the contacts cause the valves to reverse, and all the discharged air passes directly through the valve under test and the large slide valve E.

The time relationship however between pressure and flow curves may differ depending upon the resistance and compliance of the system. The cyclically varying respiratory pressures may at any instant be less than or greater than the pressure selected for static testing. Consequently leakage may not be detected by static testing. Such investigation can detect physical flaws in the seat or distortions in the disc. It cannot predict leakage under conditions of use since dynamic factors such as inertial effects on the disc and turbulence in the region of the seat are not introduced in these tests.
Dynamic leakage is leakage occurring through a valve during actual breathing, i.e., under conditions of use. It includes static leakage occurring with a closed valve at pressures selected for testing plus back leakage through the valve while it is in the process of closing. This difference between static and dynamic leakage can be attributed to valve lag in closing, which allows air to be drawn back through the valve before it completely closes.

Dynamic leakage may be tested for by four methods:

(1) The apparatus described by Silverman for dynamic leakage testing is shown in figure 5.4 Measurements of dynamic leakage are made with the pump and valve system that simulates respiration. With this apparatus it is possible to determine the effect of varying the volume and frequency of respiration and the inspiratory resistance on leakage. It is also possible to determine the amount of leakage ascribable to the reversal of flow before the valve seats, and the amount of leakage ascribable to negative pressure on the valve seating surfaces.

(2) The pneumotachogram is a tracing of the instantaneous rate of flow of respiration. The exchange volume is represented by the area under the curve. Either the inspiratory or expiratory cycle of respiration or both can be recorded. Inspiratory and expiratory check valves are employed between the pneumotachograph screen and the subject in order to prevent rebreathing. If only one cycle is recorded, the curve descends to the baseline of the graph during the interval required for the other respiratory cycle. Descent of the curve below the base line during this interval indicates leakage of the valve between pneumotachograph and subject. Since the area under the curve represents a volume, the amount of leakage can be determined by planimetry or by electrical integration of the area.

Elam and Brown 44 have employed pneumotachography to measure back flow leak during inspiratory flow produced by a mechanical ventilation analogue. They studied the Acushnet, 45 Stephen-Slater, mushroom, Sadd, and Heidbrink disc on pin valves. All had appreciable back flow leakage except the Acushnet. Valve leakage is meaningful only in terms of the pressures and flows to which valves are subjected during anesthesia. In most instances the back flow leak measurable with the pneumotachograph could not be subjectively detected by an observer breathing against the valve. The time course of the pressure drop applied across the valves during quiet breathing may produce a back flow leak which will not occur with the sudden pressure drop applied in testing a valve, nor is the valve leak incident to quiet breathing of the anesthetized patient appreciated by visual inspection of valve movement. Back flow leakage of respiratory valves at a tidal volume of 500 ml. and measured by the pneumotachograph method are listed in table 5. A back flow leakage of 150 ml. of a 500 ml. tidal volume permits 30 per cent of expired air to be rebreathed. This leak would elevate the average concentration of inspired CO₂ between 1 and 3 per cent depending on the patient's CO₂ output.

(3) In a third test for dynamic leakage the valve is used in simulated breathing while engulfed in an atmosphere of diethyl phthalate smoke. Back leakage of smoke into the valve enters a light scattering chamber where it is measured photoelectrically, presented on a cathode ray oscilloscope, and photographed for permanent record. The total leakage is obtained by integrating the area under a concentration vs. time curve. This method is similar to that used to obtain dye dilution curves in studies to measure valvular regurgitation in heart disease.

(4) As mentioned previously, valvular defects provide an opportunity for rebreathing which is equivalent to added dead space. Hence a method of determining added dead

<table>
<thead>
<tr>
<th>Valve</th>
<th>Back Flow Leak in mL per 500 ml Tidal Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acushnet</td>
<td>no leak</td>
</tr>
<tr>
<td>Stephen Slater</td>
<td>30</td>
</tr>
<tr>
<td>Mushroom dry, new</td>
<td>40</td>
</tr>
<tr>
<td>Mushroom wet, new</td>
<td>no leak</td>
</tr>
<tr>
<td>Mushroom dry, old</td>
<td>150</td>
</tr>
<tr>
<td>Mushroom dry, distorted</td>
<td>90</td>
</tr>
<tr>
<td>Sadd</td>
<td>65</td>
</tr>
<tr>
<td>Heidbrink on circle 9B</td>
<td>24</td>
</tr>
</tbody>
</table>
space such as the equal-areas method or graphical-integration method \(^4\) can be utilized for determining equivalent added dead space due to carbon dioxide accumulation from defective valves. This has been done. Kerr and Evers \(^4\) obtained equivalent added dead air volumes ranging between 170–830 ml. due to leaking inspiratory and expiratory valves. The average inspired carbon dioxide concentrations corresponding to these dead air volumes was from 1.4 to 5.9 per cent. On the other hand with intact silicone rubber valves in the mask yoke they obtained an equivalent added dead air volume of 10 ml. with a corresponding inspired carbon dioxide concentration of only 0.1 per cent. This method of analysis has the advantage of relating valve performance directly to function since an intact check valve should prevent rebreathing.

The following arbitrary classification is made for dynamic leakage on the basis of leakage per respiration: \(^4\) leakage per respiration (5 cm. resistance, 600 ml. per respiration), low, 2 ml. or less; medium, 2–4 ml., and high, > 4 ml.

**Opening Pressure.** The valve disc or flap in its closed position acts as a seal in the air duct. Before this seal can be broken, the force acting on the underside must be sufficient to lift the disc or flap away from its seat. Obviously the opening pressure for a dry valve disc will equal the weight of the disc times its cross sectional area. If a film of water should be formed on the under side of the disc, the pressure of the entering gas will then have to overcome the surface tension which will act in addition to weight in holding the disc on its seat. A spring closure in a valve also acts as a constant to increase opening pressure. It is desirable to have a low opening pressure in a valve but there is a lower limit since this pressure must be greater than that required to fill the reservoir bag.

There are 3 methods of testing for opening pressure: (1) The soap-film method has been found to be extremely sensitive to low inflows. \(^4\) The testing apparatus used is shown in figure 6. (2) The second method is an extrapolation procedure. This requires a low range flowmeter (1 to 4 l./min.) and an inclined manometer for determining resistance to air flow. By determining the curve of resistance to air flow at low flows and observing its shape, the pressure at which appreciable flow takes place can be approximated. (3) The third method is based upon simultaneous records of flow and pressure. By passing a vertical line from the start of the flow curve (on the same time line) through the pressure curve the opening pressure will be that corresponding to zero flow (fig. 7).

Figure 7 also illustrates the effect of moisture on the opening pressure of a valve. Here the expiratory valve is bathed in a film of water condensed from the expired air. At the initiation of the expiratory phase a brisk increase of pressure (5 mm. H\(_2\)O) occurs while the valve is not yet open. At this time the velocity of the air current is zero. The pressure \(P_1\) descends at the moment in which the valve opens while the flow \(V_1\) increases rapidly through the valve from zero to 280–330 cm.\(^2\)/second. As the valve continues to open, the pressure \(P_2\) decreases and there is a continued increase of flow to 470–580 cm.\(^2\)/second. Since the valve opens just after \(P_1\) reaches its initial increase at 5 mm. of water, this represents the opening or bursting pressure for this wet valve.
Opening pressures (mm. of H₂O) of 4 mm. or less, 4–10 mm., greater than 10 mm. are arbitrarily classified as low, medium, or high, respectively. Opening pressures are classified on a wet measurement.

**Location of the Respiratory Valve.** In some apparatus such as the self contained oxygen breathing apparatus used in mine rescue work the respiratory valves are located at the face mask; in the carbon dioxide absorption apparatus employed in anesthesia practice, the respiratory valves are located either at the canister or at the mask end. What is the effect of respiratory valve position on resistance to air flow?

One group commenting on the effect of valve location on resistance to air flow stated that "a valve located close to the exit of the expired air may be opened by the impact pressure of the stream of expired air, whereas a poorly located valve will not release until the static pressure is increased. The impact or total pressure is the sum of the velocity pressure, \( V^2/2g \), and the static pressure, where \( V \) is the velocity and \( g \) the acceleration of gravity. Upon striking the valve, a portion or all of the velocity pressure may be converted to energy to open the valve. If no flow takes place, the velocity pressure is zero, and the total pressure becomes equal to the static pressure." "As an air jet in motion in a given direction tends to remain in motion in the same direction, it is advantageous to have the valve situated as closely as possible to the point where the air escapes."

In comparing resistance to air flow at the mask or canister end of the respiratory appliance, it would seem necessary to assume that the same type valves are used and that the approach and exit fittings and flow patterns through the valves are similar.

The air flow resistance of a 76 cm. flexible rubber tubing commonly used for anesthesia and respiratory testing has been measured. At 30 l./min. the \( \Delta p \) is about 1 mm. H₂O. These tests were made with the tubing straight. If the tubing is allowed to hang in a curved position, as in actual use, the pressure head loss would be greater due to kinetic energy losses from change in direction of air flow. In a study of air flow resistance in anesthesia appliances, the resistance to flow through a circuit with the valves at the mask end was compared to that with respiratory valves at the canister end. The authors considered that there was little difference.

It is not only important to consider the resistance to air flow in assessing the physical behaviour and physiological effects of closed circuit respiratory apparatus but also the total pressure across the respiratory system of the patient available to activate the attached respiratory appliance. Information is needed on the extent to which the total pressure of
the breath stream available for activating the valve is decreased by changing the position of the valve from the mask end to the canister end of the rubber breathing tubes.

What is the effect of respiratory valve position on the carbon dioxide content of the gases in the above mentioned types of respiratory appliance? Conroy and Seever observed that amounts of carbon dioxide comparable to those in the mask were found 8 cm. and more up the inhalation tube of a closed circle absorption system and recommended that one way respiratory valves be inserted close to the face-piece. Another study confirmed that the carbon dioxide content in the mask was higher when the respiratory valves were located at the soda lime canister of a circle absorption system. In another study the equivalent added dead space was decreased from 45 to 40 ml. by shifting the valves from the canister end of the breathing tubes to the face piece. This however corresponded to an increase in average inspired carbon dioxide from 0.2 to 0.3 per cent.

SUMMARY AND CONCLUSIONS

The most important factors in the performance of respiratory valves are resistance to airflow, static and dynamic leakage, opening pressure, and valve location. Their importance to the anesthetized patient has been discussed. There is a need for cooperative research among anesthesiologists, engineers, and mathematicians for further understanding of respiratory valve action and to apply existing knowledge to the field of anesthesiology. Manufacturers should provide respiratory valve characteristics, including resistance curves, static and dynamic leakage, and opening pressures just as manufacturers in the electronics industry supply characteristics of their equipment. The efforts of the anesthesiologist to provide the best care to anesthetized patients have resulted in improvements in design of respiratory valves. Continuing interest in fostering improvements in design is warranted.

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