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# Letters

## Expiratory Regulation and the Servo-i Ventilator During Invasive Neonatal Ventilation

In the November 2008 issue of the Journal, DiBlasi et al found that a major cause of expiratory resistance ($R_E$) during invasive neonatal ventilation appears to be the exhalation valve assembly of the ventilator.[1] Their results showed that with the Servo-i ventilator (Maquet, Bridgewater, New Jersey) the ventilator-imposed $R_E$ was higher than with other ventilators.

In their discussion they stated that "the perfect ventilator, in terms of ventilator-imposed $R_E$ would reduce the airway pressure to PEEP [positive end-expiratory pressure] immediately at the start of exhalation and hold that pressure, so the pressure difference and ventilator-imposed $R_E$ would be zero." This statement may be true in certain patient populations, but not all.

Emeriaud et al[2] found that in intubated, spontaneously-breathing, mechanically ventilated infants with a set PEEP, the electrical activity in the diaphragm remains active during expiration. This electrical activity represents the effort to actively regulate gas outflow during expiration, maintain functional residual capacity (FRC), and prevent lung derecruitment.

The net balance of expiratory work for a neonate is at least in part preventing total or partial collapse of the lung. A small baby with a highly compliant chest wall cannot balance the profound collapsing tendency of the lung, but has to rely on active efforts to retard expiratory flow using the diaphragm. In addition, in an intubated baby the glottic activity is rendered non-functional in controlling expiratory flow. This could lead to a situation where the only means left to maintain the FRC would be by trying to regulate expiratory flow using the diaphragm.

Thus, in part, the expiratory activity in neonates might be misinterpreted as an effort to overcome expiratory resistance, while in reality the physiologic response of the diaphragm is to remain active to retard expiratory flow and prevent airway collapse.

This specific physiologic condition in the newborn baby has influenced the regulation algorithm of the expiratory valve in the Servo-i when it is used to ventilate intubated infants. In order to control for rebound effects and unregulated emptying of the low compliant baby lung, the ventilator maintains a specific expiratory outflow design to help prevent total or partial collapse of unstable airways and alveoli by controlling the speed of lung emptying.

Expiratory regulation in the Servo-i is maintained all through the expiratory phase, in contrast to the design for adult regulation in the same device.

Figure 1 illustrates the pressure and flow scalars during invasive adult ventilation with the Servo-i. Note that the outflow of gas during exhalation is unrestricted. A study by Wing and associates confirmed the low resistance properties of the Servo-i with invasive adult settings, when compared to other ventilators.[3]

In contrast Figure 2A shows a progressive reduction in the expiratory resistance during infant invasive ventilation. The valve does not open fully at the beginning of exhalation, but gradually. The initial expiratory flow is reduced. The regulation algorithm that determines the speed of valve opening is dependent on the measured time constant of the respiratory system. During the course of exhalation, the valve opens in a stepwise fashion, resulting in an early return to zero flow. This is also illustrated in Figure 8 in the paper by DiBlasi et al,[1] which shows that zero flow is accomplished at the earliest point in time with the Servo-i. This expiratory regulation algorithm in infant mode is in contrast to the other ventilators compared in the paper by DiBlasi et al.[1]

In contrast, the Servo-i is shown during noninvasive ventilation with an infant in pressure control (see Fig. 2B). Comparing the pressure-time curve in Figure 2A to that in Figure 2B, it becomes evident that the expiratory flow is unrestricted in noninvasive ventilation in the non-intubated infant. Pertinent to this discussion is the finding by Willis et al,[4] that the total work of breathing in pediatric patients (expressed as respiratory pressure-rate products) was lower on a Y-piece or a low level of pressure support than after extubation.

As the pressure-time curve is not presented in the paper by DiBlasi et al, we can only speculate on its configuration, but our assumption would be that the induced resistance with the Servo-i is due to the early regulation of the outflow. After this initial modulated resistance there is a gradual pressure drop, leading to a very quick return to zero expiratory flow.

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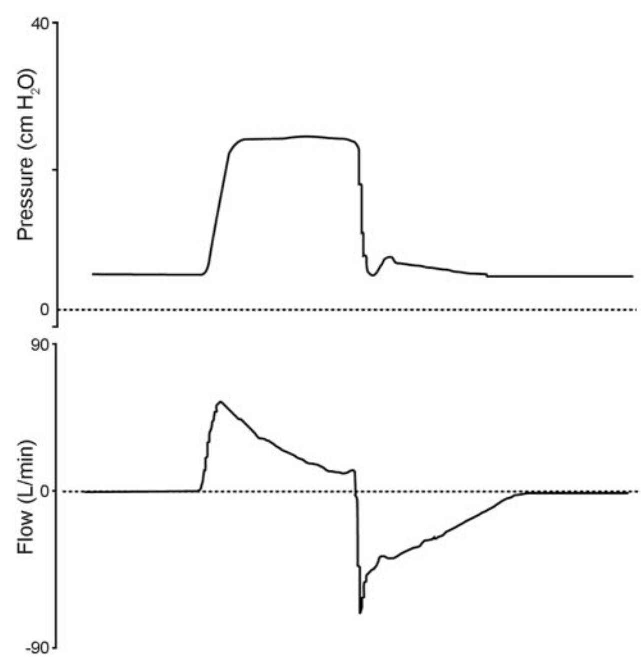


Fig. 1. Pressure-time (top) and flow-time (bottom) curves on the Servo-i screen during pressure-controlled adult invasive ventilation. Note the expiratory flow and pressure decrease unimpeded at the beginning of exhalation, allowing the patient to fully exhale to the set positive end-expiratory pressure (PEEP).

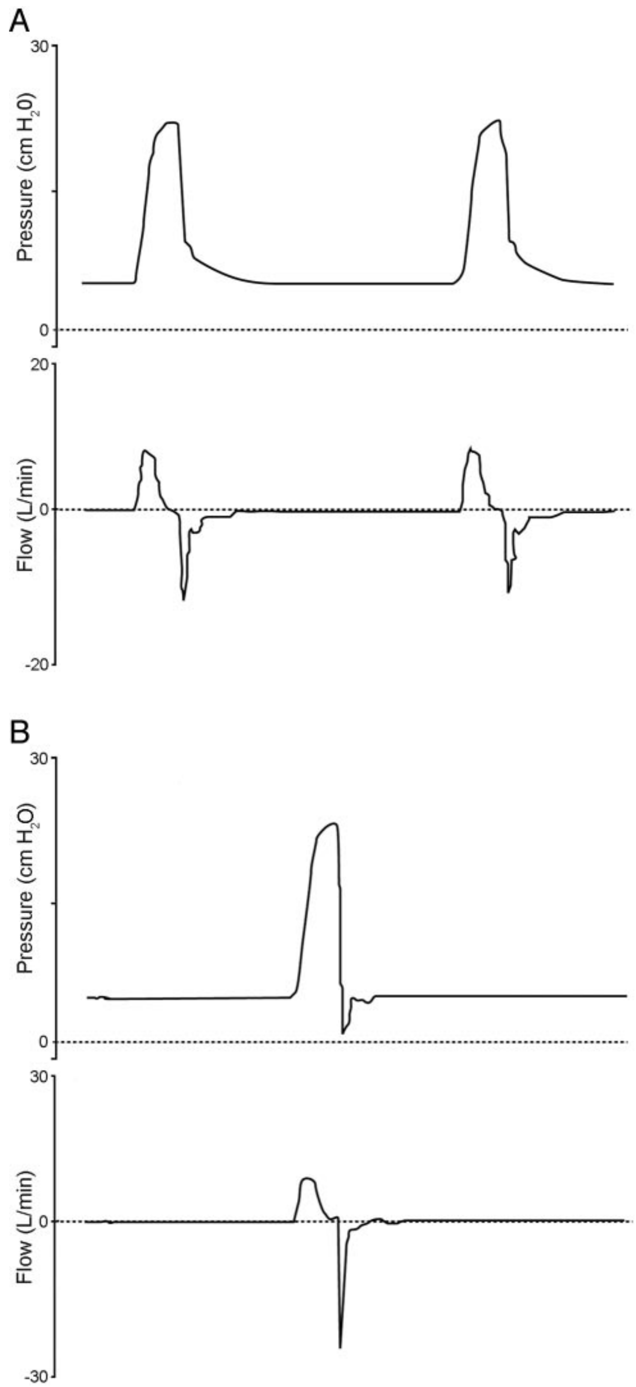


Fig. 2. Pressure-time (top) and flow-time (bottom) curves on the Servo-i screen during (A) infant invasive ventilation, and (B) infant noninvasive ventilation. In invasive ventilation note that the expiratory flow and pressure decrease are reduced at the beginning of exhalation, compared to that in adult ventilation. In noninvasive ventilation note the expiratory flow and pressure are unimpeded at the beginning of exhalation compared to that in infant invasive ventilation.

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*The authors respond:*

We are honored that Maquet responded to our bench study.[1] We appreciate the opportunity to respond in a point-by-point discussion to the interesting commentary provided by Ström and Pilbeam regarding the operational principles of the Servo-i ventilator exhalation valve.

During infant ventilation, the Servo-i ventilator is specifically designed to maintain ventilator-imposed expiratory resistance ($R_E$) to regulate the expiratory outflow by opening the valve "in a step-wise fashion." The effects of this activity can be seen in Figure 1 (of this letter) when evaluating the expiratory flow profile measured at the patient Y-piece. According to Maquet, this design algorithm was influenced by the diaphragmatic expiratory activity of premature infants with lung disease, which "retard(s) expiratory flow" in order to maintain expiratory lung volume. However, the therapeutic benefit of additive imposed resistance during neonatal ventilation is unclear. We performed a literature search to determine these effects on the lung pathophysiology of premature infants. Moomjian et al added an external resistance (30 cm $H_2O$/L/s) to gas flow during exhalation in premature infants recovering from respiratory distress syndrome.[2] That maneuver resulted in increased functional residual capacity (FRC), concomitant with increased work of breathing and reduced inspiratory-expiratory ratio. In our studies we measured ventilator imposed $R_E$ values that were, under certain conditions, approximately 6 times greater than those implemented by Moomjian et al. Of the limited amount of experimental evidence that does exist, there are no data to support the notion that lung recruitment is optimized by adding expiratory resistance beyond the set positive end-expiratory pressure (PEEP) level in intubated mechanically ventilated premature infants. Furthermore, it is unclear how infants with other forms of neonatal respiratory failure would respond to the Servo-i ventilator's disease-specific algorithm for controlling the expiratory valve.

In this in vitro study, we found that the Servo-i had the highest ventilator-imposed $R_E$ of all of the ventilators tested; however, our measurements did not render any intrinsic PEEP levels > 1 cm $H_2O$, even at respiratory rates of 100 breaths/min. This is an intriguing finding, demonstrating the superior performance of the Servo-i ventilator and for all of the ventilators tested. However, since we used a mechanical lung model, it would be very difficult to extrapolate these findings to human infants. To our knowledge, the only study that may suggest that ventilator-imposed $R_E$ impacts the lung pathophysiology has been done using a premature animal model. In premature baboons, Yoder et al identified significant differences in the animals' expiratory airway resistance related to the use of 2 different neonatal ventilators, which resulted in clinical evidence for elevated ventilator support and impaired ventilation efficiency indices in the ventilator using a microprocessor-controlled linear proportional (voice coil) exhalation valve.[3]

According to Ström and Pilbeam, the infant regulation algorithm determines the speed of valve opening and is dependent on the measured expiratory time constant of the respiratory system. This is consistent with our findings and helps to confirm why during active exhalation the imposed expiratory work of breathing was not statistically different with the Servo-i compared to the other ventilator brands tested ($P = .07$, see Fig. 9).

Ström and Pilbeam also state that intubation renders the glottic activity non-functional in controlling expiratory flow and that "this could lead to a situation where the only means left to maintain FRC would be by trying to regulate expiratory flow using the diaphragm." The Servo-i infant algorithm may or may not have important implications during the initial phase of exhalation in infants with lung disease; however, PEEP will ultimately determine the end-expiratory lung volume and FRC, especially in the portion of exhalation where expiratory flow is zero.

It would be inappropriate to speculate that the level of ventilator-imposed $R_E$ during adult mechanical ventilation is similar to the measurements we obtained from the Servo-i during these studies. Adults have larger tidal volumes and therefore, higher peak expiratory flows and separate algorithms for controlling exhalation and maintaining PEEP. Of note, the quoted study by Wing et al[4] does show a lower imposed $R_E$ with the Servo-i than with the other ventilators; however, on closer inspection of their methods for calculating ventilator-imposed $R_E$, the measurement was calculated at a single point during exhalation (peak expiratory flow). Exhalation valves controlled by precise algorithms are variable resistors; therefore, calculating resistance solely at peak flow leads to an exclusion of important information throughout the exhalation. Figure 1 of this letter shows that airway pressure and expiratory flow vary and, therefore, resistance varies considerably throughout the expiratory phase. This is why our method for calculating ventilator-imposed $R_E$ estimates an average resistance throughout the entire expiratory phase.

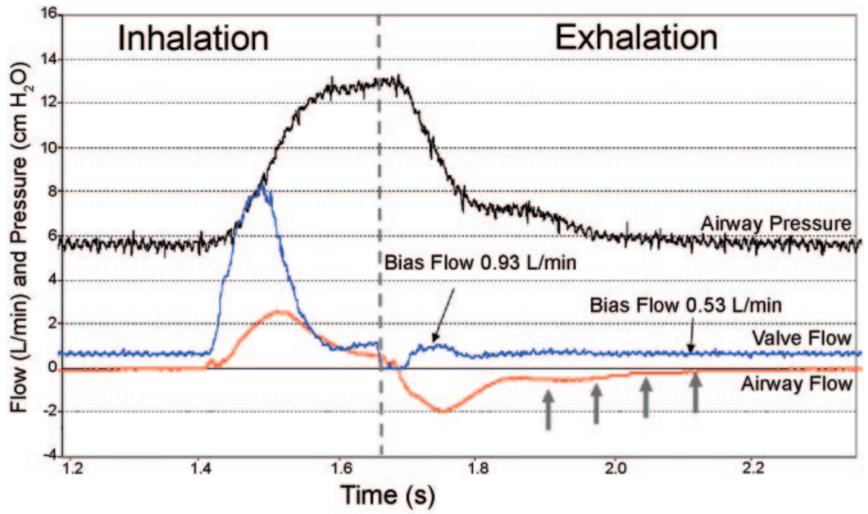


Fig. 1. Airway flow/pressure and flow-control valve measurements sampled at 1024 Hz during neonatal ventilation with the Servo-i ventilator. Data were acquired with a pneumotachometer and pressure transducer placed at the patient Y-piece and a pneumotachometer placed at the inspiratory flow-control valve outlet (at the ventilator) during pressure-regulated volume-control (PRVC) (assist-control) ventilation. The settings were: tidal volume 5 mL, respiratory rate 60 breaths/min, inspiratory time 0.25 s, and positive end-expiratory pressure 5 cm $H_2O$. The dashed gray line separates inhalation from exhalation. The bias flow (black arrows) is represented at 2 points: 120 ms following initiation of exhalation, where bias flow is re-established (0.93 L/min); and at end-exhalation (0.53 L/min). According to Maquet, the expiratory flow returns progressively toward zero flow because of the "opening of the exhalation valve in a stepwise fashion." The step-by-step decay in expiratory flow reflects the incremental changes in the valve position (gray arrows).

Ström and Pilbeam state, "during the course of exhalation, the valve opens in a stepwise fashion, resulting in an early return to zero flow. This is also illustrated in Figure 8 in the article by DiBlasi et al, which shows that zero flow is accomplished at the earliest point in time by the Servo-i." Unfortunately, an error in labeling in Figure 8 misled the authors in their assessment. The expiratory flow, which is more properly represented by the negative labeling of flow on the Y-axis, shows that complete exhalation of gases does not occur until approximately 0.65 s. Figure 1 of this letter further supports this finding.

We would like to re-emphasize that studies with human infants with various lung diseases must be performed before any clinical conclusions can be made about differences in ventilator performance with regard to ventilator-imposed $R_E$.

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The authors have disclosed relationships with Dräger, Maquet, GE Healthcare, and Cardinal/Viasys.

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