The Performance of the Engström Ventilator

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The Engström mechanical ventilator is a widely known and used machine, yet very little data is available concerning its mechanical performance. Virtually the only information published concerns analyses of the work output of the unit, compared in some instances with other types of ventilators. These studies generally serve to show a superiority of the Engström machine when ventilating patients with poor pulmonary compliance or obstructive disease.1-4

Certain unique features in the design of the Engström ventilator suggested that an investigation of some of the basic functions of the machine might be of interest. (1) The dose valve of the Engström is a pneumatic, rather than a mechanical system for measuring the volume to be insufflated. This is not found in other popular ventilators. The operation of this system depends upon a constant negative pressure being generated within a perspex cylinder containing a rubber bag ("dose bag") which is connected to the atmosphere through a calibrated variable resistance. A decrease in this resistance allows easier inflow of air into the bag, a greater volume in unit time is thus taken up to be then inflated into the patient's lungs. Since the period during which this negative pressure is held constant will vary with the rate of inflation, it seemed worthwhile to measure the output of the machine at a constant "dose" setting, but at varying rates.

(2) The expiration port of the machine is controlled by a pneumatic valve which closes when positive pressure is generated within the secondary, or patient, circuit of the machine. Recently, it has been shown that many non-rebreathing valves are incompetent. Evidence of any "air slip" or static leak in this valve was also sought.5 The Engström pneumatic valve is designed on a similar principle to the Fink and Frumin valves, which were found to be particularly competent. (3) Several additional functional features were also evaluated.

**Method**

Six Engström ventilators in routine daily use, regularly checked and serviced, were tested. These machines ranged in age from 5 years or more to virtually new machines and included nos. 150 and 200 models. All volumes measured were collected in a Godart Expiograph recording bell-type spirometer which had been calibrated over its full range using 100 ml aliquots of air. Air was used in all studies of the dose valve.

The following tests revealed the following findings:

*Output at Zero Setting.* The dose valve was tightly closed, the machine rate set at 20/minute, and the expiration port from the machine spirometer connected to the Godart spirometer. At this setting of the dose valve no flow was found in any instance, showing that there was no unexpected ingress of air that might disturb the calibration of the dose valve. It was noted that on some machines the zero setting of the dose valve did not correspond to the point of no flow, perhaps due to wear of the valve faces.

*Leakage Out of the Circuit.* The outlets from the machine spirometer and the Y connection to the patient were joined, thus bringing all passages of the secondary circuit to the same pressure. The machine was switched on briefly to allow it to generate a pressure within the system, and the rate of fall of this pressure was recorded using the manometer in the secondary circuit. The rate of fall of pressure could be brought down to or below 2 cm. of water/minute at 15 cm. of water static pressure, provided the various slip joints in the circuit were tightened. The humidifier, with its
large sealing surface, was responsible in some machines for a higher rate of leakage, and was then bypassed before further tests were carried out.

**Leakage Through the Pneumatic Valve.**

Would the pneumatic valve be competent at pressures likely to be encountered in clinical use, and could any sign of “air slip” be shown? These answers were sought firstly by connecting the expiration port of the machine spirometer to the Godart spirometer, blocking the patient connection, and allowing an inflow of oxygen from the machine’s flowmeter. This inflated the “dose bag,” and then transmitted pressure to the secondary circuit, closing the pneumatic valve. Under these conditions, any outflow from the machine into the spirometer could only come through the pneumatic valve. The inflow of oxygen was adjusted to maintain a steady pressure of 5, 10, 20 and 30 cm. of water on the manometer in the patient circuit and any leakage recorded over a period of one minute (table 1). There was a great variation in the rate of leakage between different valves, and in some the rate was so high as to be able to reduce appreciably the volume available to patients ventilated at high pressures (cf., machine 2 with a leakage of 2.5 liters/minute at 30 cm. of water pressure). The only valve that did not leak under any circumstances was found to be sticking on its seat.

Air slip through the valve was sought by connecting the machine to a “mechanical thorax,” setting a minute volume of 20 liters/minute and recording the outflow on the Godart spirometer at 120 mm./minute paper speed. Different rates of inflation and a maximum pressure of 10 cm. of water were used. It was hoped that “air slip” would show as a double outflow on the tracing, or a sudden increase in the rate of outflow at the end of expiration. No such evidence was found. However, the inertia of the spirometer might damp small flow transients, and a higher inflation pressure might produce an “air slip” as well as a static leak. But for practical purposes, there appears to be no tendency to “air slip” across this valve, at pressures likely to be used in normal circumstances.

**Calibration of the Dose Valve.** After checking that no leakage from the circuit was present, the machine was connected to a mechanical thorax (a weighted bellows that always returned to a constant expiratory position), and the outlet from the machine spirometer connected to the Godart spirometer, where volumes expired over 30-, 60- or 120-second periods were recorded. The pressures generated within the secondary circuit were kept in the range of 0 to +5 cm. of water, to minimize errors any small leaks might introduce. The dose valve was set either at 5 liters/minute or 10 liters/minute. Speeds between 10 and 30 per minute were selected, and the volume taken up in the Godart spirometer compared with the reading of the machine spirometer. Before any readings were taken, the pressures in the primary circuit were carefully adjusted without parallax to +50 cm. of water, and to the red negative pressure calibration mark. After the machine had stabilized at this setting, with the outflow tap in the “venturi” position, readings were made by switching the outflow tap to the “spirometer” position at the start of an insufflation phase. During the period of measurement the primary circuit pressures were rechecked. Readings were made in duplicate unless there was any gross discrepancy, when three or more readings were taken until a constant figure was obtained.

The findings were:

1. The output of the machine at any particular setting was remarkably uniform, frequently with a variation of less than 30 ml. in a 10-liter output.

2. The rate of inflation did not always correspond to the setting of the machine. Variations of ½ cycle per minute were common, with the error slightly greater at the lower speed end of the scale. Such errors are probably not of much practical importance, and
should not affect the minute volume output. However, in this connection it should be noted that the speed is controlled through a variator which can be damaged if adjusted while the machine is not running. Where use by inexperienced personnel makes this sort of damage possible, it is desirable to check the rates occasionally. Such a vulnerable component of the machine might be protected perhaps by some clutch mechanism that would isolate it when the motor stops.

(3) The output of the dose valve showed a considerable variation at a fixed setting when the frequency of inflation was changed. This characteristic emerged very clearly, and was found consistently in all machines (fig. 1 and table 2). At any given setting of the dose valve, output was higher the higher the rate per minute. Differences in output varied from about 15 per cent to over 30 per cent in the various machines, between ventilation rates of 10 and 30 per minute. At some unpredictable point on the speed range the machine might deliver the minute volume set on the dose valve, but this might be at a high or low rate.

(4) Accuracy of the machine spirometer was found to be good. During the course of the calibration of the dose valve, these volumes were recorded on both machine and Godart spirometers and compared. Mechanical backlash between the spirometer needle and the internal mechanism can give an error of 200–300 ml unless care is taken in resetting the needle to zero. The percentage variation between the readings of the two spirometers was usually 3 per cent or less, but proved much larger in one machine (table 3). Most spirometers tended to overread by a few per cent, and the degree of accuracy of 3 ± 1 per cent quoted by Gordh et al. can be confirmed. Certainly, reliance should be placed on the spirometer reading rather than on the setting of the dose valve.

(5) Errors introduced by inaccuracies of the primary circuit pressure gauge: One of the best ways to show the dependence of accurate output upon correct negative filling pressure of the “dose bag” is to show the extent of the error that can occur with parallax error reading of the gauge. The machine instructions emphasize that during the phase of filling of the “dose bag,” the negative pressure within the perspex cylinder must be so adjusted that the manometer needle exactly coincides with the red calibration mark. How important is this for accurate performance?

At a setting of 10 liters/minute and a rate of 16 cycles/minute the pressure was adjusted so that the needle reached just over and off the red mark, or coincided with it, or reached just below and off the mark. This sort of variation may occur due to parallax error if one sits to make the adjustment, or leans over the back of the machine to make it. Between each step there was a change of between 200–300 ml./minute, or up to 600 ml. between high and low points, representing an error of about 3 mm. on the gauge scale.

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<th>Table 2. Percentage Increase in Minute Volume with Increased Respiratory Rate</th>
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DISCUSSION

There are certain points emerging from this study that are important if this ventilator is to be used to best advantage. As is indeed emphasized by the manufacturers, the pneumatic valve requires regular checking and cleaning if leaks across it are not to occur, or expiration impeded. However, there appears to be no way of checking the valve for internal leaks whilst the machine is running, when it does leak, this volume bypasses the patient but is read on the machine spirometer as part of the minute volume. Unfortunately, since it appears that no reliance should be placed on the setting of the dose valve to deliver the chosen minute volume, the reading of the spirometer is the only guide. But this may also not be reliable if the pneumatic valve is defective. It should also be remembered that in such a breathing system where only outflow but not inflow can be measured, it is impossible to detect leaks out of or across the circuit.

Perhaps the most critical adjustment for accurate operation is the setting of the pressures in the primary circuit, inside the perspex cylinder. A parallax error of about 1 mm. may make a difference of at least 100 ml./minute in the ventilation. Whilst it is within the hands of the operator to avoid such errors, it becomes difficult to predict the output of the machine when large zero errors in the gauge are present. Such errors were not uncommon in the machines tested. In one of the 6 machines tested, the mechanism of this gauge was found to be “sticky.” This tends to introduce very large errors when one considers the construction of this particular gauge which has no direct mechanical link between the aneroid bellows and the needle actuating mechanism, but between which two components there is interposed an adjustable pivot to allow for correct zeroing of the gauge. With positive pressure the aneroid drives the pivot against the needle movement, so that a consistent positive pressure reading is obtained. During the negative phase, however, the aneroid is drawn away from the pivot, which can follow it only if its movement and the needle movement are free. A failure to follow the aneroid gives an under-reading of the negative pressure, with a tendency to set this pressure too high and to over-inflate the patient. Such an error will be magnified at faster rates of ventilation. Since this negative pressure adjustment is far more critical than the positive pressure setting, it might be an advantage to redesign the manometer to give a direct link between its moving parts with negative pressure.

CONCLUSION

The inaccuracies in even the best of equipment make it necessary to exercise clinical judgment and constant biochemical control.

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REFERENCES