The Function of Each Lung of Anesthetized and Paralyzed Man during Mechanical Ventilation

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Intralummary gas distribution of individual lungs was studied in five healthy anesthetized, paralyzed, and mechanically ventilated adult volunteers in the supine and both lateral decubitus positions. Comparison of the results with previous findings in conscious and spontaneously-breathing man indicated that the distribution of inspired gas during mechanical ventilation in anesthetized subjects is different. Inspired gas was more uniformly distributed within the individual lungs of mechanically ventilated anesthetized subjects in the supine position. There was a preferential distribution of tidal volume to the nondependent lung, in contrast to the preferential ventilation of the dependent lung in conscious, spontaneously-breathing man in the lateral position. Although relative end-expiratory lung volumes (that is, functional residual capacity) of individual lungs in persons ventilated mechanically in both positions were similar to those reported for the conscious, spontaneously-breathing subject, preferential ventilation of the nondependent lung and lesser ventilation of the dependent lung resulted in similar nitrogen clearances from the two lungs when the subjects were in the lateral position. This finding is in contrast to the significant differences between nitrogen clearances of the two lungs in spontaneously-breathing man in the lateral position. (Key words: Mechanical ventilation; Distribution of ventilation; Pulmonary N2 clearance; Body position; Differential lung function; Functional residual capacity.)

Results of a previous study† indicated that there is a different and probably more uniform intralummary distribution of inspired gas in anesthetized, paralyzed, and mechanically ventilated subjects than in the awake person. The mechanisms of the altered gas distribution have not been demonstrated. The aims of the present study were to define more clearly the changes in gas distribution and to gain insight into its possible mechanisms.

Methods

Each of five healthy unpremedicated young adult volunteers (physicians and nurse anesthetists) § was premedicated with scopolamine hydrobromide, 0.43 mg. iv, and then anesthetized with an intravenous injection of thiopental (total dose, 13 to 27 mg/kg) and meperidine hydrochloride (total dose, 1.6 to 2.7 mg/kg). Muscle paralysis was induced and maintained with continuous intravenous administration of succinylcholine chloride (total dose, 16 to 24 mg/kg). The larynx and trachea were sprayed with 4 per cent lidocaine, and the trachea was intubated with a cuffed double-lumen tube (Carlen). The subjects were studied in the supine and right and left lateral decubitus positions in various orders. Measurements were begun after the subjects had been in the position for 15 to 25 minutes. Anesthesia time was approximately 3 hours.

Uniformity of distribution of intralummary inspired gas was evaluated by analysis of pulmonary nitrogen clearance curves.2 The lungs

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† Consent to participate was given after suitable time for consideration had been allowed and after the nature of the study, the manner in which it would be conducted, and the possible risks had been carefully outlined and discussed with each subject in a lengthy interview.
FIG. 1. Diagram of circuit. The Bird Mark 7 (B7) respirator drives two Bird Mark 4 (B4) respirators. The anesthetized subject could be ventilated with either room air or oxygen by appropriate changes of the two-way valve (V1) and the specially designed multichanneled valve (V5). N, sampling needles of N2 meters; SG, strain gauges for lateral airway pressures; P, pneumotachographs; V4, unidirectional J-valves. V8, expiratory Bird valve; V9, expiratory solenoid valve; CB, collection bags for expired gases; RB, reservoir bag for analyzed inspired oxygen; CT, Carlen tube.

were ventilated through two matched nonrebreathing systems, so that the relative tidal volume of each lung was dependent only on conditions distal to the trachea (fig. 1). Oxygen flowed from a tank containing compressed and analyzed gas to a 13-liter reservoir bag, and from there to the concertina bag of a Bird Mark 4 respirator (driven by a Mark 7 respirator) and on through inspiratory lines of largebore tubing via heated Fleisch no. 1 pneumotachographs** and a multichannel valve to the lungs. The specially designed multichannel valve permitted the rapid change during exhalation from breathing air to breathing oxygen simultaneously for the two lungs. Expired gases flowed through two additional similar heated pneumotachographs, two expiratory solenoid valves †† activated by the Bird Mark 7 respirator and via large-bore tubing into two neoprene bags evacuated just prior to collection of gas. Nitrogen concentrations (nitrogen meter) of the inspired gases and lateral airway pressures were measured continuously between the multichannel valve and the endotracheal tube and recorded together with expiratory and inspiratory flow rates from individual lungs. The ECG (lead 2) and radial artery blood pressure also were recorded on a Honeywell 1912 oscillograph during the 7-minute nitrogen clearance period. Resistances to gas flow of the expiratory lines were 1.9 cm H2O at a flow rate of 0.5 l/sec. The mean flow resistances of the left and right lumina for the 39-F, 37-F, and 35-F Carlen tubes were 4.6, 6.8, 7.1, and 2.5, 6.0, and 5.1 cm H2O, respectively, at a flow rate of 0.5 l/sec. Peak inspiratory and expiratory flow rates did not exceed 0.5 l/sec. The deadspace in

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†† Skinner Electric Valve, New Britain, Conn.
The apparatus for each individual system was 18 ml. Arterial blood gas tensions and pH (electrodes) were measured at 37°C and corrected to nasopharyngeal temperature (thermistor).

Pneumotachographic resistances to gas flow were detected by a pair of matched differential strain gauges (Sanborn Model 270). They were calibrated by delivering known volumes of air from a 1,500-ml syringe. The volume of expired gas was obtained by graphic integration of the flow tracings. The nitrogen meters were calibrated before and after each study with humidified (37°C) analyzed gas. The accuracy of the meters was 0.5 to 1.0 per cent of nitrogen at concentrations of more than 10 per cent and 0.25 per cent of nitrogen at concentrations of less than 10 per cent. The mean nitrogen concentrations of the expired gases were determined for each breath from measurements of the simultaneously obtained flow rates and nitrogen concentrations corrected for lag (0.05 sec) of the nitrogen meter. Corrections also were made for nitrogen contained in the inspired gas mixture and nitrogen eliminated from blood and tissue, assuming relative blood flows to the right lung of 56, 55, and 61 per cent, respectively, for the supine and the left and right lateral decubitus positions (to our knowledge, relative blood flows to individual lungs in anesthetized, paralyzed, and mechanically ventilated man in the three positions studied are not available). The logarithm of the mean nitrogen concentration was plotted as a function of the number of breaths. The resulting curves were resolved graphically into their exponentials and ventilatory components were calculated by the method of Fowler and co-workers. The functional residual capacity of each lung was calculated from volume (gasometer) and nitrogen concentrations of alveolar (nitrogen meter) and total expired gas (duplicate Haldane analyses). The cumulative volume of ventilation needed to reduce the end-tidal nitrogen concentration to 5 per cent (vol to 0.05 F0.2) was determined from the records of flow-rate tracings and nitrogen concentrations of individual breaths for each lung.

Dynamic compliances of the individual hemithoraces were determined simultaneously for both sides in three subjects in the supine and two lateral positions at various tidal volumes after hyperinflation of the lungs three times to an airway pressure of approximately 30 cm H2O.

On another day, total lung capacities and subdivisions thereof were measured with a body plethysmograph while the subjects were in the sitting position, conscious, and breathing spontaneously.

### Results

The subjects' physical characteristics and lung volumes (seated, awake) are summarized in Table 1. All nitrogen clearance curves of the individual lungs of each anesthetized subject plotted on semilogarithmic paper were

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**Table 1. Physical Characteristics and Lung Volumes of the Subjects (Sitting, Awake, BTPS)**

<table>
<thead>
<tr>
<th>Subject</th>
<th>Sex</th>
<th>Age (Years)</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
<th>TLC</th>
<th>VC</th>
<th>FRC</th>
<th>RV</th>
<th>ERV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1†</td>
<td>M</td>
<td>29</td>
<td>172</td>
<td>70</td>
<td>6.7</td>
<td>4.9</td>
<td>4.0</td>
<td>1.9</td>
<td>2.1</td>
</tr>
<tr>
<td>2</td>
<td>F</td>
<td>24</td>
<td>156</td>
<td>44</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>3</td>
<td>M</td>
<td>33</td>
<td>183</td>
<td>76</td>
<td>8.8</td>
<td>5.6</td>
<td>5.6</td>
<td>3.2</td>
<td>—</td>
</tr>
<tr>
<td>4</td>
<td>M</td>
<td>31</td>
<td>173</td>
<td>69</td>
<td>7.1</td>
<td>5.2</td>
<td>4.2</td>
<td>1.9</td>
<td>2.4</td>
</tr>
<tr>
<td>5</td>
<td>F</td>
<td>28</td>
<td>180</td>
<td>80</td>
<td>6.8</td>
<td>5.3</td>
<td>3.4</td>
<td>1.5</td>
<td>1.9</td>
</tr>
<tr>
<td><strong>Mean</strong></td>
<td></td>
<td><strong>29</strong></td>
<td><strong>173</strong></td>
<td><strong>68</strong></td>
<td>7.4</td>
<td>5.2</td>
<td>4.3</td>
<td>2.1</td>
<td>2.2</td>
</tr>
</tbody>
</table>

*BTPS = body temperature and pressure saturated with water vapor; TLC = total lung capacity; VC = vital capacity; FRC = functional residual capacity; RV = residual volume; ERV = expiratory reserve volume.*

† Only Subject 1 was a cigarette smoker.
nonlinear and could be resolved graphically into two components, indicating that functional compartments with different nitrogen clearance rates exist in the individual lungs.

**Data Relative to Pulmonary Nitrogen Clearances of Individual Lungs of Anesthetized, Paralyzed, and Mechanically Ventilated Man**

Table 2 contains the mean values for the ventilatory components of individual lungs in the three body positions studied. Mean total functional residual capacity in the supine position was 2.52 l, which is only 0.4 l above the mean residual volume (sitting, awake) and 1.78 l below the mean functional residual capacity in the sitting and awake subjects. This appears to be an excessive reduction in functional residual capacity due to change in body position alone, and it probably includes a further reduction of functional residual capacity due to general anesthesia.

In the supine position there were significant differences between the right and left lungs in the mean values of functional residual capacity, gas volume necessary to reduce end-tidal nitrogen concentration to 5 per cent, and ideal average number of breaths (number of breaths during which nitrogen molecules would remain in a uniformly ventilated lung). The mean values of tidal volume, anatomic deadspace, fractional replacement per breath of the slowly-ventilated \( (1 - w_1) \) and fast-ventilated \( (1 - w_2) \) compartments, and pulmonary clearance delay (the extent to which complete clearance of nitrogen is retarded by the presence of uneven ventilation) in the two lungs were not significantly different.

After the subjects had been turned from the supine to the lateral decubitus position, total functional residual capacity (left plus right lung) rose significantly; the increase occurred in the nondependent lung, while the functional residual capacity of the dependent lung was not different from its value in the supine position. Similarly, total gas volume necessary to reduce end-tidal nitrogen concentration to 5 per cent was increased significantly; again, the increase occurred in the nondependent lung, while the value for the dependent lung was not different from its value in the supine position. Mean values for anatomic deadspace were significantly larger for the nondependent than for the dependent lung. With the subject in the left lateral position, mean values for tidal volume and for ideal and actual average number of breaths were significantly larger for the nondependent lung. The mean values of the other ventilatory components were not significantly different in the two lungs.

**Comparison of Function of Individual Lungs in Anesthetized and Ventilated and Spontaneously-breathing Awake Man**

Table 3 is a comparison of our data with those of Lillington et al.\(^1\) obtained previously in this laboratory with a similar technique in sedated and spontaneously-breathing normal subjects.\(^\dagger\)\(^\dagger\) Our data were obtained simultaneously from individual lungs; the data of Lillington and associates were obtained sequentially. Because of her small body size, Subject 2 of our study was excluded from the comparison in order to achieve a more uniform distribution of physical characteristics of the subjects in the two studies. Statistical significance of the comparison was not altered by this exclusion.

With the subject in the supine position and with similar tidal volumes and respiratory frequencies, no significant differences in anatomic deadspace and functional residual capacity were observed. Pulmonary nitrogen clearances were faster during mechanical ventilation than during spontaneous breathing while the patient was awake (smaller gas volume needed to reduce end-tidal nitrogen concentration to 5 per cent and smaller actual average number of breaths). The faster nitrogen clearances were achieved by a significantly larger fractional replacement per breath of the slowly ventilated compartment \( (1 - w_1) \) and of the total lungs (ideal average number of breaths) and by a significantly more uniform intrapulmonary distribution of inspired gas.

Anatomic deadspaces and tidal volumes for the nondependent lung were significantly larger in mechanically ventilated subjects in the lateral position. The functional residual

\(^1\) We replotted and analyzed the clearance curves in the study by Lillington et al. and obtained similar results.
TABLE 2. Data Relative to Pulmonary Nitrogen Clearance

<table>
<thead>
<tr>
<th>Ventilatory Component</th>
<th>Number of Subjects</th>
<th>Sputum Position</th>
<th>Left Lateral Position</th>
<th>Right Lateral Position</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Left Lung (Mean ± SE)</td>
<td>Right Lung (Mean ± SE)</td>
<td>Left Lung (Mean ± SE)</td>
</tr>
<tr>
<td>Tidal volume (ml)</td>
<td>5</td>
<td>310 ± 11</td>
<td>340 ± 53</td>
<td>5</td>
</tr>
<tr>
<td>Anatomic dead-space (not corrected for apparatus dead-space) (ml)</td>
<td>5</td>
<td>61 ± 11</td>
<td>85 ± 15</td>
<td>5</td>
</tr>
<tr>
<td>Functional residual capacity (liters)</td>
<td>5</td>
<td>1.16 ± 0.13†</td>
<td>1.30 ± 0.10</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8,7 ± 0.8</td>
<td>8,7 ± 0.8</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>4.35 ± 0.01†</td>
<td>5.49 ± 0.56</td>
<td>5</td>
</tr>
<tr>
<td>Fg, (liters) ‡</td>
<td>5</td>
<td>0.71 ± 0.03</td>
<td>0.80 ± 0.03</td>
<td>5</td>
</tr>
<tr>
<td>$\bar{1} - w_4$</td>
<td>5</td>
<td>0.13 ± 0.006</td>
<td>0.125 ± 0.009</td>
<td>5</td>
</tr>
<tr>
<td>$\bar{1} - w_3$</td>
<td>5</td>
<td>0.307 ± 0.023</td>
<td>0.201 ± 0.019</td>
<td>5</td>
</tr>
<tr>
<td>Ideal average number of breaths</td>
<td>5</td>
<td>5.08 ± 0.41†</td>
<td>0.23 ± 0.47</td>
<td>5</td>
</tr>
<tr>
<td>Actual average number of breaths</td>
<td>5</td>
<td>0.20 ± 0.38</td>
<td>7.20 ± 0.55</td>
<td>5</td>
</tr>
<tr>
<td>Pulmonary clearance delay (per cent)</td>
<td>5</td>
<td>23 ± 2.8</td>
<td>16 ± 3.1</td>
<td>5</td>
</tr>
<tr>
<td>Paco₂ (torr)</td>
<td>5</td>
<td>37 ± 2</td>
<td>37 ± 2</td>
<td>3</td>
</tr>
</tbody>
</table>

* Significant difference ($P < 0.05$) between left and right lung (lateral position).
† Significant difference ($P < 0.05$) between left and right lung (supine position).
‡ Gas volume necessary to reduce end-tidal nitrogen concentration to 5 per cent.
§ $f_i$ = fractional volume of slowly ventilated compartment; $1 - w_4$ = fractional replacement per breath of slowly ventilated compartment; $1 - w_3$ = fractional replacement per breath of the fast-ventilated compartment.
### Table 3. Comparison of Data Relative to Pulmonary Nitrogen Clearance in Sedated and Spontaneously-breathing Normal Subjects

<table>
<thead>
<tr>
<th>Ventilatory Component</th>
<th>Patient Awake; Spontaneous Ventilation* (Mean ± SE)</th>
<th>Patient Anesthetized and Paralyzed; Mechanical Ventilation (Mean ± SE)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Supine Lungs</td>
<td>Nondependent Lungs</td>
</tr>
<tr>
<td><strong>Tidal volume (ml)</strong></td>
<td>332 ± 42</td>
<td>240 ± 41</td>
</tr>
<tr>
<td><strong>Anatomic deadspace (not corrected for apparatus deadspace) (ml)</strong></td>
<td>70 ± 4</td>
<td>74 ± 5</td>
</tr>
<tr>
<td><strong>Functional residual capacity (liters)</strong></td>
<td>1.33 ± 0.11</td>
<td>2.13 ± 0.08</td>
</tr>
<tr>
<td><strong>Respiratory frequency (breaths/min)</strong></td>
<td>11.1 ± 1.7</td>
<td>12.2 ± 1.6</td>
</tr>
<tr>
<td><strong>Volume to 0.05 F&lt;sub&gt;N&lt;/sub&gt;&lt;sub&gt;1&lt;/sub&gt; (liters)</strong></td>
<td>8.13 ± 0.71</td>
<td>17.13 ± 1.58</td>
</tr>
<tr>
<td><strong>f&lt;sup&gt;1&lt;/sup&gt;&lt;sup&gt;$§$&lt;/sup&gt;</strong></td>
<td>0.82 ± 0.02</td>
<td>0.88 ± 0.02</td>
</tr>
<tr>
<td><strong>1 - w&lt;sup&gt;1&lt;/sup&gt;&lt;sup&gt;$§$&lt;/sup&gt;</strong></td>
<td>0.004 ± 0.008</td>
<td>0.042 ± 0.008</td>
</tr>
<tr>
<td><strong>1 - w&lt;sup&gt;2&lt;/sup&gt;&lt;sup&gt;$§$&lt;/sup&gt;</strong></td>
<td>0.321 ± 0.022</td>
<td>0.160 ± 0.018</td>
</tr>
<tr>
<td><strong>Ideal average number of breaths</strong></td>
<td>7.29 ± 0.71</td>
<td>17.91 ± 2.12</td>
</tr>
<tr>
<td><strong>Actual average number of breaths</strong></td>
<td>9.60 ± 0.93</td>
<td>22.79 ± 2.08</td>
</tr>
<tr>
<td><strong>Pulmonary clearance delay (per cent)</strong></td>
<td>32 ± 1.2</td>
<td>27 ± 4.2</td>
</tr>
</tbody>
</table>

* Calculated from individual data, which were obtained by Lillington and co-workers but which were not presented in their original paper.4

† Significant difference (P < 0.05) between patients awake with spontaneous ventilation and patients anesthetized, paralyzed, and with mechanical ventilation (rank sum).

§ See footnoto to table 2.

Data included in this table are mean values for two supine (left and right lung), nondependent (right lung in left lateral position and left lung in right lateral position), and dependent lungs (right lung in right lateral position and left lung in left lateral position). Subject 2 of our study is not included in this comparison (see Results). Statistical significance of the comparison has not been altered by this exclusion.
capacities were similar. The fractional replacements per breath of the slowly-ventilated and fast-ventilated compartments and of the total lung were greater for the nondependent lung in the ventilated subjects. This was caused by the increased effective tidal volume and unchanged functional residual capacity. In contrast, the dependent lungs of awake and anesthetized subjects showed similar fractional replacements per breath for the slowly-ventilated and fast-ventilated compartments. Some of the differences of the changes occurring in individual lungs of awake and anesthetized and ventilated subjects are shown diagrammatically in figure 2.

**Dynamic Compliances**

The dynamic compliances of individual hemithoraces measured simultaneously at a lung volume of 500 ml above the functional residual capacity were 33 ml/cm H2O for the left and 39 ml/cm H2O for the right hemithorax in one supine subject. The mean values for three subjects in the lateral decubitus position were 39 (SE ± 2.3) ml/cm H2O for the nondependent and 29 (SE ± 1.5) ml/cm H2O for the dependent hemithorax. This difference was significant ($P < 0.05$).

**Comment**

Traditionally, mechanical ventilation and spontaneous breathing have been thought of as being similar in basic mechanical events. This belief probably has been supported by the classic review article of Whittenberger, who, however, inferred that “... the spatial displacement of thoracic boundaries is probably different when natural breathing is compared with most forms of artificial respiration.” We, as well as others, have produced evidence for a different intrapulmonary distribution of ventilation during mechanical ventilation in anesthetized dogs and man. This paper provides further evidence for a different intrapulmonary gas distribution and data that may explain in part the earlier findings of a more uniform intrapulmonary gas distribution. Comparison of our data with those of Lillingston et al. in awake, spontaneously-breathing normal subjects in the supine position showed a more uniform gas distribution in the individual lungs; in subjects in the lateral position, our data showed a greater similarity of the nitrogen clearances (nitrogen clearance rate of a lung is determined by lung volume, deadspace-to-tidal volume ratio, and degree of nonuniformity of gas distribution) in the two lungs during mechanical ventilation than during spontaneous breathing. The difference between clearance rates for each of the two lungs under these two conditions is evident in figure 2, which was calculated from the mean data. The mean nitrogen concentrations of gas exhaled at the tenth breath were 9.5 and 13.5 per cent for the dependent and nondependent lungs in subjects in the ventilated state and 9.2 and 20.0 per cent in conscious, spontaneously-breathing subjects.

Normally, during spontaneous respiration, the dependent regions of the lungs in persons in the supine and lateral positions have a larger ventilation than those of the nondependent regions. The present study shows that during mechanical ventilation the dependent lung in the anesthetized person in the lateral position also had faster nitrogen clearance than did the nondependent lung. However, the differences between nitrogen clearances of the two lungs were less than those observed in conscious man. This finding of similar nitrogen clearances of the two lungs in subjects in the lateral position during mechanical ventilation may be the cause of the more uniform intrapulmonary gas distribution of the total lungs that we reported previously. Also, it is possible that the more uniform distribution of intrapulmonary gas observed within each lung of the supine anesthetized person during mechanical ventilation was the result of similar nitrogen clearances in the dependent and nondependent regions within the individual supine lungs.

In the subject in the lateral position, the similar nitrogen clearances of the two lungs could be the result of a decrease in vertical pleural pressure gradients during mechanical ventilation, which was recently demonstrated in dogs and rabbits. There is adequate evidence that normally the pressure inside the pleural cavity increases down the lung. Uneven distribution of inspired gas has been suggested to be the consequence of these regional differences in pleural pressure. Thus, the decrease of the regional differences in
pleural pressures during mechanical ventilation could result in different gas distribution. In a previous publication, we observed that the magnitude of the variations in nitrogen concentrations during the alveolar nitrogen plateau of the expirate was significantly less in the mechanically ventilated subject than in awake spontaneously-breathing man. The magnitude of the variations and the slope of the alveolar nitrogen plateau can decrease if either or both of the following occur: 1) the differences between nitrogen concentrations within or between the two lungs become smaller; 2) the two lungs empty more nearly synchronously. Evidence supporting the first possibility is that the intrapulmonary gas distribution is more uniform within each lung (subject in supine position) and the nitrogen clearances are similar in the two lungs (subject in lateral position). The effect of the second possibility on the slope and magnitude of the variations in nitrogen concentration remains unclear because a degree of asynchrony in emptying of the two lungs remains (fig. 3). With the subject in the supine position, the expiratory flow rates of the two lungs remained similar throughout the major part of expiration, whereas with the subject in the
lateral position during the course of an exhalation a progressively smaller proportion of the total expirate came from the dependent lung. A similar asynchronous sequence of emptying was noted by Koler et al., who observed that in erect, spontaneously-breathing man the right lower lobe emptied preferentially in early expiration and the right upper lobe in late expiration.

The decreased ventilation of the dependent lung during mechanical ventilation confirms previous observations. The gas volume received by the individual lung during mechanical ventilation is proportional to the driving pressure and inversely proportional to the impedance to gas flow. Since driving pressure was held equal for the two lungs, distribution of tidal gas was dependent only on the impedances of the two hemithoraxes. Impedance is the total opposition to gas flow into the lungs due to elastic, flow-resistive, and inertial forces of the respiratory system. If one assumes inertia to be negligible, gas flow will then be governed primarily by elastic and flow-resistive forces.

Our study does not provide direct measurements of the flow-resistive forces of the individual hemithorax, but useful inferences can be made. The mechanics of the respiratory system can be compared conveniently to a simple electric analog consisting of a linear resistor (R) and a capacitor (C) in series. The product of resistance and capacitance equals the time constant of the circuit (R × C = time constant). The time constant is the time needed to charge a capacitor to 63.2 per cent of maximal voltage, to discharge it to 36.8 per cent of its final voltage, or to charge or discharge a capacitor completely, if it continues to charge or discharge at its initial rate. In this analog, the rate of a passive expiration is determined by the product of resistance and compliance and should follow a single exponential function. Indeed, McIlroy et al.

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**Fig. 3.** Bilateral mean expiratory flow rates of five anesthetized, paralyzed, and mechanically ventilated subjects. Flow rates of expired gas from individual lungs were plotted as a function of time. Time scale reads from left to right. Expiratory rates were measured at intervals of 1/10 sec from the flow tracing of the first five breaths during the nitrogen-clearance period. Each point in the supine and left lateral position represents the mean of 25 observations from five subjects. Points describing the curves for the right lateral position represent the means of 20 determinations. Maximal expiratory flow rates of individual lungs were reached rapidly (approximately 50 msec) after exhalation commenced. The decelerating phases of expiratory flows decayed at similar rates in the two lungs in the supine position. In the lateral position flow from the nondependent lung decayed of emptying of the two lungs.
found an essentially exponential character of passive exhalations in conscious, voluntarily relaxed man.

We plotted expiratory flow rates for individual breaths of each hemithorax as a function of cumulative expired volume (fig. 4), as suggested by McIlroy et al. Each point in the supine and left lateral positions represents the mean of 25 observations from five anesthetized subjects, and in the right lateral position, the mean of 20 determinations in four anesthetized subjects. The slope of this line (tangent of θ) can be considered the time constant of each hemithorax. Time constants for the left and the right hemithoraces were similar (0.73 to 0.81 sec) for subjects in the supine and the right lateral decubitus positions and shorter for the left lung (0.47 sec) for subjects in the left lateral position.

Resistances of the two hemithoraces were calculated from the formula

\[ R = \frac{\text{time constant}}{\text{compliance}} \]

Resistance values of the left and right hemithoraces (including the Carlen's tube) were, respectively, 22.0 and 20.0 cm H₂O/l/sec with the subject in the supine position, 19.0 and 26.9 in the right lateral decubitus position, and 16.1 and 20.8 in the left lateral decubitus position. With tracheal pressure increasing throughout inspiration in a ramplike function, we can calculate the extent to which alveolar pressure in each lung approached tracheal pressure by using an electric analog. Alveolar pressure at any time (t) during the rise of airway pressure equals

\[ P_{alv} = \left( \frac{P_{trach}x_{al}}{T_1} \right) - \left( \frac{P_{trach}x_{al}x_{al}}{T_1} \right)[1 - e^{-t/R_{al}}] \]

where \( P_{trach} \) denotes tracheal pressure and \( T_1 \) the total duration of rise of tracheal pressure. Although the resistances of the left and right hemithoraces differed considerably, calculated alveolar pressures had risen to approximately the same extent in the dependent and non-dependent lungs (57 to 59 per cent of tracheal pressure) at end-inspiration. From this we conclude that the observed differences between respiratory compliances in the two hemithorax are primarily responsible for the relative distribution of the tidal volume between the two lungs.

Millie-Emili et al. have shown that at lung volumes of about 20 to 25 per cent of the total lung capacity (TLC), the dependent lung in awake, spontaneously-breathing man receives a smaller proportion of the inspired gas volume than does the nondependent lung. They suggested further that the greater expansion of the nondependent lung may be
due to airway closure in the dependent lung. Kaneko et al. showed that with the subject in the lateral position at lung volumes of less than 50 per cent TLC, the nondependent regions of the lung received a relatively larger proportion of the inspired volume. One might infer that this would explain completely our findings of preferential ventilation in the nondependent lung of the subject in the lateral decubitus position, since general anesthesia of supine subjects has been reported to reduce the functional residual capacity to levels approaching residual volume. However, we believe further investigations are necessary. The functional residual capacities of subjects in the lateral position in Lillington's and our studies were, respectively, 54 and 45 per cent of the TLC while the patient was in the erect position. Functional residual capacities of the dependent lungs (with the subject in the lateral position) were found to be the same in awake and anesthetized, paralyzed, and mechanically ventilated subjects. However, there was a greater distribution of inspired gas to the nondependent lung in anesthetized and ventilated individuals. It would seem, therefore, that intrapulmonary gas distribution is influenced by factors other than the regional distribution of alveolar volume.

In conclusion, the present study provides more evidence for a different mechanical behavior of the respiratory system in mechanically ventilated anesthetized man. At present the individual roles of general anesthesia and mechanical ventilation have not been determined. No predictions about the effect on gas exchange can be made from measurements of gas distribution alone.

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References