# *Mechanics of Respiration in Apneic Anesthetized Infants*

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**The mechanics of respiration were studied during nitrous-oxide halothane anesthesia in 15 apneic infants (weight range, 2.2–5 kg.) ventilated by a time-cycled constant flow ventilator. The dynamic lung-thorax compliance was 2.8 ± 0.3 ml./cm. of water. The dynamic lung compliance was 3.3 ± 0.3 ml./cm. of water and the dynamic chest wall compliance was 22.3 ± 3.5 ml./cm. of water. The inspiratory airway resistance (including tissue viscous resistance) was 63.9 ± 3.7 cm. of water/liter/second. The calculated inspiratory work was 6,499 ± 567 g. cm./minute. The elastic inspiratory work was 4,697 ± 427 g. cm./minute. Seventy-two per cent of the total inspiratory work was done against elastic forces. The static total, lung and chest wall compliances were determined in the same infants and did not differ significantly from the corresponding dynamic values.**

**Substituting the determined values for compliance and resistance in a simplified equation of motion for the lung thorax, it was found that the pressures required for inflation of the lung in anesthetized infants are in the same range as in adults.**

DEFINITIVE and quantitative studies on the mechanics of respiration in the anesthetized and nonanesthetized subject have served as a basis for the physiologic management of ventilation of the adult during anesthesia. Data obtained from studies on adults unfortunately cannot serve as a basis for the physiologic respiratory management of the anesthetized infant because of anatomical and physiological differences.

A review of the literature reveals one study[1] relating the mechanics of respiration in anesthetized infants, which reports only the static total or combined lung and chest wall compliance (*i.e.*, during a sustained inflation with no flow of gases). Studies on the dynamic aspects of lung inflation in the anesthetized intubated infant have not been reported. The present study was undertaken to analyze the dynamic lung, chest wall and combined lung-chest wall compliance (*i.e.*, a breath-to-breath analysis) and the nonelastic or viscous resistance of the airway and lung and chest wall tissues. This study will determine the contribution of the elastic resistance (reciprocal of compliance) of the lung and chest wall and of the nonelastic or flow resistance of the airway and lung-thorax tissues to the total pressure required for the inflation of the lungs and thorax in anesthetized infants. Data will be presented showing that this information can serve as a basis for the physiologic management of controlled respiration (intermittent positive pressure breathing) of the infant during anesthesia and operation.

## Procedure

Fifteen infants scheduled for inguinal herniorrhaphy or pyloromyotomy, ranging in age from 3 days to 105 days without apparent signs of cardiorespiratory disease, were selected for this study. The tracheas of the infants were intubated with a snugly fitting uncuffed endotracheal tube (size 14–16 French) without anesthesia one hour after premedication with 0.12 to 0.15 mg. of atropine sulfate. Induction of anesthesia was carried out by means of a Y tube insufflation technique using a 2 liter per minute flow each of $N_2O$ and $O_2$. Halothane 1 to 2 per cent was added as necessary from a Fluotec vaporizer. Induction of anesthesia averaged 8 to 10 minutes. After obtaining a surgical level of anesthesia, controlled respiration was instituted using an electronic Y tube ventilator.[2] The tidal volume was adjusted to that predicted by the Radford nomogram at a frequency of 20 to 30 cycles per minute. Dynamic respiratory

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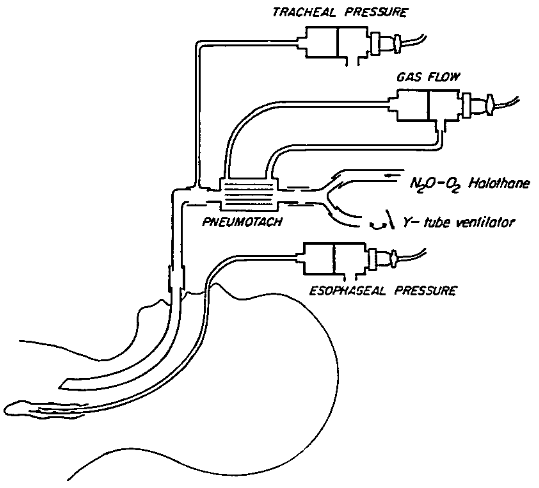


Fig. 1. Schematic representation of apparatus for measurement of airway and esophageal pressure and respiratory gas flow in an anesthetized infant.

flow, pressure and volume observations were made during a steady state of anesthesia with the infants in the supine position. Immediately following these observations the lungs were inflated to the predicted tidal volume by means of a calibrated syringe. The inflation

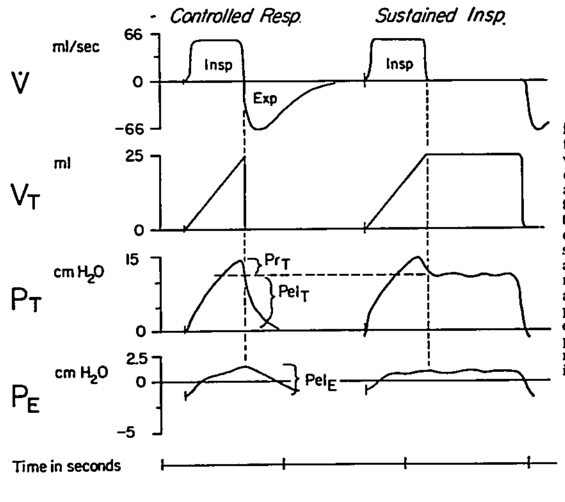


Fig. 2. Respiratory gas flow (V̇), inspiratory tidal volume ($V_T$), airway pressure ($P_T$), and esophageal pressure ($P_E$) as recorded from an anesthetized 4-kg. infant. The total airway pressure was divided into the flow resistive component ($Pr_T$) and the elastic component ($Pel_T$) by dropping a vertical line from the point of zero flow at the end of inspiration to the pressure tracing to determine the pressure at that instant.

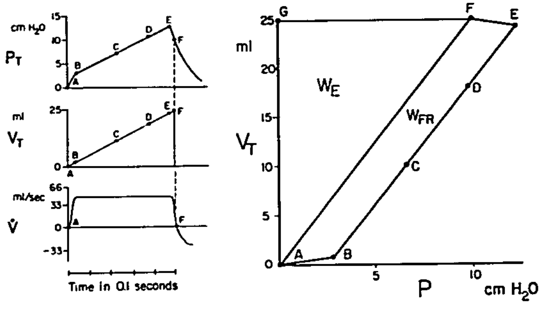


FIG. 3. Method for determining inspiratory work. The volume-pressure diagram was constructed by plotting corresponding inspiratory volume and pressure increments (points A through F) on graph paper. The area of triangle AFG represents inspiratory elastic work. The area ABEF represents flow resistive work. The units of work are g. cm. The work per minute is determined by multiplying the work per breath by the respiratory frequency.

was maintained for one second to obtain static pressure volume observations. The studies were completed within 15 minutes after induction of anesthesia prior to the start of operation.

## Methods

Respiratory flow measurements were obtained by means of a heated Fleisch pneumotachograph (number 00, dead space 1.7 ml.) in conjunction with a Statham PM 5 transducer. The pneumotachograph was calibrated for the 50 per cent $N_2O$, 50 per cent $O_2$ mixture by placing it in series with a Fischer-Porter Tri-flat flowmeter that had previously been calibrated for this gas mixture. The addition of 1 per cent halothane vapor did not affect the calibration. Inspiratory tidal volume ($V_T$) was determined by electronic integration of the flow signal and corrected to BTPS. The integrator was calibrated by passing known volumes through the pneumotachograph.

Intrathoracic pressure ($P_E$) was measured by means of an esophageal balloon technique, a modification of the method of Schilder *et al.*[3] The balloon was 4 cm. long and the teflon catheter (internal diameter 1.0 mm.) was inserted 16 to 18 cm. from the nares. The balloon volume was adjusted to less than 0.5 ml. after insertion. The tracheal pressure ($P_T$) was measured at the junction of the endotracheal tube and pneumotachograph through a catheter similar to the esophageal catheter. Statham PM 131 TC transducers were used for the pressure measurements and were calibrated against a water manometer. Figure 1 is a diagram of the arrangement of the apparatus. The flow, volume and pressure curves were simultaneously recorded on a 4-channel Grass direct writing oscillograph (fig. 2). The frequency response was 100 per cent at 8 cycles per second in the flow and pressure recording systems.

Dynamic compliance was calculated by dividing the tidal volume ($V_T$) by the appropriate pressure change ($\Delta P$) at the point of zero flow at the end of inspiration as determined by the flow curve:

$$\text{Compliance total} = \frac{V_T}{\Delta P_T}$$

$$\text{Compliance chest wall} = \frac{V_T}{\Delta P_E}$$

$$\text{Compliance lung} = \frac{V_T}{\Delta P_T - \Delta P_E}.$$

The reported data for compliance are the mean values obtained from the analysis of seven successive breaths. Similarly, mathematical calculations were made to determine the static compliance during sustained inflation of the chest; this was done one second after flow had ceased.

The flow resistive pressure (Pr) was determined during controlled respiration by subtracting the pressure at the point of no flow at the end of inspiration from the peak airway pressure. The viscous resistance (R) was then calculated by: $R = Pr/\dot{V}$, where $\dot{V}$ stands for inspiratory flow velocity. This viscous resistance consists of the resistance to gas flow

TABLE 1. Physical Characteristics and Results: Dynamic and Static Mechanics of Respiration in Infants During Halothane-$N_2O$ Anesthesia

| Pt. | Age (days) | Wt. (kg.) | Ht. (cm.) | Controlled Respiration | | | | | | Sustained Inflation | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | $V_T$ (ml.) | f (br./min.) | Ct (ml./cm. $H_2O$) | Cl (ml./cm. $H_2O$) | Cw (ml./cm. $H_2O$) | R (cm. $H_2O$/liter/sec.) | $V_T$ (ml.) | Ct (ml./cm. $H_2O$) | Cl (ml./cm. $H_2O$) | Cw (ml./cm. $H_2O$) |
| 1 | 13 | 3.4 | 51.6 | 33.0 | 20 | 2.6 | 3.0 | 28.8 | 48.7 | | | | |
| 2 | 3 | 2.2 | 40.5 | 21.0 | 20 | 4.7 | 5.6 | 28.0 | 63.4 | | | | |
| 3 | 38 | 3.1 | 52.0 | 28.4 | 20 | 2.9 | 3.6 | 13.5 | 63.8 | | | | |
| 4 | 17 | 3.5 | 49.5 | 31.2 | 22 | 2.3 | 3.0 | 10.4 | 82.1 | | | | |
| 5 | 30 | 3.6 | 50.8 | 23.3 | 30 | 2.7 | * | * | 60.7 | | | | |
| 6 | 10 | 2.4 | 45.7 | 26.8 | 20 | 2.9 | 3.2 | 44.7 | 49.0 | 27.5 | 3.0 | 3.2 | 44.4 |
| 7 | 105 | 4.2 | 55.3 | 30.2 | 25 | 1.8 | 2.3 | 13.1 | 56.8 | 27.5 | 2.1 | 2.5 | 13.8 |
| 8 | 60 | 4.8 | 54.0 | 27.9 | 30 | 3.7 | 4.9 | 15.5 | 50.2 | 27.5 | 3.6 | 4.7 | 15.3 |
| 9 | 49 | 4.3 | 58.4 | 34.2 | 28 | 2.0 | 2.5 | 8.7 | 78.2 | 27.5 | 1.7 | 2.1 | 10.6 |
| 10 | 56 | 4.4 | 56.3 | 30.3 | 30 | 2.3 | 2.8 | 11.4 | 45.3 | 33.0 | 2.3 | 2.7 | 15.5 |
| 11 | 2 | 3.0 | 48.2 | 27.5 | 20 | 1.5 | 2.0 | 9.2 | 84.1 | 22.0 | 1.5 | 1.7 | 11.2 |
| 12 | 31 | 4.3 | 58.4 | 33.0 | 28 | 4.9 | 5.7 | 33.0 | 51.0 | 27.5 | 5.0 | 5.8 | 31.3 |
| 13 | 42 | 3.7 | 60.3 | 38.3 | 20 | 1.8 | 2.0 | 28.7 | 94.4 | 27.5 | 1.8 | 2.0 | 27.5 |
| 14 | 76 | 5.1 | 54.6 | 32.3 | 30 | 2.6 | 3.1 | 17.2 | 74.9 | 33.0 | 2.9 | 3.5 | 16.5 |
| 15 | 90 | 5.7 | 61.0 | 31.4 | 30 | 2.5 | 2.6 | 48.1 | 56.1 | 33.0 | 2.6 | 2.7 | 47.2 |
| Mean | 41.5 | 3.8 | 53.9 | 29.9 | 24.9 | 2.8 | 3.3 | 22.3 | 63.9 | 28.7 | 2.6 | 3.1 | 23.6 |
| S.E. | | | | ±1.1 | | ±.3 | ±.3 | ±3.5 | ±3.7 | ±.8 | ±.3 | ±.4 | ±4.4 |

* These data not obtained because esophageal catheter slipped from proper position.
$V_T$ = tidal volume; f = respiratory frequency; Ct = total compliance; Cl = lung compliance; Cw = chest wall compliance; R = Resistance

in the airway and the viscous resistance of the lung and chest wall tissues. The airway resistance is the major portion of the total viscous resistance.

The inspiratory work was calculated graphically as indicated in figure 3.

## Results

The vital statistics of the 15 infants studied and the mean values for dynamic and static compliance and the airway resistance are tabulated in table 1. The mean age of the infants was 41.5 days with an average weight of 3.8 kg. The dynamic total lung-thorax compliance during controlled respiration ranged from 1.5 ml./cm. of water to 4.9 ml./cm. of water with a mean value of 2.8 ml./cm. of water. The mean static total lung-thorax compliance was 2.6 ml./cm. of water with a range of 1.5 to 5.0 ml./cm. of water; this value is not significantly different from the dynamic value for total lung-thorax compliance ($P > 0.4$).

Dynamic lung compliance averaged 3.3 ml./cm. of water, range 2.0 to 5.7 ml./cm. of water. There was no significant difference between the dynamic and the static lung compliance, 3.1 ml./cm. of water ($P > 0.5$).

Dynamic chest wall compliance ranged from 8.7 ml./cm. of water to 48.1 cm./cm. of water with a mean value of 22.3 ml./cm. of water. This value was not significantly different from the static chest wall compliance 23.6 ml./cm. of water ($P > 0.5$). There was no apparent correlation of any of the compliance values with age, weight, or height within this group of patients.

The inspiratory resistance averaged 63.9 cm. of water/liter/second, with a range of 45.3 to 94.4 cm. of water/liter/second. There was no apparent correlation with age, weight, or height within this group of patients.

The average calculated work of inspiration was 6,499 g. cm./minute. Elastic work averaged 72 per cent of the total of inspiratory work (table 2).

## Discussion

The dynamic total lung-thorax compliance value of 2.8 ml./cm. of water in this study is lower than the value of 5 ml./cm. of water reported by Richards and Bachman[1] in a group of infants of similar age. This discrepancy may be due to a difference in technique for determining the pressure and volume relation rather than the difference in anesthetic agents. In Richards and Bachman's cases, the static compliance was determined after chest inflation had been maintained for 10 seconds. Prolonged inflation has been shown to increase compliance, probably by increasing the number of alveoli expanded[4] or by the phenomenon of stress relaxation.[5] In our study the static compliance was determined after one second of inflation, and there was no difference between the dynamic and the static compliance. According to Mead[6] there should be no difference between static and dynamic compliance in patients with normal lungs.

We have observed that the lung-thorax compliance of infants obtained during routine clinical anesthesia and operation approximates the value for total compliance reported in this study. The compliance of infants requiring prolonged intermittent positive pressure breathing because of nervous system disease is also within the same range. Smythe[7] reported values for total lung-thorax compliance in curarized newborns with tetanus that are similar to our values.

The values for lung compliance obtained in this study of anesthetized infants are only two thirds of the values obtained by Cook *et al.*[8] and by Swyer *et al.*[9] in nonanesthetized infants of slightly younger age. Similarly in adults, the reported values for dynamic pulmonary compliance during controlled respiration in anesthetized patients or in patients with neurological disease requiring prolonged artificial respiration are decreased in comparison to the values during spontaneous respiration.[10, 11] The decreased compliance may result from a decrease in lung size either with or without alveolar collapse.[12]

The chest wall compliance found in the infants in this study is very high compared to the lung compliance. Agostoni[13] also found very high compliance in newborn puppies. The high chest wall compliance may be associated with the horizontal position of the ribs in infants. In adults the chest wall compliance approaches a value equal to the lung compliance.[14] These findings show that when

TABLE 2. Inspiratory Work During Controlled Respiration: Halothane-$N_2O$ Anesthesia

| Pt. | $W_T$/min. | $W_E$/min. | % $\frac{W_E}{W_T}$ |
|---|---|---|---|
| 1 | 5,312 | 4,432 | 83.4 |
| 2 | 4,020 | 2,664 | 66.3 |
| 3 | 6,062 | 4,476 | 73.8 |
| 4 | 7,949 | 5,988 | 75.3 |
| 5 | 4,962 | 3,054 | 61.5 |
| 6 | 3,360 | 2,424 | 72.1 |
| 7 | 6,608 | 5,068 | 76.7 |
| 8 | 5,292 | 3,432 | 64.8 |
| 9 | 7,118 | 5,454 | 76.6 |
| 10 | 10,851 | 7,716 | 71.1 |
| 11 | 6,284 | 5,114 | 81.4 |
| 12 | 5,191 | 2,957 | 57.0 |
| 13 | 10,832 | 7,304 | 67.4 |
| 14 | 8,217 | 6,336 | 77.1 |
| 15 | 5,421 | 4,029 | 74.3 |
| Mean | 6,499 | 4,697 | 71.9 |
| S.D. | 2,196 | 1,655 | 7.3 |

inflating an infant only a small increment in pressure is required to overcome the elastic resistance of the chest wall.

The total lung-thorax airway resistance, 63 cm. of water/liter/second, is considerably higher than the pulmonary resistance, 29 cm. of water/liter/second, reported by Cook *et al.*[8] for nonanesthetized young infants. His value for resistance does not include chest wall tissue viscous resistance, but only gas flow resistance and lung tissue resistance. No measurements of chest wall viscous resistance have been made in infants. In adults it has been found to be as high as 40 per cent of the total viscous resistance.[15, 16] The principal reason for the discrepancy in airway resistance is the added resistance of the endotracheal tube. The resistance of the endotracheal tubes used in this study was 35 to 45 cm. of water/liter/second. The variation in resistance from patient to patient is great; Cook also found a wide range in airway resistance in nonanesthetized infants.

The total work of inspiration in these infants is considerably increased over values reported by Cook *et al.*[8] for pulmonary work in nonanesthetized infants. His values for work of respiration do not include the work necessary to inflate the chest wall because he measured work during spontaneous respiration.

The high compliance of the chest wall in infants requires that little work be done to inflate it, however. The increased work in the apneic anesthetized infant is to be expected because of the decrease in compliance of the lung associated with anesthesia and artificial respiration and the increase in airway resistance associated with intubation.

The peak inspiratory airway pressure is frequently used as a guide to lung inflation during clinical anesthesia. This parameter is the sum of the dynamic or flow resistive and the static or lung expansive pressures. Thus, the peak inspiratory pressure reading is not a good indication of the degree of inflation of the lung because it also reflects the flow resistive pressure. Infant airways are narrow and flow resistive pressure thus may become the major component of the peak airway pressure particularly when the inspiratory flow of gas is rapid.

The pressure necessary to obtain the desired tidal volume during controlled respiration can be determined by substituting our values for compliance (2.8 ml./cm. of water) and resistance (60 cm. of water/liter/second) in the young infant in a simplified equation of motion for the lungs (see Appendix for derivation):

$$P_T = \frac{1}{C} V_T + R\dot{V}.$$

The pressure necessary for inflation of the lungs in the average 4 kg. infant to a tidal volume of 28 ml. at a peak inspiratory flow rate of 6 liters/minute (100 ml./second) will be:

$$P_T = \frac{1}{2.8 \text{ ml./cm. } H_2O} (28 \text{ ml.}) + \frac{60 \text{ cm. } H_2O}{\text{liter/sec.}} \frac{(0.1 \text{ liter})}{\text{sec.}} = 16 \text{ cm. } H_2O.$$

The peak pressure of 16 cm. of water necessary to obtain the predicted tidal exchange in an anesthetized infant during controlled respiration is of the same magnitude required to produce the predicted tidal volume in adult patients. When instantaneous inspiratory flow is more than 6 liters/minute through a tube of 4 mm. internal diameter, the flow becomes turbulent;[17] the last term in this equation becomes more complex ($R\dot{V} + K\dot{V}^2$, where K = a constant), and the pressure necessary to overcome resistance increases disproportionately more rapidly than the increase in flow. This emphasizes the need for slow flow rates during artificial respiration in infants as pointed out by Mushin *et al.*[18] When anesthetists use excessively high flow rates (12–20 liters/minute) to control respiration in the infant, a high inspiratory peak pressure is necessary to ventilate the infants because of the high flow resistive component of the total inspiratory pressure. The use of pressure-cycled ventilators in infants results in inadequate ventilation when the inspiratory flow is high unless the cycling pressure is also set at a high value. If the cycling pressure is set low the ventilator triggers prematurely because the pressure cycled valve responds to the sudden high peak pressure due to flow resistance and an adequate tidal volume is not achieved. Therefore, it is essential to set an appropriate peak pressure to assure proper cycling.

## Summary

The mechanics of respiration were studied during nitrous oxide halothane anesthesia in 15 infants ranging in age from 3 to 105 days and weighing from 2.4 to 5.7 kg. Air flow and volumes were measured by pneumotachography and airway and esophageal pressures were measured to enable calculation of compliance and resistance. The dynamic total lung-thorax compliance was 2.8 ± 0.3 ml./cm. of water. The dynamic lung compliance was 3.3 ± 0.3 ml./cm. of water, and the dynamic chest wall compliance was 22.3 ± 3.5 ml./cm. of water. The inspiratory airway resistance (including tissue viscous resistance) was 63.9 ± 3.7 cm. of water/liter/second. The calculated inspiratory work was 6,499 ± 567 g. cm. per minute. The elastic inspiratory work was 4.697 ± 427 g. cm./minute or 72 per cent of the total.

The static total, lung and chest wall compliance, were also determined in the same patients by inflation of the chest with a known volume from a syringe. There was no significant difference between the static and dynamic compliances.

The mechanics of respiration in these apneic anesthetized infants were compared with previous studies in nonanesthetized infants reported by other authors. Lung compliance was decreased compared to the nonanesthetized spontaneously breathing infant. The airway resistance was increased due chiefly to the added resistance of the endotracheal tube. Thus, the work of inspiration was increased.

The values for compliance and resistance that were determined in this study were substituted in a simplified equation of motion for the respiratory system, and it was found that the pressure necessary for inflation of the lung of anesthetized infants is of the same magnitude as required in adults.

## Appendix

### Derivation of Equation of Motion

The total or peak inspiratory pressure ($P_T$) needed during controlled respiration is the sum of the pressure necessary to overcome the elastic ($Pel_T$) and the airway resistance ($Pr_T$):

$$P_T = Pel_T + Pr_T \quad \text{(Equation 1)}$$

Compliance is the tidal volume ($V_T$) divided by the pressure necessary to overcome elastic resistance:

$$C = \frac{V_T}{Pel_T}; \quad Pel_T = \frac{1}{C} V_T \quad \text{(Equation 2)}$$

Resistance is the pressure necessary to overcome flow resistance divided by the flow rate:

$$R = \frac{Pr_T}{\dot{V}}; \quad Pr_T = R\dot{V} \quad \text{(Equation 3)}$$

Therefore, substituting equations 2 and 3 in equation 1:

$$P_T = \frac{1}{C} V_T + R\dot{V} \quad \text{(Equation 4)}$$

This equation is a simplified form of the complete equation of motion of the lungs. It is true for low instantaneous flow rates such as occur during normal quiet respiration.

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