**RESPIRATORY THERAPY**

**Evaluation of a Fluidic Ventilator: A New Approach to Mechanical Ventilation***

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Fluid amplifiers and control devices have found wide application in industry when stability and reliability are required. This technology is now being applied to the construction of ventilators for medical use. The clinical and laboratory evaluation of a commercial fluidic ventilator** indicates considerable promise for machines of this design.

The emerging technology of fluid amplifiers and control devices has provided a new approach to the design and construction of mechanical ventilators. Fluidics, as this technology has come to be known, has not yet found wide application in medicine, and the fundamentals of fluid control devices are not familiar to many in that field. These are basically simple devices that employ fluids (gases and liquids) to perform operations such as amplification and on and off switching that one might normally associate with electrical devices. As in any amplifier, a large signal is modulated by a small signal. In this instance the power jet of gas is modulated by smaller control jets or switched on and off by being directed from one channel to another by a control jet. The channels through which gas travels are cut into a solid block of suitable material. The fluidic circuit itself contains no moving parts, and potential for mechanical difficulty is reduced accordingly.

Fluid amplifiers and control devices have found wide and sophisticated application in industrial and space equipment where stability is vital. With mass production and miniaturization techniques, fluidic circuits have become relatively inexpensive.

Quite a number of ventilators of various capabilities and description are available here and abroad. They are popularly classified as pressure cycled, volume cycled, or time cycled, although they might more accurately be called pressure preset or volume preset machines. The new device under consideration (Fig 1) may be either pressure, volume, or time cycled.

Inspiratory flow in pressure cycled machines continues until a preset pressure is reached and then terminates. In some machines such as the Bennett PR-1 or 2, inspiration terminates when flow falls to a low terminal point at the preset pressure. Changes in pulmonary resistance or compliance will alter the volume of gas delivered from pressure cycled ventilators. Therefore, volume cycled ventilators are generally preferred in circumstances requiring continuous mechanical ventilation.

Volume cycled ventilators deliver a metered volume of air (tidal volume) by utilizing whatever pressure is necessary to overcome total pulmonary resistance. The tidal volume delivered is relatively constant, unless pressure and flow capabilities of the machine are exceeded by high resistance and low compliance of the lungs and thorax. In addition, there are some volume losses due to the compliance of the machine delivery system and compressibility of gas. These losses are small, however, and of little or no clinical significance in adults.

In time cycled ventilation, more common to Europe than America, the inspiratory and expiratory phase times (or the rate, or ratio) are set, and the volume delivered becomes a function of the inspiratory flow rate and inspiratory time. Pressure preset machines may be time cycled by using an automatic rate control mechanism. In time cycled devices the effect that changes in resistance and compliance have upon flow become critical, for the tidal volume and minute ventilation are altered accordingly.

Several sophisticated volume preset ventilators are available today. Among the performance characteristics desirable in such machines are extreme reliability, the

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**The Monaghan 225 volume controlled ventilator, Monaghan Co., Littleton, Colorado.

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Figure 1. View of instrument panel of fluidic ventilator. Dials are self-explanatory. Patient delivery tubing and tubing to exhalation manifold and drug medication nebulizer not shown for simplicity. Tidal volume bellows maximum output 3,300 ml (see Fig 3).
capacity for patient triggering, the ability to adjust inspiratory and expiratory ratios over a wide range, and an accurately calibrated continuously adjustable oxygen delivery system to control the inspired oxygen fraction (FIO₂). In addition, difficult problems in ventilatory management require machines with high pressure capability, able to maintain adequate flows despite increases in impedance. The ability to set a pressure limit to offset the dangers of extreme pressures is also desirable. An adjustment for positive end-expiratory pressure has become available on some machines subsequent to the demonstration of the therapeutic utility of this waveform in many cases of acute respiratory failure such as the adult respiratory distress syndrome.5-6 Finally, simplicity of design, low initial cost, lack of noise and ease of maintenance would be positive attributes in any piece of equipment. We believe that our experience with a new ventilator in the clinical and laboratory setting indicates that a fluidic ventilator may achieve these ends.

**GENERAL DESCRIPTION**

The Monaghan 225 ventilator is shown in Figure 1. A detailed description of the theory of operation and construction of this ventilator is to be found elsewhere.1 Basically, it employs a series of fluidic modules, each of which is functionally distinct and interchangeable in kind. The power source is the standard 50 psi oxygen source. Excluding alarms and control knobs, there are only three moving parts. No electricity is required. The gas consumption is 8 to 10 liters per minute in excess of minute ventilation. Although quite different in principle, the ventilator is entirely comparable to other sophisticated ventilators in current use as regards the adjustment and application of the device. Volume, time, or pressure cycling is possible. A single visible bellows with a volume scale mounted on the canister is continuously adjustable from 100 ml to 3,300 ml. The bellows employs the bag-in-box principle for expulsion of gas. The bellows platform stop is adjusted to the desired tidal volume. Only the space from the platform to the top of the compartment is pressurized during inspiration, thereby minimizing inspiratory time delays and the effects of compartment compliance. As the bellows falls, oxygen is proportionately entrained with room air in the bellows compartment, and this gas mixture fills the bellows for the next inhalation, since air and oxygen concentration is detected by tidal volume, inspiratory pressure, or flow. The bellows unit is easily removed from the body of the ventilator to facilitate cleaning. Interchangeable bellows mechanisms may permit pediatric applications of the ventilator in the future.

The breathing rate is adjustable from less than 4 to over 90 breaths per minute. The inspiratory pressure wave form is a square wave pattern and flow is continuously adjustable from near zero to 100 liters per minute with a 50 psi oxygen supply. Patient triggering sensitivity is adjustable from +1 to −10 cm of water. A mode switch provides either controlled ventilation, in which case the patient is unable to initiate inspiration, or assist or control which allows either patient or rate control to initiate inspiration. A third assist setting requires the patient to initiate inspiration. A pressure limit feature is adjustable from approximately
10 cm to 100 cm of water. Two gauges indicate the pressure in the patient circuit and the preset pressure limit. There are three fluorescent visual indicators, all of which are pneumatically powered. They indicate patient triggering, time cycling and pressure cycling. If the selected pressure limit is exceeded, inspiration is terminated, and the pressure indicator flashes. If the machine is adjusted to volume cycle, but too low an inspiratory flow rate is chosen relative to the cycle rate and tidal volume, the time cycle indicator will flash, indicating the preset volume is not being delivered. When time cycling is employed, the inspiratory-expiratory ratio is adjustable from 1:1 to 1:4, and this ratio is maintained regardless of changes in cycle rate. During volume or pressure cycling, I:E ratio is a function of volume, breathing rate, and inspiratory flow settings.

Positive end-expiratory pressure may be set from zero to 20 cm of water. As is true of nearly all other ventilators with built-in PEEP, the positive pressure is created by bleeding gas into the exhalation valve mushroom, thereby creating a threshold resistor during the expiratory phase. On this ventilator, the PEEP control automatically biases the patient trigger sensitivity, and adjustment of the trigger sensitivity is not usually required as PEEP is varied. The controls are not otherwise independent, except as described during time cycling.

**Laboratory Evaluation**

The waveform, flow and volume performance of the ventilator was evaluated by using a simple lung model designed to simulate the impedances to ventilation that may occur in normal or disease states. The lung model and the volume performance testing followed guidelines that have been proposed elsewhere for the purpose of evaluating the performance of mechanical ventilators. The model incorporates a compliance and a resistance connected in series. The compliance chambers were 20 liter glass bottles filled with water to give the desired compliance volume. Resistances linear ±10 percent over the flow rates indicated were constructed from filter materials as described elsewhere. Flows were measured with a modified Monaghan 403 pulmonary function analyzer. This instrument was found to be accurate to ±5 percent for flows from 5 to 800 liters per minute, and is unaffected by changing impedance distal to the sensor. Volume was obtained by integrating flow with this same instrument. The pressure in the patient circuit (P1, airway pressure) proximal to the flow meter and the pressure in the compliance chamber (P2, alveolar pressure) were measured with Validyne DP7 transducers and ed 16 carrier demodulators. P1, P2, flow and volume were recorded on a Gulton TR-444 recorder.

Testing was performed using a complete patient circuit including a Monaghan 610 humidifier filled with unheated water. All tests were performed with the oxygen setting at 21 percent. Test gas conditions included: temperature, 21°C; relative humidity, 30 percent; barometric pressure 620 mm Hg; delivered oxygen concentration, 23 percent. Recorded flows and volumes were not corrected to standard conditions.

The waveform performance was tested with conditions of high compliance and low resistance (C=0.05 liters per cm H2O; R=5 cm H2O per liter per second) and those of low compliance and high resistance (C=0.020 liters per cm H2O; R=20 cm H2O per liter/second) at volumes of 500 and 1000 ml. The cycle rate was set at 20 breaths per minute. The machine has an arbitrary flow scale indicator graduated from 0 to 10. This was set at "1.5" for 500 ml tidal volumes and "4" for 1000 ml tidal volumes, in order to provide an I:E ratio of approximately 1:2. No other adjustments were made during the laboratory testing. To assess the effects that changes in supply pressure might have upon the performance of the ventilator, the tests were performed at the standard 50 psi supply pressure and at 35 psi. These tracings are recorded in Figure 2.

**Figure 3. Volume performance at increasing rates and against load.** The dashed line is the maximum theoretical volume at 100 L/min with I:E ratio of 1:2. The solid line is volume performance with the bellows set at the theoretical maximum volume against no load. The broken line shows volume performance with machine time cycling, I:E set at 1:2 and the bellows at 3,300 ml using ventilator analog with C=0.020 L/cm H2O, R=20 L/sec/cm H2O. The difference between the latter two curves is secondary to bellows compartment compliance.

**Figure 4. Ventilator flow vs pressure with increasing resistance and infinite compliance (room).** Solid line shows high flow capability and relatively linear flows despite increasing impedance. For contrast, similar data from another volume ventilator is shown (dashed line). Data from manufacturer's operating manual.
Volume performance was evaluated under conditions of relatively low compliance and high resistance (C=0.020 liters/cm\textit{H}O and R=20 cm\textit{H}O/liter/second). Both volume cycling and time cycling modes were employed, as illustrated in Figure 3. For volume cycling the machine was set to the theoretical maximum volume obtainable at 100 liters per minute flow with an I:E ratio of 1:2. For time cycling, the machine was set at an I:E ratio of 1:2 and to maximum flow, and the volume limit was set to its maximum of 3,300 ml. At a volume of 2 liters, the 100 cm pressure limit was reached. Maximum flow capabilities against increasing liters/cm\textit{H}O and R=20 cm\textit{H}O/liter/second) were recorded in Figure 4.

**CLINICAL EVALUATION**

The ventilator was used in our adult medical and surgical intensive care units over a period of several months. Twenty patients were ventilated, for a total of nearly 1100 hours. As

<table>
<thead>
<tr>
<th>Case</th>
<th>Diagnosis</th>
<th>Duration of Ventilation (hrs)</th>
<th>Peak Pressure (cm\textit{H}O)</th>
<th>Tidal Volume (ml)</th>
<th>Rate (breaths/min)</th>
<th>Average Minute Ventilation (liters)</th>
<th>Positive End-Expiratory Pressure (cm\textit{H}O)</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Postop evacuation of intracerebral hematoma</td>
<td>120</td>
<td>30</td>
<td>800</td>
<td>24</td>
<td>14.4</td>
<td></td>
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<td>2</td>
<td>Postop craniotomy for intracerebral aneurysm; pneumonia</td>
<td>120</td>
<td>22</td>
<td>800</td>
<td>20</td>
<td>14.0</td>
<td></td>
<td>Survived</td>
</tr>
<tr>
<td>3</td>
<td>Peritonitis; obesity-hypoventilation syndrome</td>
<td>48</td>
<td>40</td>
<td>900</td>
<td>25</td>
<td>18.0</td>
<td></td>
<td>Died, non-respiratory causes</td>
</tr>
<tr>
<td>4</td>
<td>Chronic airways obstruction; acute respiratory failure</td>
<td>24</td>
<td>50</td>
<td>400</td>
<td>18</td>
<td>5.2</td>
<td></td>
<td>Survived</td>
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<tr>
<td>5</td>
<td>Postop; aspiration pneumonia</td>
<td>12</td>
<td>40</td>
<td>750</td>
<td>15</td>
<td>11.2</td>
<td>10</td>
<td>Survived</td>
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<tr>
<td>6</td>
<td>Postresuscitation from cardiac arrest; CAO, congestive heart failure</td>
<td>24</td>
<td>24</td>
<td>700</td>
<td>24</td>
<td>15.0</td>
<td></td>
<td>Died; cardiac causes</td>
</tr>
<tr>
<td>7</td>
<td>Blunt chest trauma; flail chest; adult respiratory distress syndrome</td>
<td>96</td>
<td>35</td>
<td>800</td>
<td>15</td>
<td>11.3</td>
<td>10</td>
<td>Survived</td>
</tr>
<tr>
<td>8</td>
<td>Postop; pulmonary edema; pneumonia</td>
<td>96</td>
<td>40</td>
<td>700</td>
<td>24</td>
<td>16.0</td>
<td>10</td>
<td>Survived</td>
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<tr>
<td>9</td>
<td>Cardiogenic shock; pulmonary edema; CAO</td>
<td>48</td>
<td>42</td>
<td>450</td>
<td>19</td>
<td>6.8</td>
<td></td>
<td>Died; cardiac causes</td>
</tr>
<tr>
<td>10</td>
<td>Blunt chest trauma; flail chest; CAO</td>
<td>72</td>
<td>30</td>
<td>850</td>
<td>16</td>
<td>12.8</td>
<td></td>
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<tr>
<td>11</td>
<td>60% 3rd and 2nd degree burns; acute respiratory failure</td>
<td>5</td>
<td>60</td>
<td>790</td>
<td>44</td>
<td>33.4</td>
<td></td>
<td>Died; non-respiratory causes</td>
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<tr>
<td>12</td>
<td>Drug overdose; aspiration pneumonia; ARDS</td>
<td>30</td>
<td>16</td>
<td>550</td>
<td>24</td>
<td>13.2</td>
<td></td>
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<tr>
<td>13</td>
<td>Blunt chest trauma; pulmonary contusion</td>
<td>48</td>
<td>24</td>
<td>600</td>
<td>24</td>
<td>14.4</td>
<td></td>
<td>Survived</td>
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<tr>
<td>14</td>
<td>Pneumonia; carcinomatosis</td>
<td>120</td>
<td>60</td>
<td>600</td>
<td>20</td>
<td>12.0</td>
<td></td>
<td>Survived</td>
</tr>
<tr>
<td>15</td>
<td>CAO; acute respiratory failure</td>
<td>12</td>
<td>22</td>
<td>500</td>
<td>16</td>
<td>8.0</td>
<td></td>
<td>Survived</td>
</tr>
<tr>
<td>16</td>
<td>Postop thoracotomy and laparotomy for multiple gunshot wounds</td>
<td>48</td>
<td>30</td>
<td>850</td>
<td>16</td>
<td>13.6</td>
<td></td>
<td>Survived</td>
</tr>
<tr>
<td>17</td>
<td>Postop mitral valve replacement</td>
<td>96</td>
<td>35</td>
<td>1000</td>
<td>16</td>
<td>16.0</td>
<td></td>
<td>Survived</td>
</tr>
<tr>
<td>18</td>
<td>Postop laparotomy; peritoneal sepsis</td>
<td>12</td>
<td>60</td>
<td>1000</td>
<td>29</td>
<td>20.0</td>
<td></td>
<td>Died; non-respiratory causes</td>
</tr>
<tr>
<td>19</td>
<td>Drug overdose</td>
<td>36</td>
<td>30</td>
<td>600</td>
<td>14</td>
<td>8.4</td>
<td></td>
<td>Survived</td>
</tr>
<tr>
<td>20</td>
<td>50% 3rd degree burns; Gram-negative sepsis and pneumonia</td>
<td>24</td>
<td>25</td>
<td>800</td>
<td>14</td>
<td>11.2</td>
<td></td>
<td>Died; respiratory causes</td>
</tr>
</tbody>
</table>

**Table 1—Clinical Experience with the Fluidic Ventilator**
may be noted in the table, a wide spectrum of disease requiring mechanical ventilation was included. After gaining some experience with the ventilator, we commonly chose cases that we regarded as difficult problems in ventilatory care. A number of patients required positive end-expiratory pressure. Since we have at our disposal several modern volume ventilators, including the Bennett MA-I,* the Ohio 560,** and the Emerson* postoperative ventilator, we rarely had reason to choose the fluidic ventilator specifically other than to gain further experience in its use. By the same token we found it comparable and as versatile as those ventilators to which we were accustomed. The advantages of smaller external dimensions and quieter operation than some ventilators in common use were noted by physicians and nursing personnel. Although the machine may be volume, time or pressure cycled, we use it for volume cycled ventilation only. Humidification was provided by either of two heated cascade humidifiers, the Bennett model, or a Monaghan cascade humidifier prototype model 610. The machine was powered from standard oxygen outlets in the intensive care areas, frequently in parallel with other ventilators or IPPB devices with no difficulty.

**Discussion**

The promise of ventilators utilizing fluid logic was emphasized a few years ago by Weitzner and Urban. As our clinical and laboratory experience with this fluidic ventilator demonstrate, the Monaghan 225 is a sophisticated device with performance equal to that required for difficult problems in adult ventilatory care. To determine if a drop in the supply pressure of 30 percent would adversely affect the machine's usefulness, waveform testing was performed at both 50 and 35 psi. At the lower supply pressure, flow rates dropped proportionately, resulting in a 10 percent decline in breathing rate and minute ventilation. No alterations in performance other than those related to flow were noted in these circumstances. As the P1 (system pressure) tracings in Figure 2 reveal, a 100 millisecond inflation hold is a characteristic of the ventilator. The flow pattern, as is the case for most ventilators, is a square wave pattern. Under conditions of increased resistance, an accelerating portion of the flow curve is noted, the result of the ventilator's internal compliance.

The volume performance was tested with the bellows adjusted to the theoretical maximum volume (100 liters per minute × inspiratory time) and with the bellows set to the maximum of 3,300 ml. The difference between the two curves is the result of bellows chamber compliance. As mentioned above, this compliance is minimized by the unique bellows chamber design.

The pneumatic circuitry of this instrument offers an advantage in flow performance relative to most conventional ventilators. As shown in Figure 4, flow is maintained in a nearly linear fashion over a wide range of impedance (back pressure). Changes in resistance or compliance that might occur in the course of clinical volume preset ventilation will not alter the inspiratory/expiratory ratio or result in an uncomfortable pressure wave form for the patient. The importance of adequate flow capability in conditions of high resistance has been emphasized recently by Mills. Inadequate flows in some circumstances may result in unfavorable inspiratory/expiratory ratios and insufficient time for exhalation, resulting in possibly dangerous increases in residual volume. Of six ventilators tested by Mills, five allowed significant residual volumes in a test lung model under conditions simulating high airway resistance.

The nearly linear flow pattern against increased back pressure is fundamental to time cycled ventilation, because with such a pattern, changes in resistance and compliance will not result in significant changes in tidal volume and thus minute ventilation. Therefore, this ventilator functions essentially as a volume cycled machine when it is in the time cycled mode.

The ventilator has pneumatic-actuated fluorescent signals for pressure limit, time cycling and patient triggering. An optional alarm system, discussed in detail elsewhere, is currently marketed with an electric expiratory sensor that allows monitoring and display of tidal volume, rate and minute ventilation; it also provides audible and visible alarms for variations from preset limits for rate or tidal volume. Other alarm systems could be employed.

During the clinical trials, the delivered oxygen concentration was checked with a Hudson oxygen meter* that had been calibrated with room air and 100 percent oxygen. Within the limitations of this simple technique, the set and delivered concentrations were identical.

No provision for sigh is made on this machine. The need for periodic hyperinflation during anesthesia or volume ventilation has remained controversial. It became common practice to include a mechanism for sigh on volume ventilators after data appeared indicating that normal adults and poliomyelitic patients in tank ventilators had improved compliance after hyperinflation. In anesthetized patients, periodic hyperinflation appeared to improve pulmonary compliance and to decrease atelectasis and shunting. Subsequent work in anesthetized patients, animals, and in patients on positive pressure ventilators has not substantiated the earlier observations. Because of the relatively large tidal volumes typically employed, patients on positive pressure ventilation would seem unlikely to be benefited by sigh. It is possible that some patients in selected circumstances, particularly if ventilated with unusually small tidal volumes, might be benefited by periodic hyperinflations. However, it does not follow that a sigh mode need be provided on the ventilator. Proper suctioning technique, which should include hyperinflation of the lungs with gas delivered by means of a self inflating bag, will remain the mainstay in the prevention of atelectasis.

This instrument is small, light weight, pneumatically powered and quiet in operation. It would lend itself exceptionally well to mobile and military applications.

Fluidic circuits are basically maintenance free. A single minor mechanical difficulty encountered in our experience was apparently due to particulate matter in a fluid amplifier. Although no foreign material was discovered, the problem was resolved by cleaning the amplifier pneumatically. It is unlikely that particulate matter caus-

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* Bennett Respiration Products, Santa Monica, California.
** Ohio Medical Products, Madison, Wisconsin.
†† H. Emerson Co., Cambridge, Massachusetts.

* Hudson Oxygen Therapy, Temecula, California.
ing a fluidic circuit malfunction would be a common problem when medical gases are passed through the 5 micron sintered metal filter that the machine employs.

Fluidic technology has led to the development of a new mechanical ventilator with performance and sophistication equal to ventilators in common use. Additional manufacturers will be offering instruments of fluidic design in the near future. The promise of these ventilators lies in low initial cost, low maintenance, and excellent performance.

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