Intrapulmonary Gas Trapping during Mechanical Ventilation at Rapid Frequencies

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When anesthetized, paralyzed patients were mechanically ventilated at rapid frequencies such that the time available for exhalation was insufficient, gas was retained in the thorax. Gas trapping became more pronounced as respiratory frequency increased. For any patient, the minimum length of time needed for virtual completion of exhalation could be predicted from measurements of total respiratory compliance and resistance. At moderately rapid respiratory frequencies, incomplete exhalation due to insufficient available time was partially compensated by increases in transthoracic pressure that permitted exhalation of larger volumes in the time available and were accompanied by increases in end-expiratory lung volume. (Key words: Gas trapping; Respiratory mechanics; Mechanical ventilation.)

ANESTHETIZED, paralyzed patients exhale passively. The entire force for exhalation is derived from elastic potential energy stored in the respiratory system during the preceding inspiration, and respiratory muscles are completely inactive. The following equation describing the time course of a passive exhalation can be derived from the equation of motion of the respiratory system:

$$V(t) = V_0 e^{-(1/RC)t} \quad (1)$$

where $V(t)$ is volume of gas remaining in the thorax at any time in seconds (t) following the beginning of exhalation, V_0 is the volume of gas in the thorax above resting expiratory level at the beginning of exhalation (*i.e.*, total exhaled volume for that breath), e is the base of natural logarithms, R is total respiratory resistance, and C is total respiratory compliance.[1] This equation shows that expulsion of gas from the lung during passive exhalation should proceed in an orderly and predictable

manner. The product "RC" in equation 1 is the time constant of the respiratory system.

When passive exhalations of anesthetized, paralyzed patients were evaluated, it was apparent that deviations from the ideal, predicted exponential time course had occurred. Also, the time constant for passive exhalation was not independent of volume exhaled, as might be predicted from theoretical considerations, but increased as volume exhaled became larger.[2] These discrepancies could be attributed for the most part to the use of linear functions for respiratory resistance and compliance in theoretical analysis. In the respiratory system both resistance and compliance are nonlinear.[3,4] Because of the curvilinear nature of the respiratory pressure–volume relationship, the transthoracic pressure gradient available for passive exhalation of a given volume depends on the end-inspiratory volume from which inspiration is initiated (fig. 9). In spite of these deviations from ideal behavior, it was nevertheless concluded that as a first approximation equation 1 might be applicable in many situations where mathematical expression of the time course of passive exhalation is needed.

An interesting consequence which follows from consideration of equation 1 is that a finite time interval is necessary for passive exhalation. The magnitude of this interval should be determined by mechanical properties of the respiratory system, both resistance and compliance. In one time constant (*i.e.*, an interval of time in seconds numerically equal to the product of respiratory resistance multiplied by respiratory compliance) the volume of gas remaining in the thorax should be approximately 37 per cent of its pre-expiratory value. Three time constants should be needed for 95 per cent completion of passive exhalation, and in four time constants exhalation should be 98 per cent complete. These are general properties of exponential functions and are
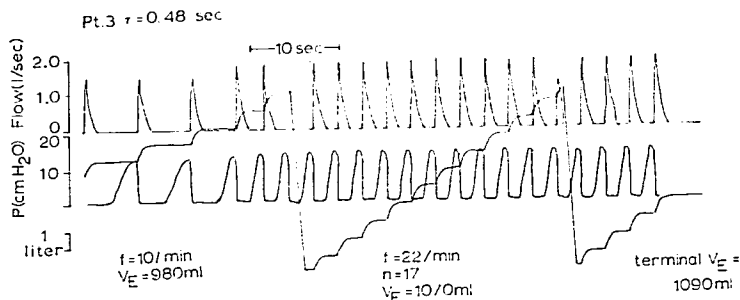
FIG. 1.   Transthoracic pressure, expiratory volume, and expiratory flow rate during mechanical ventilation, 17 breaths at 22/min.   Expiratory volume is the stair-step tracing with automatic recycling of the spirometer.   For complete explanation, see text.
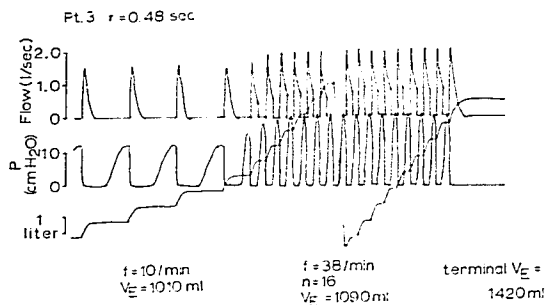

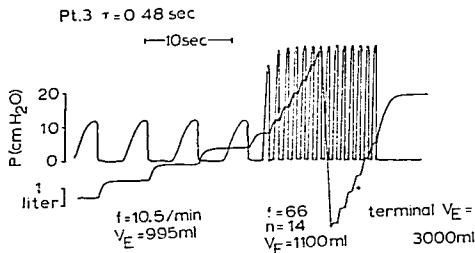FIG. 2.   Same as figure 1, 16 breaths administered at 38/min.

FIG. 3.   Same as figure 1, 14 breaths at 66/min.   The recorded plateau of transthoracic pressure during rapid ventilation represents the upper limit of the pressure transducer.   Actual transthoracic pressure must have been higher.
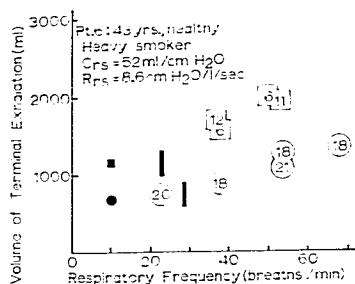
FIG. 4. Volume of the terminal exhalation following abrupt discontinuation of mechanical ventilation as a function of respiratory frequency during the period of rapid ventilation in a single subject. Circles represent inspired volumes near 500 ml and squares represent those near 1,000 ml. Solid symbols are exhaled tidal volumes at 10/min. Numbers within the open symbols are the numbers of breaths delivered at that particular frequency. Vertical bars represent the frequencies at which exactly three time constants were available for exhalation.
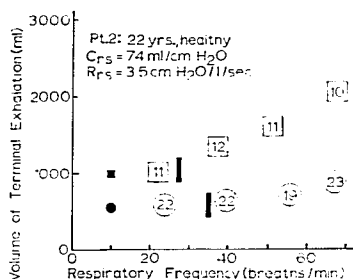

FIG. 5. Results similar to those presented in figure 4, for a different subject.

more extensively discussed elsewhere.[5] Several predictions can be made based on the preceding considerations. If the time available for exhalation is not sufficient (i.e., about four time constants), gas should be trapped in the thorax. The volume of gas trapped under these conditions in any individual should be predictable if the mechanical properties of his respiratory system are known.

The present study was undertaken to test these predictions experimentally and to study the mechanical response of the respiratory system under conditions where gas trapping due to insufficient time for exhalation might be anticipated. Results are presented primarily in a descriptive manner since many data provided by the unsteady state during the studies were not suitable for precise quantification.

Methods

Subjects of the study were seven male patients whose ages ranged from 22 to 55 years. Each had been scheduled for elective hernia repair or lower-extremity surgery. Consent for the study was obtained by the investigator, and clinical anesthesia was managed by an anesthesiologist who did not

participate in the study. Anesthesia was maintained with approximately 60 per cent nitrous oxide in oxygen and either 1 per cent halothane or 0.5 per cent methoxyflurane, using a tight-fitting cuffed endotracheal tube. Sufficient d-tubocurarine was administered to abolish all spontaneous respiratory activity.

Initially, total respiratory compliance and total respiratory resistance were measured by analysis of transthoracic pressure, volume, and flow recordings obtained during thoracic inflation and subsequent passive exhalation using a method described previously.[2] Tidal volumes of both 500 and 1,000 ml were studied in each subject. Time constants of the respiratory system were calculated as the product of total respiratory compliance (expressed as $l/cm\ H_2O$) multiplied by total respiratory resistance. (Values presented for individual subjects in the illustrations have been corrected for apparatus resistance. Values for time constants used in calculations included apparatus resistance.)

Subjects were then mechanically ventilated, using a variable-speed-piston respiratory pump and a nonrebreathing circuit. Anesthetic gas from the anesthesia machine was stored in a reservoir and was delivered to the patient by the pump, while the patient exhaled into a 10-liter waterless spirometer (Wedge Spirometer, Med-Science Electronics, St. Louis, Missouri) which automatically recycled when the limit of its excursion was attained. Airway (transthoracic) pressure, expiratory flow rate, and exhaled volume were continuously re-

corded. The respiratory pump could be stopped abruptly at any point in the respiratory cycle by switching the motor off. The pump had a sinusoidal respiratory pattern with equal durations of inspiration and exhalation. Respiratory rate was initially 10/min for each subject, and tidal volume was approximately 500 or 1,000 ml. Following collection of several exhalations at this frequency, the respiratory rate was suddenly increased to a higher frequency by rapid advancement of the variable-speed control of the motor. After a predetermined number of breaths at this more rapid frequency, the pump was abruptly stopped early in an expiratory phase and remained stopped until expiratory flow had ceased. Then, mechanical ventilation at a frequency of 10/min was resumed. This sequence was repeated several times for each subject, using different rapid frequencies and durations of rapid ventilation. In most subjects, both 500-ml and 1,000-ml tidal volumes were studied. The following values were measured and calculated for each individual study of a period of rapid ventilation:

1) Exhaled tidal volume at a frequency of 10/min: V_{E10}

2) Exhaled tidal volume toward the end of the period of rapid ventilation: V_{ER}

3) Volume of the terminal exhalation immediately following the period of rapid ventilation: V_{ETerm}

4) Number of breaths delivered at the rapid frequency (N) and respiratory frequency during the period of rapid ventilation; the duration of exhalation (E) was half the duration of the respiratory cycle with the sinusoidal breathing pattern used.

5) Measured volume of gas trapped during the period of rapid ventilation: the difference between volume of the terminal exhalation and the exhaled tidal volume at 10/min:

$$V_{ETerm} - V_{E10}$$

6) Predicted volume of gas which should have been trapped during the period of rapid ventilation in the absence of any compensatory changes: the difference between the volume exhaled at 10/min and the volume which should have been exhaled in the time available for exhalation times the number of breaths delivered at rapid frequency:

$$N(V_{E10} - V_{E10}e^{-1/RC \times E})$$

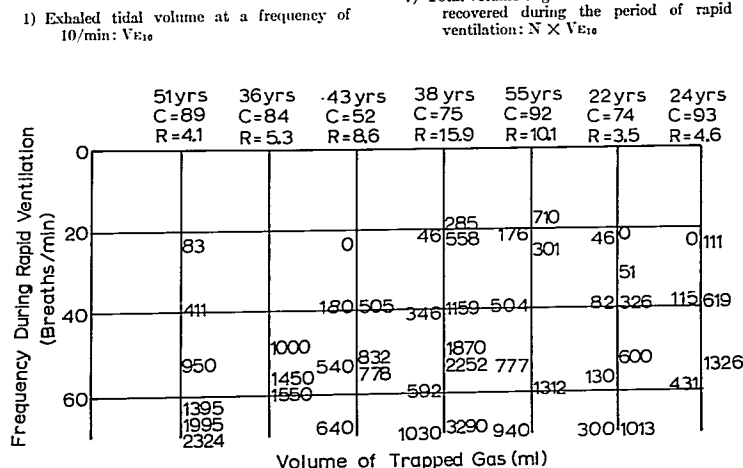7) Total volume of gas which should have been recovered during the period of rapid ventilation: $N \times V_{E10}$

FIG. 6. Volumes of trapped gas ($V_{ETerm} - V_{E10}$) after rapid ventilation at different frequencies in all seven subjects. Values for 1,000-ml breaths are on the right and those for 500-ml breaths are on the left of the vertical lines descending from the descriptions of the subjects. C is total respiratory compliance (ml/cm H_2O) and R is total respiratory resistance (cm H_2O/l/sec) corrected for apparatus resistance.
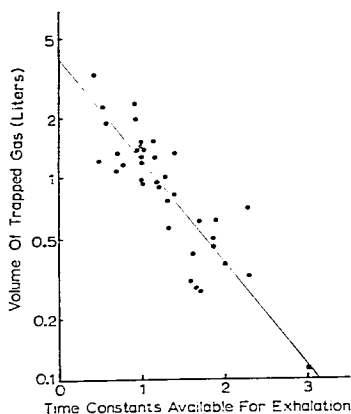
FIG. 7. Volume of trapped gas ($V_{ETerm} - V_{E10}$) as a function of the number of time constants available for exhalation for inspired tidal volumes of 1,000 ml. The volume of trapped gas increased logarithmically as the number of time constants available for exhalation decreased. The regression line for these data, calculated by the method of least squares, was:

$$\text{Volume of trapped gas} = 3873 \; e^{-1.156T}$$

where T is the number of time constants available for exhalation. Using this equation, it can be shown that for breaths of 1,000 ml, 95 per cent completion of passive exhalation (i.e., retention of less than 50 ml of actual trapped gas) required 3.7 time constants in subjects of this study. Similar results could be demonstrated for breaths of 500 ml.

8) Total volume of gas actually recovered during and immediately following the period of rapid ventilation: $(N - 1)V_{ER} + V_{ETerm}$

Results

Representative recordings from one subject are shown in figures 1–3. The time constant for passive exhalation of 1,000 ml in this subject was 0.48 sec when apparatus resistance was included in total respiratory resistance. Ventilation was increased from 10 to 22 breaths/min and was then abruptly stopped after 17 breaths at the higher frequency (fig. 1). The volume of the terminal exhalation was not appreciably different from the volume exhaled at 10/min or at 22/min. The duration of

exhalation was about 1.4 sec, or approximately three time constants, sufficient for 95 per cent completion of exhalation. A measurable amount of gas had not been trapped during ventilation at 22/min. When the period of rapid ventilation was 16 breaths administered at 38/min, transthoracic pressure increased at the high frequency (fig. 2). At 38/min, about 0.79 sec was available for exhalation, which represents 1.6 time constants in this subject. This should be sufficient for exhalation of only 80 per cent of his tidal volume ($e^{-1.6}=0.2$), and it was therefore predicted that he should have trapped about 3,100 ml of gas in 16 breaths. The presence of a terminal exhalation appreciably larger than the preceding exhalations and failure of the flow tracing to return to the baseline during exhalation at rapid frequency indicated that gas was trapped during the period of rapid ventilation. Since the volume of the terminal exhalation was about 330 ml greater than exhaled volume during the preceding period of rapid ventilation, it is apparent that only about 10 per cent of the total predicted trapped gas was recovered in the terminal exhalation. Approximately 16 liters of gas should have been recovered during and immediately following the period of rapid ventilation, but about 10 per cent more than this was actually recovered. Figure 3 shows results of administration of 14 breaths at 66/min. At this frequency, slightly less than one time constant was available for exhalation, and approximately 5,500 ml of gas should have been trapped in 14 breaths. About 38 per cent of this predicted trapped volume was recovered in the terminal exhalation. Again, total recovery of gas was about 10 per cent greater than predicted and transthoracic pressure was markedly increased during rapid ventilation.

The volume of terminal exhalations as a function of frequency during periods of rapid ventilation for tidal volumes of 500 ml (circles) and 1,000 ml (squares) in two patients are shown in figures 4 and 5. Solid circles and squares represent exhaled tidal volume at 10/min. Solid vertical bars represent that frequency at which three time constants were available for exhalation. At all frequencies lower than those represented by the bars, there should have been sufficient time for 95 per cent or greater completion of exhalation.

Numbers within the open symbols represent numbers of breaths administered at those particular frequencies. At frequencies where three or more time constants were available for exhalation, the volumes of the terminal exhalation following abrupt cessation of rapid mechanical ventilation were not measurably different from that at 10/min. At higher frequencies, volumes of the terminal exhalation progressively became larger as ventilatory frequencies during rapid ventilation increased.

Similar results occurred in all patients studied (fig. 6). During rapid ventilation at frequencies where at least three time constants were available for exhalation, no detectable gas trapping occurred. As time for exhalation decreased, volume of the terminal exhalation progressively increased. Measured volume of trapped gas ($V_{ETerm} - V_{E10}$) increased logarithmically as the number of time constants available for exhalation became less (fig. 7). The exhaled tidal volume toward the end of the period of rapid ventilation (V_{ER}) was greater than that at 10/min (V_{E10}) in most studies. The difference could not be precisely quantified because of recording requirements. The number of breaths administered at a particular rapid frequency did not influence the volume of the terminal exhalation. The total fraction of the predicted volume of trapped gas which was actually recovered in the terminal exhalation was greatest when the number of breaths administered at rapid frequencies was small and decreased as the period of rapid ventilation was prolonged (fig. 8). The total volume of gas actually recovered during and immediately after the period of rapid ventilation was 2–20 per cent greater than the volume which should have been recovered.

Discussion

Several considerations suggested that it would be unprofitable to subject the data of the present study to more extensive and sophisticated analysis. First, observed behavior of the respiratory system deviates from ideal predicted exponential characteristics, as stated previously. In addition, technical requirements necessitated selection of a recorder sensitivity which did not permit discrimination of small volume changes which would have permitted more accurate quantifi-
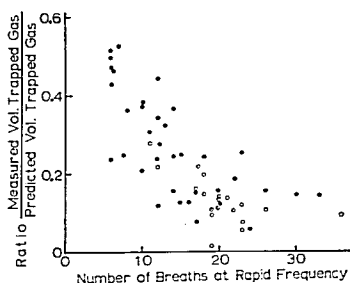

FIG. 8. Ratio of the measured volume of trapped gas to the predicted volume of trapped gas during periods of rapid ventilation as a function of the number of breaths delivered at the rapid frequency. Solid dots represent inspired tidal volumes of 1,000 ml and open dots, tidal volumes of 500 ml. This ratio decreased as the number of breaths at rapid frequency became larger. This suggests that compensation for gas trapping was progressive and became more effective as the number of breaths administered at the rapid frequency increased.

cation of the extent of gas trapping and compensation. Attainment of a new steady rapid respiratory frequency required several breaths after advancement of the speed control of the ventilator. Increases in alveolar ventilation occurred at rapid frequencies. The resulting marked but unmeasured increased carbon dioxide elimination and decreased oxygen uptake must have influenced experimental results and contributed to the recovery of a volume of gas greater than anticipated during and immediately following rapid ventilation. For these reasons results of this study are presented largely in a descriptive manner.

The results of the present study demonstrate that predictions concerning responses to ventilation at rapid frequencies proposed in the introduction are valid. The time needed for passive exhalation by any individual could be predicted when the mechanical properties of his respiratory system (resistance and compliance) were known. When the time available for passive exhalation in anesthetized, paralyzed, mechanically-ventilated subjects was insufficient for virtual completion of passive exhalation, gas was retained in the thorax. The data of figure 7 confirm that if trapping
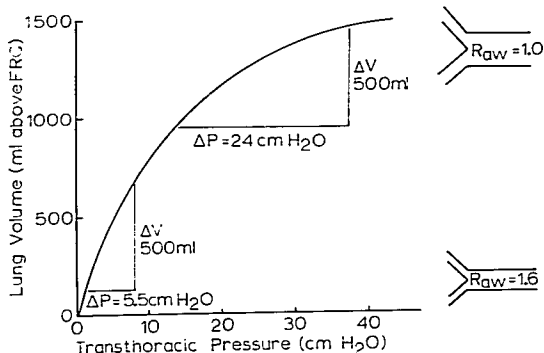
Fig. 9. Mechanisms involved in compensation for gas trapping where insufficient time for exhalation is available. Due to the changing slope of the respiratory pressure–volume curve, a greater transthoracic pressure gradient may be available for expulsion of a given volume when exhalation is initiated at a higher lung volume. Also, airway resistance (R_{aw}) decreases at larger lung volumes as a consequence of the increase in bronchial diameter.[6]

of less than 5 per cent of tidal volume is desired, three to four time constants must be allowed for passive exhalation. When gas trapping occurred as a consequence of rapid ventilation, trapped gas escaped when sufficient time for exhalation was permitted.

In response to rapid mechanical ventilation, compensatory changes which tended to maintain exhaled tidal volume and minimize the extent of gas trapping occurred in the respiratory system. With the institution of rapid ventilation, end-inspiratory transthoracic pressure increased over five or six breaths to attain a new value which, in most cases, was two or more times that at a frequency of 10/min. In addition, the exhaled tidal volume during rapid ventilation was greater than that at 10/min even though the inspiratory stroke of the ventilator remained constant. It was not possible to obtain sufficient data to define compensatory changes in transthoracic pressure and exhaled tidal volume during rapid ventilation, since in most individuals, particularly those with large tidal volumes, pressures exceeded the upper range of the pressure transducer (about 35 cm H_2O). In addition, as stated previously, small volume changes could not be quantified with certainty. Compensatory changes did not occur immediately with the onset of rapid ventilation but required several breaths to become established. This is shown by recovery of a higher fraction of the total predicted trapped gas in the terminal

exhalation following a few rapid breaths than after more prolonged periods of ventilation at rapid frequency (fig. 8), as well as by the observed pattern of a gradual increase of transthoracic pressure. In many instances compensation for insufficient time for exhalation must have been virtually complete, since fairly sizable increases in the numbers of breaths delivered at a particular frequency produced very little, if any, increase in volume of the terminal exhalation. The ability of the respiratory system to provide such compensation must be limited. However, it appears that at moderate frequencies of rapid ventilation, gas trapping is not progressive, and a new steady state at augmented lung volume is approached. Mechanisms which tend to maintain exhaled tidal volume during rapid ventilation are probably quite complex. In addition to increased transthoracic pressure, there is probably a shift to a different portion of the respiratory pressure–volume curve, as well as alterations in respiratory pressure–flow characteristics with increased lung volume (fig. 9).

In the present study, a volume-controlled ventilator was used. With pressure-controlled mechanical ventilation, where inspiration ceases on attainment of a preset cycling pressure, a different response to rapid ventilation with inadequate time for completion of exhalation might be anticipated in a subject with a normal respiratory system. With each

exhalation, a portion of the inspired gas should be retained in the thorax, and end-expiratory lung volume increases. However, end-inspiratory lung volume, determined by cycling pressure of the ventilator, remains constant. Therefore, smaller volumes of gas are introduced into the thorax with each breath, and increasing hypoventilation at augmented resulting lung volume should occur. Eventually, complete lack of tidal exchange might be anticipated in extreme situations.

In a previous study, the mean measured time constant for passive exhalation of 500 ml was 0.42 seconds in a group of healthy anesthetized subjects. In another group of patients with mild symptoms of chronic pulmonary disease and moderate elevations of respiratory resistance, the mean time constant was 0.73 seconds.[2] Results of the present study show that about 3.5 time constants must be available for passive exhalation if gas trapping is to be avoided. Therefore, with equal durations of inspiration and exhalation and a tidal volume of 500 ml, a healthy patient is likely to exhibit gas trapping at frequencies above 20/min, and a patient with mild chronic pulmonary disease could trap gas at a frequency of 12/min. These conditions are undoubtedly frequently attained or exceeded during "routine" anesthesia. It is probable, therefore, that many anesthetized, mechanically-ventilated patients are in a state of compensated gas trapping. This should be easily demonstrable in any patient by the presence of a terminal exhalation appreciably larger than the preceding exhalations upon abrupt discontinuation of mechanical ventilation. Gas trapping, however, may not always be undesirable. The state of compensated gas trapping at ventilatory rates where sufficient time is not available for complete exhalation demonstrated in this study is in reality constant positive-pressure breathing. Although pressure at the airway opening falls to zero during exhalation (figs. 2 and 3), the impedance of gas flow imposed by airway resistance causes retention in alveoli of some of the gas which should have been exhaled. Thus, alveolar pressure must remain above atmospheric pressure throughout the respiratory cycle, and end-expiratory lung volume is augmented. Establishment of a state of compensated gas trapping by a deliberate decrease in the time available for exhalation may represent an easy method for provision of CPPB which does not require use of auxiliary equipment or apparatus. It is probable that many patients who have been mechanically ventilated for respiratory failure have inadvertently received benefits of CPPB. The frequencies at which gas trapping might occur in these individuals with marked abnormalities of respiratory mechanics could easily be exceeded in clinical practice.

References

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