PERFORMANCE OF VENTILATORS
EFFECT OF CHANGES IN LUNG-TORAX COMPLIANCE

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As mechanical ventilators are substituted for the educated hand, the nature of their performance demands clear understanding. In clinical anesthesia we are accustomed to sense alteration in the patient's lung-thorax resistance and compliance by the "feel" of the bag. We alter as necessary the force on the bag to maintain adequate ventilation. Ideally, the perfect ventilator would perform equally satisfactorily and at the same time indicate the pressures and volumes delivered. To what extent some contemporary devices approach this ideal is demonstrated by the preliminary study of 5 different ventilators (1–3).

The technique and results herein reported are limited to assessing the performance of a given ventilator under the varying chest compliances which can occur in anesthetized adults. Only the controller types of machines are included in this preliminary survey.

SELECTION OF COMPLIANCE VALUES

It is generally agreed that anesthesia is accompanied by a decrease in lung-thorax compliance. The mean value for anesthetized adults in the series of Nims, Conner and Comroe (4) is 0.062 liter per centimeter of water. Holaday (5) observed an average compliance of 0.034 and a minimum of 0.022 liter per centimeter of water. Safar (6) reports values ranging from 0.018 to 0.071 liter per centimeter of water. Both these latter studies involve multiple factors including different body type, posture, various agents, relaxants and surgical encumbrance of the chest or abdomen. From their observations, a compliance value of 0.04 liter per centimeter of water is selected to represent "average" compliance. The value for "decreased" compliance is arbitrarily taken as 0.02 liter per centimeter of water. For "increased" compliance a pressure-volume relationship of 0.10 liters per centimeter of water is selected. This figure is of the order of those given by Nims, Conner and Comroe (4) and Comroe et al. (7) for conscious adults although somewhat higher than the maximum in Safar’s series (6) in anesthetized subjects.

The following 5 ventilators were available for this study: the Controller-Assistor device (1956 model) manufactured by J. H. Emerson

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& Co., described originally by Maloney, Derrick, and Whittenberger (1); the Jefferson Ventilator manufactured by Air-Shields, Inc., described by Gibbon et al. (2); the Roswell Park Respirator (3); the Moch Surgical Respirator distributed by V. Mueller and Co., and the Controlled Respiration Unit of the Stephenson Corporation.

**METHOD**

_Description of Test Equipment._—The ventilator, a Heidbrink 9B circle, and the simulated lung-thorax system were arranged as shown in figure 1. The absorber contains lime and the entire circuit utilizes 3 conventional corrugated breathing tubes. The compliance systems consisted of 3 rigid reservoirs. The "average" compliance system was a 40-liter carboy; the "decreased," a 20-liter reservoir; and the "increased," a 30-gallon drum.

![Diagram of test equipment](image)

**FIG. 1. Test equipment for assessing performance of ventilator with varying compliances.** One of 3 rigid reservoirs simulates the compliance of the patient’s chest. Strain gauges are calibrated to record the pressures and volumes delivered to the system by the ventilator being tested.

_Recording of Pressure and Volume._—A Statham strain gauge (0.4 PSIG) measured pressure changes in each of the three systems. The signal, amplified and recorded with Sanborn equipment, was calibrated against a water manometer during static conditions after successive increments of air were added or withdrawn. Gain and attenuation settings were the same for all systems. A deflection of 1.7 mm. on the Sanborn record was obtained in all three systems for each centimeter of water applied (fig. 1).

Another Statham pressure transducer (PR23-2D-30, range ± 10 cm. of mercury) indicated the volumes of air delivered into the rigid system. This measurement was calibrated by injecting and withdrawing known volumes of air with a large syringe. Attenuation settings were changed for each system so that increments of 100 cc. produced comparable recorded deflections (table 1).

_Test Procedure._—The 3 reservoirs described above were independ-
TABLE 1
CALIBRATION OF RECORDED VOLUMES IN LUNG-TORAX SYSTEMS

<table>
<thead>
<tr>
<th>Lung-Thorax System</th>
<th>Sanborn Amplifier Atten</th>
<th>Liters Introduced</th>
<th>Sanborn Deflection (mm.)</th>
<th>Pressure Developed (cm. H₂O)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average compliance (0.04 l./cm. H₂O)</td>
<td>5</td>
<td>0.1</td>
<td>5.0</td>
<td>2.5</td>
</tr>
<tr>
<td>Decreased compliance (0.021 l./cm. H₂O)</td>
<td>10</td>
<td>0.1</td>
<td>4.8</td>
<td>4.8</td>
</tr>
<tr>
<td>Increased compliance (0.102 l./cm. H₂O)</td>
<td>2</td>
<td>0.1</td>
<td>5.2</td>
<td>1.0</td>
</tr>
</tbody>
</table>

ently arranged so that simultaneous recording of pressure and volume could be made from any one of them by simple switching.

Each ventilator was adjusted to deliver a tidal volume of about 0.5 liters twenty times per minute in the “average” lung-thorax system. Then, without altering the controls, the ventilator was connected in turn to the “decreased” and the “increased” compliance systems, and changes in its action recorded. The pressures and volumes were not corrected to S.T.P. (the laboratory temperature was 25 C. and the atmospheric pressure was 752 mm. of mercury at the time of the experiments).

![Emerson controller-assistor](image1)
![Jefferson ventilator](image2)
![March surgical respirator](image3)
![Stephenson controlled respiration unit](image4)

**Fig. 2.** Pressure and volume records for four contemporary ventilators. Each ventilator’s adjustments are prefixed to deliver about 500 cc. into the “average” compliance system (0.04 liters/cm. of water). The effects of changes in the compliance upon the pressures and volumes produced by the ventilator are then determined.
RESULTS

The records of pressure and volume for 4 of the 5 devices investigated are reproduced in figure 2 and indicate the particular pattern employed for each. The effects of the three compliances upon the performance is evident. Silhouettes of the actual tracings facilitate comparisons of the peak excursions. The areas subtended are not pertinent.

<table>
<thead>
<tr>
<th>Ventilator</th>
<th>Emerson</th>
<th>Jefferson</th>
<th>Morch</th>
<th>Roswell Park</th>
<th>Stephenson</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume (cc.)</td>
<td>420</td>
<td>440</td>
<td>480</td>
<td>510</td>
<td>490</td>
</tr>
<tr>
<td>Pressure (cm. H$_2$O)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum</td>
<td>+13.0</td>
<td>+9.6</td>
<td>+7.9</td>
<td>+11.9</td>
<td>+13.0</td>
</tr>
<tr>
<td>Minimum</td>
<td>+1.1</td>
<td>-2.8</td>
<td>-5.7</td>
<td>-2.5</td>
<td>-1.1</td>
</tr>
<tr>
<td>Effective pressure change (cm. H$_2$O)</td>
<td>11.9</td>
<td>12.4</td>
<td>13.6</td>
<td>14.4</td>
<td>14.1</td>
</tr>
</tbody>
</table>

TABLE 2

VOLUMES AND Pressures Delivered by Ventilators in Average Compliance System (0.04 l./cm. of Water)

<table>
<thead>
<tr>
<th>Ventilator</th>
<th>Emerson</th>
<th>Jefferson</th>
<th>Morch</th>
<th>Roswell Park</th>
<th>Stephenson</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume (cc.)</td>
<td>230</td>
<td>230</td>
<td>400</td>
<td>400</td>
<td>450</td>
</tr>
<tr>
<td>Pressure (cm. H$_2$O)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum</td>
<td>+15.0</td>
<td>+9.6</td>
<td>+14.7</td>
<td>+18.1</td>
<td>+21.0</td>
</tr>
<tr>
<td>Minimum</td>
<td>+1.4</td>
<td>-3.1</td>
<td>-7.4</td>
<td>-3.4</td>
<td>-2.5</td>
</tr>
<tr>
<td>Effective pressure change (cm. H$_2$O)</td>
<td>13.6</td>
<td>12.7</td>
<td>22.1</td>
<td>21.5</td>
<td>23.5</td>
</tr>
</tbody>
</table>

TABLE 3

VOLUMES AND Pressures Delivered by Ventilators in Decreased Compliance System (0.02 l./cm. of Water)

<table>
<thead>
<tr>
<th>Ventilator</th>
<th>Emerson</th>
<th>Jefferson</th>
<th>Morch</th>
<th>Roswell Park</th>
<th>Stephenson</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume (cc.)</td>
<td>900</td>
<td>760</td>
<td>500</td>
<td>570</td>
<td>530</td>
</tr>
<tr>
<td>Pressure (cm. H$_2$O)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum</td>
<td>+11.6</td>
<td>+7.9</td>
<td>+3.9</td>
<td>+5.7</td>
<td>+5.7</td>
</tr>
<tr>
<td>Minimum</td>
<td>+0.8</td>
<td>-1.1</td>
<td>-2.0</td>
<td>-0.8</td>
<td>-0.8</td>
</tr>
<tr>
<td>Effective pressure change (cm. H$_2$O)</td>
<td>10.8</td>
<td>9.0</td>
<td>5.9</td>
<td>6.5</td>
<td>6.5</td>
</tr>
</tbody>
</table>

The volume and pressure values corresponding to figure 2 are given in tables 2, 3 and 4. The effects of changes in compliance upon the performance of the machines will be considered separately for each ventilator.

_Emerson Controller-Assistor._—Following the delivery of 420 cc. in the "average," there was a fall to 230 cc. in the "decreased" compli-
ance system and a slight increase in the pressure from 11.9 to 13.6 cm. of water (tables 2 and 3). However, the effect of an increased compliance was remarkable in that the ventilator delivered 900 cc. with an effective pressure of only 10.8 cm. of water (table 4). Thus, the three compliances resulted in relatively large changes in volume delivered with minor variations in pressure (fig. 2).

It was noted that the manometers on the ventilator indicated the same pressures for all three compliances.

The ventillator on this machine clearly indicated changes in minute volume. However, the values read too high in the “decreased” compliance and too low in the “increased” compliance systems. None the less, the ventillator readings were within 20 per cent of the recorded measurements, an accuracy sufficient for clinical purposes. Greater discrepancies occur when condensed water blocks the taps of the Venturi tube.

*Jefferson Ventilator.*—The volume of 440 cc. delivered in the “average” compliance system was similarly reduced to 230 cc. in the “decreased” compliance system without significant change in the pressure developed (tables 2 and 3). The effect of an increased compliance was a greater volume at a somewhat lower effective pressure (table 4). This device performed similarly to the Emerson (fig. 2).

The slight alterations in pressures read on the ventilator manometer might, with very careful observation, serve as an indication of changes in the patient’s chest compliance, but cannot be interpreted in terms of volumes.

*Morch Surgical Respirator.*—For all tests with this machine the lever labelled “pressure” was set at the maximal position, reading “high.” The 480 cc.-volume delivered in the “average” compliance fell only to 400 cc. when the compliance was decreased (tables 2 and 3). This response was attended by a rise in the delivered pressure from 13.5 to 22.1 cm. of water. The effect of increasing the compliance was an increase to only 500 cc. as a result of a lower effective pressure of only 5.9 cm. of water (table 4). Thus, in contrast to the preceding ventilators, this device responded to changes in compliance with lesser variations in volume and considerable changes in pressure (fig. 2).

In a closed system, free from leak, the volume scale on the device is reliable. Further, the aneroid manometer clearly depicts changes in the patient’s chest compliance.

*Roswell Park Respirator.*—The volume of 510 cc. in the “average” fell to 400 cc. in the “decreased” compliance system, despite an increase in delivered pressure from 14.4 to 21.5 cm. of water (table 2 and 3). An increase to 570 cc. at a pressure of 6.5 cm. of water was obtained in the “increased” compliance system (table 4). Probably the less efficient performance of this device relates to the peaked form of the curve employed.
As was observed with the Morch Surgical Respirator, the volume scale reflects the performance within about 20 per cent whereas the aneroid manometer serves to indicate changes in the patient's lung-thorax compliance.

*Stephenson Controlled Respiration Unit.*—During all tests with this ventilator, the weights on the positive and negative pressure beams were set at extreme positions marked +36 and −20 mm. of mercury.

A tidal volume of 490 cc. in the "average" fell only to 450 cc. in the "decreased" compliance system as a result of an increase in pressure from 14.1 to 23.5 cm. of water. With an increase in compliance a volume of only 530 cc. was obtained at a pressure of 6.5 cm. of water. Accordingly, in response to the three compliances, this ventilator demonstrated the smallest changes in delivered volume and, concomitantly, the widest changes in pressure.

In the absence of an aneroid manometer on this ventilator, the only evidence of altered compliance was minor changes in the excursion of the accessory bellows. The variations in these excursions were so slight that they would not serve as a reliable indication of changes in compliance.

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**Fig. 3.** Summary of results obtained with two classes of ventilators. Values for the Emerson and Jefferson are averaged. These machines, by their performance, conform to the designation "'pressure-limited, volume-variable.'" Values for the Morch, Roswell Park, and Stephenson ventilators are also averaged as their responses to compliance changes are comparable. Their performance is classified as "'volume-limited, pressure-variable.'"
CLASSIFICATION OF VENTILATORS

The foregoing results clearly demonstrate two classes of ventilators, and thereby suggest an informative classification based upon their pressure and volume behavior in response to varying external impedance. All 5 of these devices are time-cycled, that is, the cycling rate is prefixed by the operator, and thereafter remains relatively constant. Only one of these machines, the Emerson, is in addition patient-cycled; however, its performance as an assistor is not considered here.

The Emerson and Jefferson devices tend to attain pressures for which they are set and accordingly deliver volumes which vary primarily in response to changes in the system into which they operate. Thus both these machines may be classified as "pressure-limited, volume-variable."

The Moreh and Stephenson machines, on the other hand, possess diametrically opposite features. These ventilators tend to maintain the volume for which they are set and accordingly develop pressures which vary primarily under the influence of the system into which they operate. Therefore, this group is best designated "volume-limited, pressure-variable."

This classification is useful in suggesting not only the safe use of a particular ventilator but also the pertinent meter for depicting its performance continuously. A given machine should indicate numerically that information which the anesthesiologist otherwise obtains qualitatively through clinical skill.

RECOMMENDATIONS

For the "pressure-limited, volume-variable" machines a meter should be available on the device to indicate change in the volume delivered. In the "volume-limited, pressure-variable" types a manometer in the system is essential for showing changes in the patient's lung-thorax resistance and compliance. When either of these types of ventilator is employed in systems which are not closed, a volume meter at the patient's airway would be very advantageous. A suitable means for metering volume on the Jefferson machine is urgently recommended. Two schemes are available for this latter purpose.

The ventigrator, described by Maloney, Derrick, Whittenberger and Isaacs (8), may be used in a to-and-fro arrangement at the airway and calibrated to approximate the patient's minute volume.

An automatic type respiratory valve, as described by Ruben (9), and a ventilation meter* or dry gas meter† may be placed in the expiratory or "exhaust" line.

In the closed system without significant leakage, both pressure and volume are conveniently indicated without these measures only in the "volume-limited, pressure-variable" type.

* J. J. Monaghan Co., Denver, Colorado.
It is constructively recommended that a bellows and scale replacing the enclosed bag would improve the Jefferson ventilator. An aneroid manometer attached to the patient’s circuit would improve the Stephenson unit.

**Summary**

Pressure and volume measurements relating ventilator performance to changes in lung-thorax compliance are presented. This study demonstrates the need for the anesthesiologist to repeatedly readjust the controls of the Jefferson and Emerson devices to maintain alveolar ventilation within the patient’s requirements. Without these readjustments based on the anesthesiologist’s interpretation of the changes in the patient’s lung-thorax mechanics, the pressure-limited ventilator will inevitably produce either hypoventilation or hyperventilation depending upon the changes in chest compliance. The evidence for wide alterations in this property are now well established for anesthetized adults.

On the contrary, the current test favors the performance of the Stephenson and Morch devices in the face of such alterations in compliance. These “volume-limited, pressure-variable” machines, despite compliance variations of a half to twofold, maintain their preset stroke volume within 10 to 20 per cent and, furthermore, reveal the compliance variation by the simple expedient of an aneroid manometer. An informative meter for the “pressure-limited, volume-variable” devices must indicate volume, preferably at the patient’s airway. Availability of such a device would improve the safety use of all ventilators.

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**References**