CARBON DIOXIDE HOMEOSTASIS DURING ANESTHESIA. II. TOTAL SAMPLING FOR DETERMINATION OF DEAD SPACE, ALVEOLAR VENTILATION, AND CARBON DIOXIDE OUTPUT * †‡

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The carbon dioxide analyzer and pneumotachograph permit a detailed analysis of certain homeostatic adjustments during inhalation anesthesia which have not been elucidated previously. By means of the calculations herein described, the carbon dioxide and flow data may be resolved to yield breath-by-breath determinations of dead space, alveolar ventilation, inspired carbon dioxide concentration, alveolar carbon dioxide concentration, and carbon dioxide output. Results of these determinations in conscious and anesthetized adults are discussed from a physiologic viewpoint.

Generally, the maintenance of normal carbon dioxide tension in the arterial blood depends upon an equality between production and output of carbon dioxide. Specifically, in the patient anesthetized with a closed system, carbon dioxide homeostasis involves: the rate of its production in the tissues, the capacity for and the transport rate of carbon dioxide by the blood, and the rate of its elimination from the lungs and rebreathing system. Obviously, carbon dioxide elimination depends upon both the alveolar ventilation and the adequate removal of carbon dioxide from the air rebreathed.

The occurrence of respiratory acidosis incident to inhalation anesthesia has been found by several investigators (1–6). This evidence is based on the demonstration of elevated carbon dioxide tensions in the arterial blood or upon remarkably high concentrations of this gas in the expired or tracheal air (7). Although the importance of adequate ventilation cannot be challenged, the excessive alveolar ventilation required to maintain arterial carbon dioxide tension within normal limits (5) suggests that either carbon dioxide production is inordinately increased or carbon dioxide rebreathing is present. No data on the rate of production of carbon dioxide in anesthetized man appear in the literature. The presence of significant concentrations of carbon dioxide in the inspired air, indicating inefficiency of the closed system

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886
(8), is frequently suspected. However, rebreathing of carbon dioxide has not been indicted previously as a major cause of the observed accumulation of carbon dioxide.

Customarily, alveolar ventilation is estimated by subtracting the product of respiratory rate and an assumed dead space from the minute ventilation. Neither alveolar ventilation nor dead space is subject to direct measurement. Estimations are confounded by the controversy concerning not only the magnitude and variability of the dead space but also its definition. Accordingly, an analysis of the methods and calculations employed to determine the dead space is appropriate. The pertinence of the calculated value for alveolar ventilation is limited by the method selected to measure the dead space. In methods which involve arterial gas tension to calculate alveolar ventilation, the dead space is regarded as a ventilatory shunt which does not affect the gas composition of the blood. By contrast, using gas methods which reconstruct a boundary between the dead space and alveolar air during expiration, the dead space is regarded as that fraction of the inspired tidal volume which did not, in effect, dilute alveolar air. By definition, the arterial and the gas methods deal with separate physiological entities which are related but not identical. The dead space values obtained from carbon dioxide and flow records reveal breath-to-breath variations whereas the arterial method yields an average value. These records further suggest a mixing phenomenon in the lung which is related to cardiac action. Rapid gas analysis affords the most convenient technique for studying such effects.

**Methods of Calculation**

The primary data consist of simultaneous records of carbon dioxide concentration in respired gas, both inspiratory and expiratory, and instantaneous flow rate of the respired gas. Time is marked at one second intervals.

The following methods pertain specifically to records obtained with total sampling of respired gas. Similar calculations are applicable to records utilizing fractional sampling to obtain the carbon dioxide concentration if the response time and the volume of the sampling tube are taken into account.

*Inspired or expired volume* is obtained by measuring the area between zero flow and the line indicating flow rate on the record. Since the pneumotachographic measurement is linear, the volume is represented by this area, which may be determined by either of two procedures: use of a planimeter or summation of increments.

*Tidal volume* is obtained by averaging inspired and expired volumes from at least four respiratory cycles.

*Minute volume* is the product of respiratory rate and tidal volume. *Carbon dioxide dead space* is obtained by graphic analysis of the
carbon dioxide and flow records. The first fraction of expired air has the same concentration of carbon dioxide as the last fraction of inspired air (fig. 1A). During the next part of expiration, the carbon dioxide concentration rises rapidly and reaches a "plateau." These two phases represent passage through the analyzer sampling tube of that volume of dead space air and alveolar air which is required to displace the dead space. In other words, the gas expired previous to attainment of the plateau consists of a mixture of dead space air and alveolar air. Estimation of the dead space from these records involves procedures by which the dead space air is separated from alveolar air.

The method which Fowler employed on records of flow and nitrogen concentration (9) is equally applicable to the records of flow and carbon dioxide concentration. A tangent to the initial part of the plateau of the carbon dioxide curve is drawn (fig. 1B). A vertical line is placed on the carbon dioxide record so that areas X and Y are equal. If the flow rate is constant, this vertical line indicates when alveolar air would appear if there were no mixing with dead space air. The vertical line is extended through the simultaneously recorded flow curve (neglecting correction for differences in response time). The area bounded by the expired flow curve and the vertical line represents the volume of dead space air. The remaining area under the expired flow curve represents alveolar air. The dead space volume includes the patient's dead space and part of the instrumental dead space. The latter is that part of the analyzer sampling tube between the patient and the path of the infrared beam (25 or 32 cc.). This method affords a convenient approximation of the dead space.

![Fig. 1A.](http://anesthesiology.pubs.asahq.org/pdfaccess.ashx?url=/data/journals/jasa/931679/)
FIG. 1B.

FIG. 1C.

Fig. 1. Records obtained by total sampling of respired air with carbon dioxide analyzer and pneumotachograph. A, Area on the expired flow curve before the carbon dioxide plateau is recorded represents kinetic dead space. Subsequent area represents undiluted alveolar air. B, Approximation method for determination of dead space from carbon dioxide and flow curves. C, Calculation of dead space by application of Bohr formula to successive intervals between the initial rise in expired carbon dioxide concentration to the alveolar plateau.

provided the flow rate is essentially constant during the interval between the appearance of carbon dioxide and attainment of the plateau. DuBois, Fowler, Soffer and Fenn (10) divided into short intervals the time during which the carbon dioxide concentration is rising. Then
these authors employed the Bohr equation to divide the volume expired during each interval into the alveolar and dead space fractions. The carbon dioxide concentration of the alveolar fraction in each interval is obtained by drawing a tangent to the plateau of the carbon dioxide curve (fig. 1 c). The average concentration actually expired in each interval is obtained by inspection of the record. The volume expired during each interval is obtained by multiplying the time by the average flow rate. Then the volume of alveolar air in the gas expired during each interval is calculated:

\[
\frac{\text{Volume \ alveolar \ air}}{\text{Volume \ expired}} = \frac{\text{"Average CO}_2\% \ expired"}}{\text{Estimated alveolar CO}_2\%}.
\]

These calculations are repeated for each of the intervals between the initial rise in carbon dioxide concentration and the point at which the plateau is attained. The total volume of alveolar air expired during this period is obtained by adding the volumes expired during the successive intervals. The dead space volume is the difference between this sum and the total volume of gas expired during this period. For convenience, the intervals selected were 0.04 second, since Sanborn recording paper was used with a recorder speed of 2.5 cm. per second.

Another method for deriving the dead space is a modification of the procedure employed by Hatch, Cook, and Palm (11). Again, the record is divided into convenient intervals. The carbon dioxide content (in cubic centimeters) of the gas expired during each interval is calculated by multiplying the volume expired by the average carbon dioxide concentration expired (fig. 1 c). The cumulative sums of carbon dioxide contents are plotted against the cumulative sums of ex-

![Fig. 2A.](image-url)
Fig. 2. A, Graphic analysis for determination of physiologic dead space, external dead space, carbon dioxide output per breath, alveolar ventilation per breath and average expired alveolar carbon dioxide concentration. B, Graphic method adapted for presence of carbon dioxide in inspired air.

pired volumes (fig. 2 A). A tangent is drawn to the first portion of the plotted curve which appears approximately constant in slope. This portion corresponds to the plateau on the carbon dioxide record. The intercept "C" of this tangent on the expired volume axis represents the dead space volume.

Carbon dioxide output was also measured by graphic determinations. A curve similar to that plotted for dead space determination (fig. 2 A) is carried on through the succeeding inspiration. The cumulative sums of inspired volume increments are plotted on an extension of the expired volume axis. The increments of carbon dioxide content during inspiration (representing the sampling tube volume and other external dead space) are subtracted from the total carbon dioxide expired. The quantity of carbon dioxide eliminated during the respiratory cycle may be read from the graph at the end of inspiration ("B" in fig. 2 A).

External dead space may be derived from the above graph. Two tangents are drawn to the inspiratory curve (fig. 2 A). The horizontal coordinate of the intersection of these tangents ("A") represents a dead space. This dead space volume includes the instrumental dead space distal to the infrared path (85 cc.) and the external dead space imposed by the breathing circuit.

Alveolar ventilation is calculated for each breath by:

\[
\text{Alveolar ventilation per breath} = \left( \frac{\text{Tidal volume}}{\text{Total dead space}} \right)
\]
For this calculation, dead space includes the patient’s dead space, the instrumental dead space (110 cc.) and the dead space of the breathing circuit.

**Average expired alveolar carbon dioxide concentration** is determined by dividing the net carbon dioxide content per breath by the alveolar ventilation per breath. The vertical coordinate of point “B” represents the net carbon dioxide content.

**Determinations in presence of elevated inspired carbon dioxide concentration.** The foregoing calculations are applicable when negligible carbon dioxide is inspired from the breathing circuit. Additional graphic procedures are required when there is incomplete absorption in the canister or significant leak of the breathing valves. In this case the graph constructed as in figure 2 A assumes the form shown in figure 2 B. The carbon dioxide dead space and the average expired alveolar carbon dioxide concentration are obtained as follows: in figure 2 B two lines are drawn which are tangents, respectively, to the first part of the expiratory curve and to the part corresponding to the plateau in the carbon dioxide record. These tangents intersect at “C.” The horizontal coordinate of “C” represents the physiologic dead space and part of the instrumental dead space (25 or 32 cc.). The average expired alveolar carbon dioxide concentration is obtained from the vertical coordinates of “C” and “A” by use of the following equation:

$$\text{Average expired alveolar CO}_2 \text{ concentration} = \frac{\left( \text{Total cc. of CO}_2 \text{ expired} \right) \text{ cc. of CO}_2 \text{ in dead space air}}{\left( \text{Alveolar ventilation per breath} \right) \text{ "A"}} \left( \text{"C"} \right).$$

The amount of carbon dioxide reaching the alveoli during inspiration is also calculated from the vertical coordinates of points indicated in figure 2 b:

$$\text{cc. of CO}_2 \text{ inspired into alveoli} = \left( \text{Total cc. of CO}_2 \text{ expired} \right) \text{ cc. of CO}_2 \text{ eliminated air} \left( \text{"A"} \right) \left( \text{"B"} \right) \text{ cc. of CO}_2 \text{ in dead space air} \left( \text{"C"} \right).$$

The minimum concentration of carbon dioxide inspired from the breathing circuit may be read directly from the analyzer record. Determinations of carbon dioxide output, alveolar ventilation and external dead space are made as previously described.

**Results**

Dead space measurements were obtained in 4 male and one female (J. B.) subjects, with ages ranging from 25 to 35 years (table 1). Three of these subjects were studied in both the sitting and standing
TABLE 1

<table>
<thead>
<tr>
<th>Subject</th>
<th>Posture</th>
<th>Tidal Volume (cc.)</th>
<th>Physiologic Dead Space (cc.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Average</td>
<td>Range</td>
</tr>
<tr>
<td>J. M.</td>
<td>Standing</td>
<td>765</td>
<td>665–810</td>
</tr>
<tr>
<td></td>
<td>Sitting</td>
<td>715</td>
<td>665–785</td>
</tr>
<tr>
<td>E. J.</td>
<td>Standing</td>
<td>1,050</td>
<td>750–1,280</td>
</tr>
<tr>
<td></td>
<td>Sitting</td>
<td>1,275</td>
<td>1,010–1,330</td>
</tr>
<tr>
<td>B. E.</td>
<td>Standing</td>
<td>535</td>
<td>425–680</td>
</tr>
<tr>
<td></td>
<td>Sitting</td>
<td>535</td>
<td>460–605</td>
</tr>
<tr>
<td>C. N.</td>
<td>Standing</td>
<td>825</td>
<td>710–940</td>
</tr>
<tr>
<td>J. B.</td>
<td>Standing</td>
<td>510</td>
<td>400–665</td>
</tr>
</tbody>
</table>

positions. Each value represents an average for 5 to 20 expirations which were selected from records that indicated a steady state.

Approximately 2.5 times the volume of the dead space must be exhaled during a normal expiration before undiluted alveolar air appears. The relation of the dead space to the volume required to wash it out (kinetic dead space) for all 5 subjects is shown in Figure 3. This relationship is linear for a single individual. For tidal volumes of 300 to 350 cc. or less, the dead space in adults is not completely exhaled during normal expiration. The lower volumes for dead space on this plot represent values obtained after breath-holding.

The interrelated effects of tidal volume and lung volume upon the

![Graph](image-url)  

**Fig. 3.** Relationship between physiologic dead space and kinetic dead space for 5 normal subjects.
dead space of one male subject are shown in figure 4. Both the functional residual volume and the tidal volume were varied stepwise and independently. When tidal volume was maintained nearly constant but functional residual volume was increased stepwise, an increase of 14 cc. was found in the dead space for each liter increase in functional residual volume. Similarly, when tidal volume was increased from 1 liter upward and the functional residual volume was maintained constant, the same increase in dead space per liter increase in tidal volume was observed.

For tidal volumes of less than 1 liter, the dead space was markedly reduced by small decreases in tidal volume. A reduction of 100 cc. in the tidal volume reduced the dead space by 15 to 20 cc.

Breath-holding, or a short postinspiratory pause, reduced the dead space (fig. 5). The dead spaces found after varying intervals of
breath-holding were plotted as percentage of the dead space found when there was no pause. Breath-holding for two seconds was found to reduce the dead space by about 50 per cent. A significant reduction in dead space below 50 per cent required a very much longer period of breath-holding.

Cyclic variations appeared in the expired carbon dioxide concentration which were related to the cardiac cycle (fig. 6). The volumes of air moved at the pneumotachograph during these cardiopneumographic cycles were found to range between 2.5 and 35 cc. The cyclic variations in the carbon dioxide concentration involved 0.25 cc. of carbon dioxide in an expired volume of 180 cc.

The methods described above may be applied to the study of carbon

**Fig. 5.** Rate of decrease in physiologic dead space during breath-holding.

**Fig. 6.** Cyclic variations in expired carbon dioxide concentration related to the cardiac cycle.
dioxide homeostasis during anesthesia (table 2). An adult patient was coupled to the carbon dioxide analyzer and the pneumotachograph by means of a rubber mouthpiece, and the nasal airway was occluded. The carbon dioxide and flow records were started prior to intravenous premedication, and continued without interruption for one and a half hours until plane 3, stage III ether anesthesia was attained and the

<table>
<thead>
<tr>
<th>Time and Medication</th>
<th>Average Inspired CO₂ Concentration (% per minute)</th>
<th>Respiratory Rate (per minute)</th>
<th>Tidal Volume (cc)</th>
<th>Minute Ventilation (LPM)</th>
<th>Dead Space Effective (cc)</th>
<th>Without ext. ds (cc)</th>
<th>Alveolar Ventilation (LPM)</th>
<th>Alveolar CO₂ (mm. Hg)</th>
<th>CO₂ Output (cc. per min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11:40 (basal, before premed.)</td>
<td>0.03</td>
<td>172</td>
<td>320</td>
<td>55</td>
<td>180</td>
<td>70</td>
<td>2.40</td>
<td>39.0</td>
<td>123</td>
</tr>
<tr>
<td>10 mg. morphine sulphate, 0.4 mg. Atropine Sulphate IV at 11:45</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12:00</td>
<td>15 minutes after IV prem.</td>
<td>0.03</td>
<td>143</td>
<td>350</td>
<td>4.7</td>
<td>175</td>
<td>65</td>
<td>2.24</td>
<td>40.5</td>
</tr>
<tr>
<td>12:15</td>
<td>30 minutes after IV prem.</td>
<td>0.03</td>
<td>120</td>
<td>350</td>
<td>4.2</td>
<td>175</td>
<td>65</td>
<td>2.10</td>
<td>40.5</td>
</tr>
<tr>
<td>Demerol 100 mg., Scopolamine 0.5 mg. IV (completed 12:30)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12:45</td>
<td>15 minutes after Dem. Scopolamine</td>
<td>0.03</td>
<td>85</td>
<td>450</td>
<td>3.6</td>
<td>175</td>
<td>65</td>
<td>2.17</td>
<td>36.0</td>
</tr>
<tr>
<td>Circle filter with 10 LPM O₂ inflow (semi-closed system started 12:40)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12:49</td>
<td>0.40</td>
<td>5.0</td>
<td>520</td>
<td>2.6</td>
<td>160</td>
<td>70</td>
<td>1.69</td>
<td>41.0</td>
<td>85</td>
</tr>
<tr>
<td>Circle filter closed (300 cc. O₂ inflow), Ether started 12:50.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12:54</td>
<td>1.6</td>
<td>113</td>
<td>425</td>
<td>4.8</td>
<td>160</td>
<td>70</td>
<td>2.04</td>
<td>44.0</td>
<td>85</td>
</tr>
<tr>
<td>12:56</td>
<td>1.6</td>
<td>120</td>
<td>330</td>
<td>4.0</td>
<td>175</td>
<td>65</td>
<td>1.80</td>
<td>45.0</td>
<td>76</td>
</tr>
<tr>
<td>Absorber filled with fresh soda lime at 12:57</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1:00</td>
<td>0.15</td>
<td>10.4</td>
<td>490</td>
<td>5.1</td>
<td>160</td>
<td>70</td>
<td>324</td>
<td>42.0</td>
<td>170</td>
</tr>
<tr>
<td>1:03</td>
<td>1st plane anaesthesia</td>
<td>0.1</td>
<td>13.0</td>
<td>440</td>
<td>5.7</td>
<td>160</td>
<td>70</td>
<td>3.30</td>
<td>39.5</td>
</tr>
<tr>
<td>1:07</td>
<td>2nd plane anaesthesia</td>
<td>0.1</td>
<td>25.6</td>
<td>365</td>
<td>9.95</td>
<td>175</td>
<td>65</td>
<td>4.75</td>
<td>39.5</td>
</tr>
<tr>
<td>1:15</td>
<td>3rd plane anaesthesia</td>
<td>0.1</td>
<td>18.0</td>
<td>350</td>
<td>6.3</td>
<td>175</td>
<td>65</td>
<td>3.08</td>
<td>39.5</td>
</tr>
</tbody>
</table>

surgical procedure was started. A low basal carbon dioxide production rate of 123 cc. per minute was found in this emaciated patient. Thirty minutes after intravenous premedication, the respiratory rate was depressed, the tidal volume elevated and the alveolar carbon dioxide tension increased by 1.5 mm. of mercury. Intravenous demerol-scopolamine produced further decrease in respiratory rate and increase in tidal volume without significant elevation of the alveolar
carbon dioxide tension. With several minutes’ use of the closed system, elevation of the inspired carbon dioxide concentration was attended by rapid rise in alveolar carbon dioxide tension. The soda lime in this absorber had been used previously for two hours. Substitution of an absorber containing fresh soda lime reduced the inspired carbon dioxide concentration and permitted the patient to maintain normal alveolar carbon dioxide tension. These data illustrate the utility of the carbon dioxide and flow measurements for detecting the rapid effects of and adjustments to anesthetic drugs.

The striking changes in carbon dioxide output during anesthesia, which this study shows, have not previously been demonstrated. Carbon dioxide output dropped to 85 cc. per minute with opiate depression. Subsequently, during induction of ether anesthesia, the carbon dioxide output further decreased to 76 cc. per minute and the alveolar carbon dioxide tension was elevated. However, a marked increase in carbon dioxide output appeared with the attainment of the surgical planes. The maximal value of 235 cc. per minute during plane 2 was obtained after alveolar carbon dioxide concentration had returned to normal. The latter value probably reflects the previous interval of carbon dioxide accumulation.

**DISCUSSION**

Continuous analysis of carbon dioxide concentrations in respired air reveals, when properly executed, the variations in ventilation. In contrast with arterial blood methods, the rapid infrared carbon dioxide analyzer promptly indicates departures from the steady state. Indeed, conscious normal subjects seldom exhibit uniformity of ventilation and the records show irregular variations, the average of which represents, over prolonged periods, a “steady state.” On the other hand, comatose or anesthetized patients may have a remarkable uniformity of breathing so that the “steady state” values may be read with each cycle.

The major source of error in the use of the carbon dioxide analyzer for measurement of respired carbon dioxide concentrations is instrumental response time. Impedance matching between the Model 16 electronic section and the oscillographic recorder may be necessary to obtain optimal damping of the recorded signal. In order to follow the changing carbon dioxide concentrations in respired air rapidly enough to obtain interpretable alveolar plateau values, a 90 per cent response time of 0.10 second is required. With slower response, the alveolar plateaus are not reliable when the patient’s respiratory rate exceeds 20 per minute.

Another source of error is the failure to sample undiluted alveolar air when tidal volume is inadequate. Leaks in the connections between sampling tube and the patient also vitiate the results.

The primary limitation of the total sampling method for analysis
of respired carbon dioxide is the 50 or 64 cc. external dead space of the sampling tube. Even this slight increase in total dead space is excessive for children or for any patient unable to accommodate by increasing tidal volume. In such patients fractional sampling is preferable. However, an endotracheal tube reduces the dead space of the upper airway of an adult patient by approximately 50 cc. Total sampling avoids the dilution of the alveolar gas which occurs with fractional sampling when the sampling flow rate exceeds the respiratory flow rate. Moreover, total sampling does not require additional sampling equipment.

The difficulties of measuring the average alveolar carbon dioxide concentration at the upper airway were pointed out by Lindhard (12). Since alveolar air is not sampled during inspiration, the values observed are discontinuous, and the carbon dioxide concentration measured represents only alveolar concentration during a relatively short portion of expiration. Estimations of average alveolar carbon dioxide concentrations from measurements of expired air after breath-holding have been calculated by DuBois, Brit, and Fenn (13). These calculations indicated that the average alveolar carbon dioxide concentration occurs in the alveoli slightly after midexpiration.

From the foregoing considerations it may be seen that a strict agreement of alveolar measurements with arterial determinations would be fortuitous. A precise correlation should demonstrate the blood values to be systematically greater than the expired alveolar carbon dioxide concentrations. Collier, Affeldt and Farr, utilizing the fractional sampling technique with the carbon dioxide analyzer, have recently compared arterial carbon dioxide tensions with infrared plateau values (14). They found the arterial values to exceed the plateau values by a mean deviation of 1.0 mm. of mercury (S.D. = 1.7 mm. of mercury).

Since the dead space value calculated from arterial measurement includes all the physiological factors operating between arterial blood and the external environment, it may properly be termed the physiologic dead space. Factors which influence the physiologic dead space include the average ventilation-perfusion ratio, the arterial-alveolar carbon dioxide diffusion gradient, and the inefficiency of gas exchange resulting from the period gas remains in tracheobronchial tree.

In contrast, the dead space value obtained by delineation of the boundary between dead space air and alveolar air is an aerodynamic measure of that part of tidal air which, in effect, did not dilute alveolar air. This aerodynamic dead space is not dependent upon absolute values of the alveolar gas concentration. The single requirement of this method is that a segment of the alveolar plateau be established. From this segment the boundary between dead space and alveolar air can be delineated. Only an increase in the physical dimensions of the tracheobronchial tree can increase this dead space value. All other
factors tend to reduce its volume. These factors include sequential ventilation and gaseous or mechanical diffusion of alveolar air into the bronchial tree. The anatomical dead space is the upper limit of the aerodynamic dead space.

A number of investigators have studied the dead space. Henderson reported values for carbon dioxide dead space in normal adult subjects ranging from 154 cc. to 1,200 cc., the larger values associated with tidal volumes of 2 to 4 liters (15). The dead space was calculated on the assumption that end-expiratory carbon dioxide concentration represents the average alveolar concentration. Since the alveolar carbon dioxide concentration increases during expiration, the calculation of dead space is in error by a factor which may be as large as 4.

Haldane obtained a range of dead space values between 111 cc. and 683 cc., the magnitude of carbon dioxide dead space varying with tidal volume (16). His modification employed an average of the end-inspiratory and end-expiratory concentrations.

Krogh and Lindhard, using Siebeck’s method involving single inspirations of hydrogen, found in one individual dead space values ranging from 136 to 156 cc. with tidal volumes between 600 and 1100 cc. (17). They disputed the large increases in dead space which Henderson and Haldane had reported.

Fowler reported a mean value of 156 cc. (S.D. = 28 cc.) for the nitrogen dead space in 49 subjects (9). Dead space values ranged between 106 and 209 cc. and tidal volumes varied between 276 and 1,449 cc. He concluded that the nitrogen dead space was a variable fraction of both tidal and lung volume.

The values for dead space for normal adults herein reported agree closely with the larger series of Fowler (9). An increase in dead space results from an increase in tidal volume and from an increase in functional residual volume. The value of 200 cc. for the dead space with tidal volumes of 1,000 cc. approximates the estimates of anatomical dead space (18–19). For increases in tidal volume above a liter, the increment found in the carbon dioxide dead space does not exceed that which would be produced by expansion of the bronchial tree. For tidal volumes less than 1 liter, the change in dead space with change in tidal volume is of greater magnitude. These data suggest that with lower tidal volumes not all of the potential dead space participates in ventilation.

A definite increase in the dead space was found when normal subjects changed from the standing to the sitting position. In the sitting position, diaphragmatic breathing is restricted and relatively greater expansion of the upper chest occurs. As relatively more of the lung, namely the apices, participates in ventilation, a concomitant increase in dead space would be anticipated.

Previous studies by others of the cardiopneumographic pattern (fig. 6) have shown volumes ranging from 4 to 30 cc. (20). The me-
chanical effects of the cardiac contraction would be expected to produce greater movement of air within the chest than would appear at the upper airway. It is postulated that the portions of the lung adjacent to the heart are ventilated at the cardiac rate with a volume of about 50 cc. As a result, the carbon dioxide concentration in these alveoli decreases below that in the remainder of the alveoli during inspiration and slowly approaches the alveolar carbon dioxide concentration prevailing elsewhere as expiration is prolonged. A "pendel-luft" between various portions of the lung would introduce alveolar air into the bronchial tree. Such an effect would reduce the bronchial dead space rapidly by a to-and-fro movement of air between communicating bronchi. The movement of air between the main stem bronchi would probably not markedly dilute the dead space air within the trachea. This may account for the observed rate of decrease in the physiologic dead space with breath-holding. The rapid decline which was demonstrated to require about 2 seconds probably represents essentially complete mixing of bronchial dead space air with alveolar air. Therefore, the physiologic dead space would be reduced to about half the normal value. The slower decline in the remaining dead space would represent gradual mixing and diffusion between tracheal and bronchial air. Fowler has attributed the diminution in dead space during breath holding to the diffusion of alveolar air into the bronchial tree (11). However, the mixing produced by movements of the heart is probably a more important factor. The cardiac effect would reduce the dead space more rapidly but more irregularly than would diffusion. Since the cardiac beat does not occur regularly with any specific time relationship to the beginning of expiration, the dead space values of consecutive breaths should vary despite uniformity in respiratory flow pattern and tidal volume. A variation of 20 cc. in dead space values has been noted in anesthetized patients with endotracheal intubation during a regular uniform pattern of breathing.

From the foregoing considerations it is apparent that alveolar ventilation calculated from the dead space values obtained by analysis of the carbon dioxide and flow records will differ from that calculated using arterial carbon dioxide concentration. It is also evident that the estimation of alveolar ventilation by subtraction of an assumed dead space value from the tidal volume is inaccurate, particularly in view of the several factors that influence the volume of the dead space air. In this study these factors have been demonstrated to include tidal volume, residual lung volume, duration of inspiration and post-inspiratory pause, and the time relation between the heart beat and the beginning of expiration.

**Summary**

Procedures and calculations for total sampling of respired gas with the rapid infrared carbon dioxide analyzer and the pneumotachograph
have been applied to the determination of physiologic dead space, alveolar ventilation and carbon dioxide output.

Data in normal subjects have demonstrated that the physiologic dead space is altered by changes in posture, inspired volume, functional residual lung volume, duration of breath-holding and the time relationship of expiration to the cardiac cycle. The dead space values observed for tidal volumes exceeding 1 liter agree with estimates of anatomical dead space. The reduction of the dead space during the first 2 seconds of breath-holding is postulated to result primarily from the 'pendelluft' produced by the heart beat.

The observed cyclic changes in expired carbon dioxide concentration which are related to the cardiac cycle suggest that segments of the lung adjacent to the heart are, in effect, hyperventilated as a result of the heart beat.

During anesthesia, the carbon dioxide and flow recording technique has been used to monitor continuously the alveolar carbon dioxide concentration. Analysis of selected segments of these records permits determinations of alveolar ventilation and carbon dioxide output throughout anesthesia. The methods described provide detailed evidence of rapid or transient effects of anesthetic agents upon the patient's carbon dioxide homeostasis.

REFERENCES