Passive Deflation Time Constant of 7-Week-Old Rabbits

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ABSTRACT. The purpose of our study was to determine the effects of insufflation time (T_I) and of tidal volume (V_T) on the passive deflation time constant (τ) of juvenile rabbits. We sedated and paralyzed nine 7-wk-old New Zealand rabbits (wt 1.2 ± 0.2 SD kg) and placed them on a time-cycled, pressure-limited mechanical ventilator. Measurements of τ and dynamic compliance of the respiratory system were made at nine ventilator settings. T_I was adjusted to 0.2, 0.4, and 0.6 s and V_T was adjusted to 10, 15, and 20 mL so that the effects of T_I and V_T on τ could be determined independently. Respiratory system quasi-static and static compliances were also measured and served as a basis for discussing the physiologic explanations for the effects of T_I and V_T on τ . In general, increases in T_I resulted in increases in τ and increases in V_T also resulted in increases in τ . Increasing T_I from 0.2 to 0.6 s plus increasing V_T from 10 to 20 mL resulted in an increase in τ from 0.220 ± 0.007 to 0.282 ± 0.010 s (mean $\pm$ SEM) ($p < 0.05$, student Newman-Kuels), which is a 28% increase. At a V_T of 10 mL, dynamic compliance increased from 1.95 ± 0.10 to 2.14 ± 0.10 mL/cm H₂O ($p < 0.05$) when T_I was increased from 0.2 to 0.6 s; however, dynamic compliance decreased 19% as V_T was increased from 10 to 20 mL. Quasi-static compliance increased from 2.04 ± 0.07 to 2.17 ± 0.12 mL/cm H₂O ($p < 0.05$) as deflation volume was increased from 10 to 20 mL, yet static compliance remained relatively constant at 2.6 mL/cm H₂O in the volume range of 10 to 20 mL. We conclude that both T_I and V_T affect τ in the small, healthy rabbit and that neither the viscoelastic properties of the lung nor parallel modeling with a distribution of time constants can fully explain our observations. (*Pediatr Res* 28: 75-78, 1990)

Abbreviations

T_I , insufflation time
 V_T , tidal volume
 τ , passive deflation time constant
 C_{dyn} , dynamic compliance
 C_{qs} , quasi-state compliance
 C_{st} , static compliance

Passive deflation time constants are used to characterize the mechanics of the respiratory system and are clinically useful for predicting the time required for a complete exhalation during mechanical ventilation. Shannon (1) suggests that τ , arterial PCO_2 , alveolar PCO_2 , and functional residual capacity provide the

minimum information needed for rational management of infants and children on mechanical ventilation. Because both respiratory gas flow and volume are dependent on τ , to provide optimal gas exchange it is necessary to match the mechanical breathing device to the mechanical properties of the respiratory system.

Recently, experiments in healthy rabbits demonstrated that τ is influenced by T_I (2). This observation could be explained by the viscoelastic properties of the respiratory system (3) or by a distribution of passive exhalation time constants (4); presently, there are no methods available for distinguishing if one of the two phenomena dominates.

The purpose of our study was to investigate the effects of V_T , as well as T_I , on τ of the lungs of small rabbits. As a basis for discussing the possible effects of stress relaxation and a distribution of τ on the measured τ , we calculated the compliance of the respiratory system by three different methods. We measured C_{dyn} , C_{qs} , and C_{st} .

MATERIALS AND METHODS

Animal preparation. We studied nine 7-wk-old New Zealand White rabbits weighing between 1100 and 1350 g (1239 ± 230 g, mean $\pm$ SD). We anesthetized each rabbit with ketamine (30 mg/kg), acepromazine (1 mg/kg), and rompun (0.7 mg/kg) and then placed them in the supine position. Using lidocaine as a local anesthetic, we then introduced an endotracheal tube (3.0-mm inner diameter) through a tracheostomy and tied sutures around the trachea to prevent air leakage. We mechanically ventilated the rabbits using a time-cycled, pressure-limited infant ventilator (Baby Bird, Bird Corp, Palm Springs, CA). Finally, we cannulated the femoral artery for drug administration and for monitoring arterial blood pressure and blood-gas tensions. We used changes in arterial blood pressure and heart rate as a guide for the subsequent administration of anesthetics during the experiment. Before measurements, we paralyzed each animal with 0.1 mg/kg of pancuronium bromide.

Equipment. We measured respiratory flow using a Fleisch "00" pneumotachometer (OEM Medical, Inc., Richmond, VA) that was placed between the ventilator tubing "T" and the endotracheal tube. For C_{qs} measurements, we fabricated a "clamp connector" using a 3-cm length of 3/8-inch inner diameter polyvinylchloride tubing. We connected the clamp connector to a fitting that was designed to house the large (15-mm) end of an endotracheal tube adapter, similar to the ventilator T connector. One end of the clamp connector was attached to the pneumotachometer and the other end was connected to the endotracheal tube adapter. This allowed us to obstruct flow at a position between the pneumotachometer and the rabbit (5). We monitored airway pressure through a luer-lock side port of the endotracheal tube adapter (Respiratory Support Products Inc., Costa Mesa, CA). Forceps were used to pinch the clamp connector and obstruct flow.

We used three 6-inch long pieces of 1/16-inch polyvinyl-

Received November 10, 1989, accepted March 19, 1990.

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Supported by Grant 6-525 from The March of Dimes Birth Defects Foundation.

chloride tubing to couple the pressure transducers to the pneumotachometer and to the endotracheal tube adapter. We used variable reluctance pressure transducer-carrier demodulator systems (MP-45-871, CD 257, Validyne, Inc., Northridge, CA) with the pneumotachometer (± 2 cm H₂O) and for the airway pressure (± 50 cm H₂O). We conditioned the pressure signals using a 50 Hz low-pass filter (Validyne, Inc.) and then fed the signals to a 12-bit resolution analog to digital converter (Model 570, Keithley, Cleveland, OH). The computer (IBM Inc., Boca Raton, FL) sampled the data at 0.010-s intervals.

Measurement methods. We measured the τ during mechanical ventilation using methods similar to those described by LeSouef *et al.* (5); however, we did not obstruct flow to allow pressures to reach equilibrium throughout the lung. This allowed the respiratory units having a short time constant to become more fully charged than the respiratory units having longer time constants; this reasoning assumes that a distribution of τ exists. We calculated time constants from the passive deflation flow-volume curves (Fig. 1), which we recorded after adjusting the ventilator to each of the nine different settings.

The ranges of T_I and V_T chosen encompass the ventilator settings and V_T most frequently used on infants in our newborn intensive care unit. We increased the inflation time from 0.2 to 0.4 s and then to 0.6 s while the tidal volumes were kept constant at 10, 15, and then 20 mL by adjusting both the peak inflation pressure and the ventilator flow rate. We maintained the positive end-expiratory pressure at 2 cm H₂O to reduce the possibility of partial or sequential airway closure during exhalation. When T_I was 0.2 and 0.4 s, the ventilator was time cycled rather than pressure limited. Therefore, the airway pressure increased throughout the time of inflation except during the brief period at the very end of inflation when the ventilator cycled for deflation and yet inflation continued briefly as long as the airway pressure was greater than the alveolar pressure. When the T_I was 0.6 s, the ventilator was pressure limited and the airway pressure remained constant for a portion of the ventilator inflation cycle. During this time, when the ventilator was pressure limited, the insufflation flow returned to 0 before the ventilator cycled for deflation. Throughout each experiment, we held the ventilator deflation cycle constant for all of the ventilator settings and adjusted them sufficiently long to insure complete deflation of the lung to a relaxation volume at 2 cm H₂O pressure.

Fig. 1. Passive deflation flow-volume curve of juvenile rabbit receiving mechanical ventilation with a T_I of 0.2 s. Three successive breaths are plotted demonstrating good reproducibility and that the plots are linear except in the initial part of deflation where inertial effects dominate.

We calculated time constants using a linear regression with seven points weighted evenly in volume, as opposed to time, from 30–90% of the deflation volume (6). We determined respiratory system C_{dyn} from the quotient of V_T and the difference between the airway pressures at end-inflation and end-deflation. An interpolation subroutine estimated the airway pressures when the flow equaled 0 at end-inflation and end-deflation.

To determine C_{qs} , we clamped the polyvinyl-chloride tubing of the fabricated clamp-connector at, or very near end inflation, disconnected the rabbit from the ventilator while allowing pressures within the lung to reach equilibrium for 2 s, and then released the clamp so that the rabbit exhaled to the atmosphere. We calculated respiratory system C_{qs} from the quotient of the volume exhaled to the atmosphere and the airway pressure measured just before the release of the clamp. We made the C_{qs} measurements at volumes of 10, 15, and 20 mL.

We obtained static pressure-volume curves for the respiratory system over a volume range of 30 mL. First, we disconnected the rabbits from the ventilator and allowed them to exhale to atmospheric pressure. Then, using a 50-mL glass syringe connected to the endotracheal tube, we insufflated the lungs with 30 mL of air and allowed pressures in the lung to equilibrate for 2 s. We then withdrew 5-mL volumes of air and sampled the airway pressure at each lung volume after allowing 2 s for pressures to equilibrate at each volume. We calculated the chord compliances by dividing the volumes of 10, 15, and 20 mL by the pressure differences between the airway pressures at these volumes and the airway pressure at 0 mL. We sighed the animals with 30 cm H₂O airway pressure for 2-s just before all measurements: dynamic, quasi-static, and static.

Statistics. All data are reported as mean value $\pm$ SEM. We used two-way analysis of variance, with student Newman-Kuels test, to assess differences between the results of the τ , C_{dyn} , and C_{qs} measurements determined at the different T_I and V_T settings. A $p < 0.05$ was considered significant.

The research protocol was reviewed and approved by the Baylor Animal Protocol Review Committee.

RESULTS

Increasing T_I from 0.2 to 0.6 s while V_T was held constant at 10 mL resulted in an increase in τ of 11% ($p < 0.05$) (Fig. 2) and an increase in C_{dyn} of 10% ($p < 0.05$) (Table 1). Increasing V_T from 10 to 20 mL while holding T_I constant also led to an average increase in τ of 11% ($p < 0.05$), but C_{dyn} decreased 10% ($p < 0.05$).

Fig. 2. τ (in s) of rabbits vs T_I and V_T (SEM < 0.01 s for all values).