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Adult ICU ventilators to provide neonatal ventilation: a lung simulator study

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Abstract *Background:* Traditionally, specific ventilators have been manufactured to only provide neonatal mechanical ventilation. However, many of the current generation of ICU ventilators also include a neonatal mode. *Methods:* Using the IngMar ASL5000 lung simulator the Puritan Bennett 840, the Maquet Servo i, the Viasys AVEA, the GE Engström, the Drager Evita XL and Babylog 8000 Plus were evaluated during assisted ventilation in the pressure assist/control mode. Three lung mechanics were set: resistance 50 $cmH_2O/L/s$, compliance 2 mL/cmH_2O; resistance 100 $cmH_2O/L/s$, compliance 1 mL/cmH_2O; and resistance 150 $cmH_2O/L/s$, compliance 0.5 mL/cmH_2O. A maximum negative pressure drop of 4 and 7 cmH_2O was achieved during simulated inspirations. Each ventilator was evaluated with PEEP 5 cmH_2O, peak pressure 20 cmH_2O and inspiratory time 0.3 s and with PEEP 10 cmH_2O, peak pressure 30 cmH_2O and inspiratory time 0.4 s. Each ventilator setting was then repeated with a leak of 0.3 L/min at a constant pressure of 5 cmH_2O. *Results:* Overall each of the 5 ICU ventilators responded faster or greater than the Babylog with respect to: pressure to trigger (except the Servo i), time to trigger (except the Evita XL), time between trigger and return of pressure to baseline, time from start of breath to 90% of peak pressure (except the Avea) and pressure time product of breath activation. Expiratory tidal volume was also greater with all ICU ventilators except the Avea. Variation in mechanics, leak, PEEP and muscular effort had little effect on these differences. *Conclusion:* All ICU ventilators tested were able to at least equal the performance of the Babylog 8000 Plus on all variables evaluated.

Keywords Ventilators, mechanical · Neonatal · Respiratory mechanics · Respiration, artificial · Intensive care units · Equipment safety · Models

Introduction

Historically, specific mechanical ventilators have been designed for the ventilatory support of neonates and small infants and others for the mechanical ventilation of larger children and adults [1]. One of the first neonatal ventilators introduced in 1966 was the Bourns LS-104 [2]. The LS-104 was a volume ventilator operated by a piston. However, most of the neonatal ventilators manufactured after the LS-104 were designed similar to the classic Bird pressure targeted ventilators [3]. The most recognized of these early ventilators was the Babybird (1971) [4] and the IMVbird ventilators (1975) [5]. From the mid 1970's until the mid 1990's new models of neonatal ventilators were regularly introduced into the market. However, with the introduction of the Siemens 300 ventilator in the early 1990s the philosophy of neonatal ventilators began to change. Manufacturers began to introduce ventilators designed to ventilate patients of all ages and sizes from neonates to adults.

Today, most of the ICU ventilators include a neonatal mode that insures that pressures and volumes suitable for the neonate are only delivered with trigger sensitivity modified to respond to the weak inspiratory efforts made by neonates. As a result of this change in mechanical ventilator philosophy, no new neonatal ventilators have been introduced to the market since the Drager Babylog 8000 Plus.

We questioned if this new generation of ICU ventilators could respond to the triggering efforts of neonates and if gas delivery would be appropriately modified to meet the needs of neonates. Our hypothesis was that this new generation of ICU ventilators, capable of ventilating patients of all ages, would not respond to the efforts of neonates nor modify gas delivery as well as a ventilator designed specifically for ventilation of the neonate. We tested our hypothesis by comparing the triggering and initial gas delivery capabilities of a number of ICU ventilators in their neonatal modes to that of the Drager Babylog 8000 Plus using a neonatal lung simulator. The results of this study have been previously published in abstract form [6].

Methods

Using the IngMar Medical ASL5000 (IngMar Medical, Pittsburg, PA, USA) computerized lung simulator, we compared five ICU ventilators in their neonatal mode (Puritan Bennett 840, Bolder, CO, USA; Maquet Servo i, Danvers, MA, USA; Viasys Avea, Conshohocken, PA, USA; the Drager Evita XL, Telford, PA, USA; and GE Engström, Madison, WI, USA) to that of the Drager Babylog 8000 Plus (Telford, PA, USA) during assisted ventilation in the pressure assist/control mode. We only evaluated pressure ventilation since the Babylog 8000 Plus only provides pressure ventilation.

Study setup

Three levels of resistance and compliance were programmed into the Lung Model: resistance 50 $cmH_2O/L/s$ with compliance 2 mL/cmH_2O (R50/C2); resistance 100 $cmH_2O/L/s$ with compliance 1 mL/cmH_2O (R100/C1); and resistance 150 $cmH_2O/L/s$ with compliance 0.5 mL/cmH_2O (R150/C0.5). Each set of lung mechanics was evaluated under two maximum negative muscle pressures (4 cmH_2O and 7 cmH_2O) [8]. Each ventilator was set to deliver breaths under four different circumstances for each of the six test scenarios defined above for the lung model. Each ventilator was evaluated with a PEEP of 5 cmH_2O, a peak pressure of 20 cmH_2O, an inspiratory time of 0.3 s, and a backup rate of 20 breaths/min and again with a PEEP of 10 cmH_2O, a peak pressure of 30 cmH_2O, an inspiratory time of 0.4 s, and a backup rate of 20 breaths/min. Each test was then repeated with a leak of 0.3 L/min at a constant pressure of 5 cmH_2O. In total, each ventilator was subjected to 24 different test scenarios (Electronic supplementary material Table S1).

Variables evaluated

The following variables were evaluated among all ventilators: pressure to trigger (PT): the magnitude of the maximum negative airway pressure deflection needed to trigger the ventilator. Time to trigger (TT): The time in milliseconds from the start of the patient's effort to the maximum negative airway pressure deflection needed to trigger the ventilator. Time between trigger and baseline (T to B): The time in milliseconds from the maximum negative airway pressure deflection to the reestablishment of baseline pressure (PEEP). Inspiratory T90 (T90): The time in milliseconds from the start of the breath to the point when 90% of target pressure is reached. Pressure time product (PTP): The integration of the difference between airway pressure and PEEP from the start of effort until the reestablishment of baseline pressure. Expired tidal volume (ETV): the volume exhaled from the beginning of expiration to the end of expiration. See Electronic supplementary material Figure S1 for illustration of these evaluated variables. All of the above defined variables, including tidal volume, were measured by the Ingmar.

Data collection and analysis

Approximately 60 breaths were collected during a 124 s simulation for each ventilator under each of the 24 test conditions. Each evaluated variable was expressed as a mean ± SD. All statistical analysis was preformed using SPSS (Chicago, IL, USA). ANOVA and Bonferroni test for multiple comparisons were used for overall comparisons between ventilators, for comparisons of lung mechanics within each ventilator and for comparisons between levels of muscle pressure, PEEP level and presence of leak within each ventilator and across ventilators. A $P < 0.05$ was considered significant, however, only those comparisons that were both statistically significant and differing by at least 10% are discussed as being different.

See online supplement for greater details.

Results

Overall performance

Figure 1 illustrates the collective results for each ventilator across all 24 test scenarios compared to the Babylog. All ventilators had a lesser PT than the Babylog except the Servo i. All ICU ventilators had a faster TT than the Babylog except the Evita XL. All ICU ventilators responded faster than the Babylog with respect to T to B. The Servo i, PB 840, GE Engström, and Evita XL all had Inspiratory T90 shorter than the Babylog but the Avea did not. All five ventilators had a smaller PTP than the Babylog. Finally, the ETV of the GE Engström, Evita XL, PB840 and Servo i was all greater than the Babylog. All of the above findings were significant at the $P < 0.05$ level and greater than 10% different.

See online supplement for greater details.

Effect of lung mechanics

Figure 2 depicts the changes associated with different lung mechanics settings for each of the evaluated variables. As resistance increased and compliance decreased, the PT decreased for the Babylog, Servo i, PB 840, and Evita XL at all settings but only from R100/C1 to R150/C0.5 for the Avea and the GE. The Babylog had a smaller PT than the Servo i under R150/C0.5. The TT for the Avea, Babylog, Engström and Evita XL did not change across the varying lung mechanics. The Servo i's TT increased from R100/C1.0 to R150/C0.5. The TT for the PB840 increased from R100/C1 to R50/C2. The Babylog, Servo i, and Evita XL all showed increases in T to B from R100/C1 to R150/C0.5. The PB840 and Babylog increased T to B from R100/C1 to R50/C2 and the Evita XL decreased from R100/C1 to R50/C2. T90 and PTP generally decreased as resistance increased and compliance decreased. The Babylog had a smaller PTP than the Servo i under R150/C0.5. ETV for all ventilators decreased markedly as resistance increased and compliance decreased. All of the above findings were significant at the $P < 0.05$ level and greater than 10% different.

Effect of PEEP

Figure 3 illustrates the effect of PEEP. PT in the Babylog, PB840, and Evita XL were unaffected by alterations in

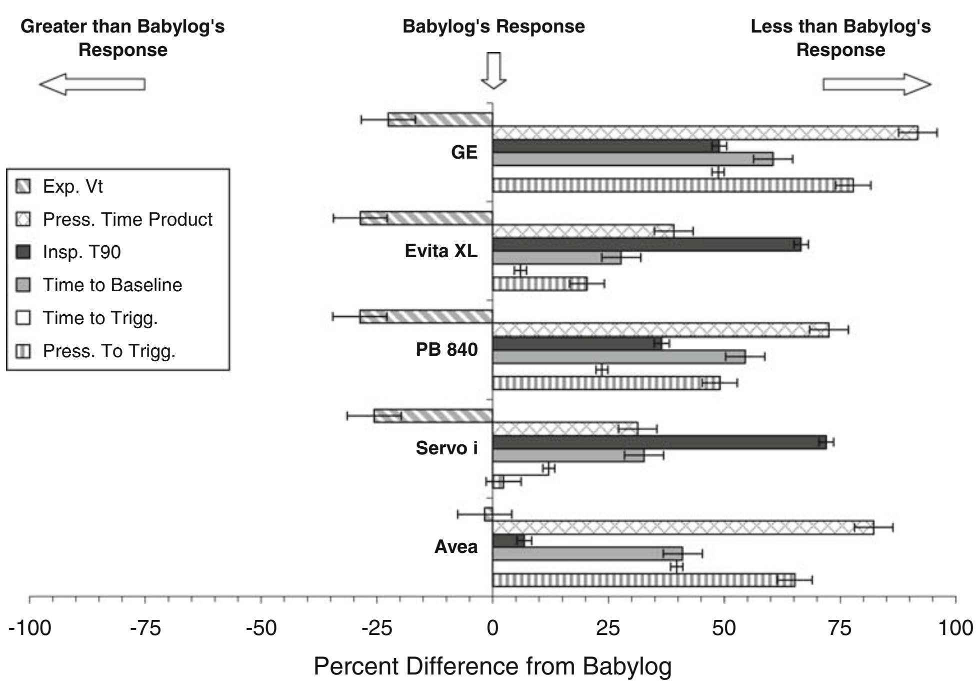

Fig. 1 Illustration of the mean results for each ventilator across all 24 test scenarios compared to the Babylog's mean performance. Each variable is a different *bar*. The *centerline* is the Babylog's mean response. The graph depicts the percentage (greater or less) a ventilator responded with respect to the Babylog's mean response. The *error bars* show the 95% confidence level. The Babylog's mean responses are as follows: PT = −0.820 cmH_2O, TT = 97.9 ms, *T* to *B* = 18.4 ms, T90 = 131 ms, PTP = 41.9 cmH_2O ms, ETV = 25.3 ml

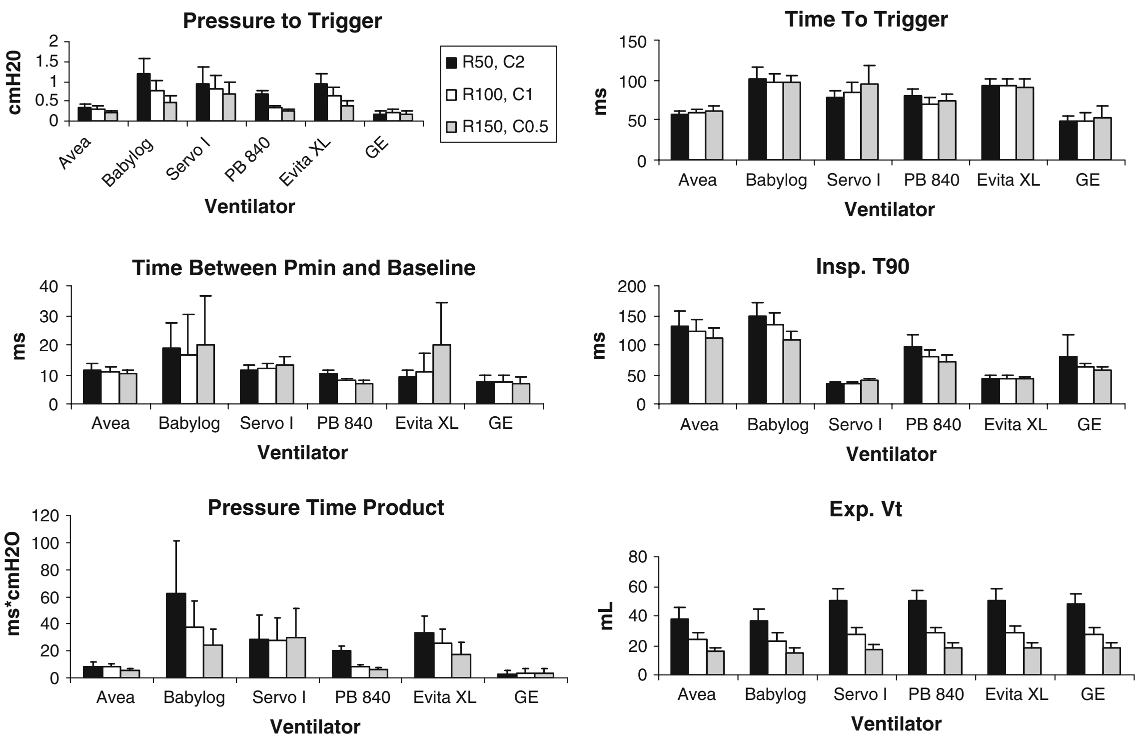

Fig. 2 Changes associated with different lung mechanics settings for each of the evaluated variables. The *grey colored bar* represents R150/C0.5, the *white* represents R100/C1, and the *black bar* represents R50/C2. The *error bars* show standard deviation

PEEP. The Avea had a decrease in PT as PEEP increased and the Servo i and GE Engström had an increase in PT as PEEP increased. The Babylog had a smaller PT than the Servo i under High PEEP. TT was unaltered in all ventilators except the Servo i, which showed an increase in TT as PEEP increased. The T to B for the Servo i, PB840, GE Engström and Evita XL remained unaltered as PEEP was changed. With the Avea T to B decreased with High PEEP, whereas T to B increased in the Babylog as PEEP increased. Generally, T90 increased from Low to High PEEP. The only ventilator unaffected was the Servo i. The GE Engström and Servo i increased PTP as PEEP increased. PTP in the Babylog, PB840 and Evita XL were not affected by PEEP. With the Avea PTP decreased as PEEP increased. ETV increased for all ventilators as PEEP increased. All of the above findings were significant at the $P < 0.05$ level and greater than 10% different.

Effect of muscular pressure

Figure 4 depicts the effect of changing simulated patient muscle effort. The mean PT increased with all ventilators from Low to High Pmus, except the GE Engström. The TT only decreased with the higher Pmus in the PB840 and GE Engström. The Evita XL decreased T to B, whereas the Servo i, GE Enström, PB840 and Babylog were unaffected and the Avea increased T to B as Pmus increased. T90 increased in the Servo i and PB840 as Pmus increased. Overall, the PTP increased as the Pmus increased in all ventilators except the PB 840, which was unaffected, and the GE Engström, which decreased PTP. ETV was not affected by Pmus in any ventilator. All of the above findings were significant at the $P < 0.05$ level and greater than 10% different.

Effect of leak

Figure 5 illustrates the impact of a leak. PT and TT increased in the Servo i and Babylog with the introduction of a leak and decreased in the GE Engström, all other ventilators were not affected. Mean T to B increased in the Babylog and decreased in the Evita XL and GE Engström as a leak was added. All other ventilators remained unchanged as the leak was introduced. The Babylog had a faster T to B than the Evita XL under No Leak. T90 was not affected in any ventilator by a leak. The Babylog, Servo i, and PB840 all increased PTP and the Avea, Evita XL and GE Engström decreased PTP with the leak. ETV was not affected by the leak. All of the above findings were significant at the $P < 0.05$ level and greater than 10% different.

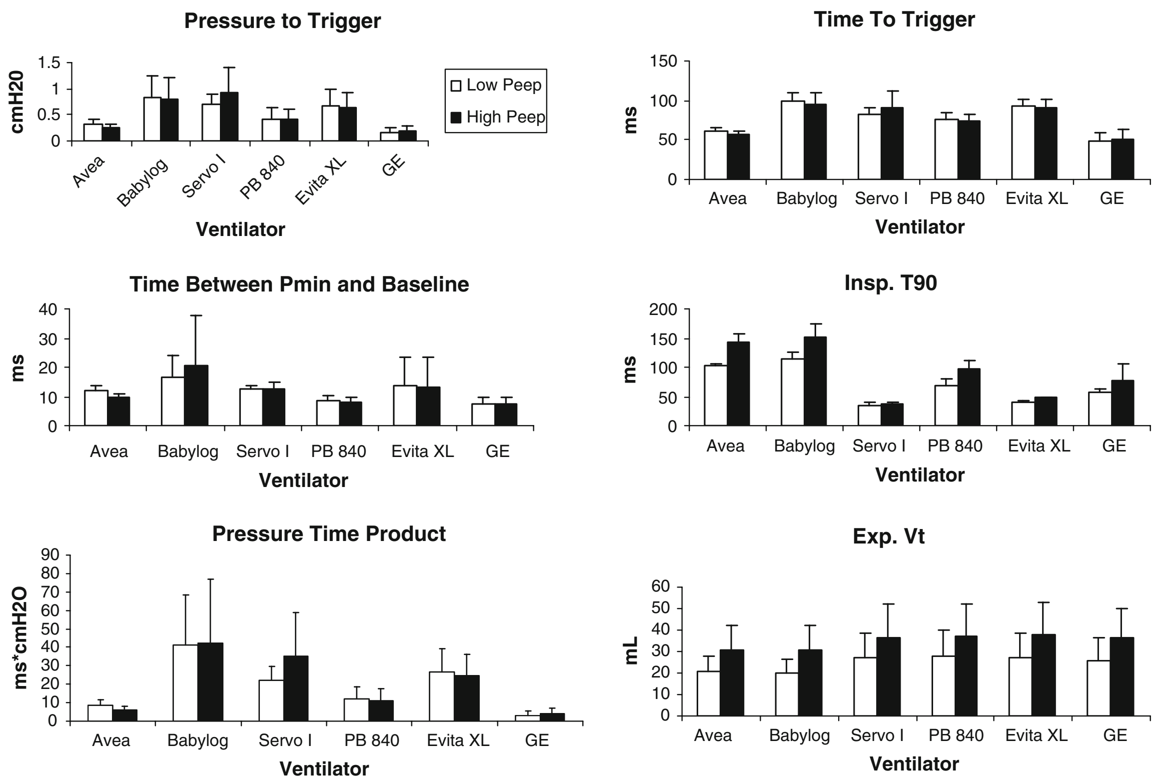

Fig. 3 The effect of high and low PEEP levels on all evaluated variables. The *white bar* represents low PEEP (5 cmH_2O) and the *black bar* represents high PEEP (10 cmH_2O). The *error bars* show standard deviation

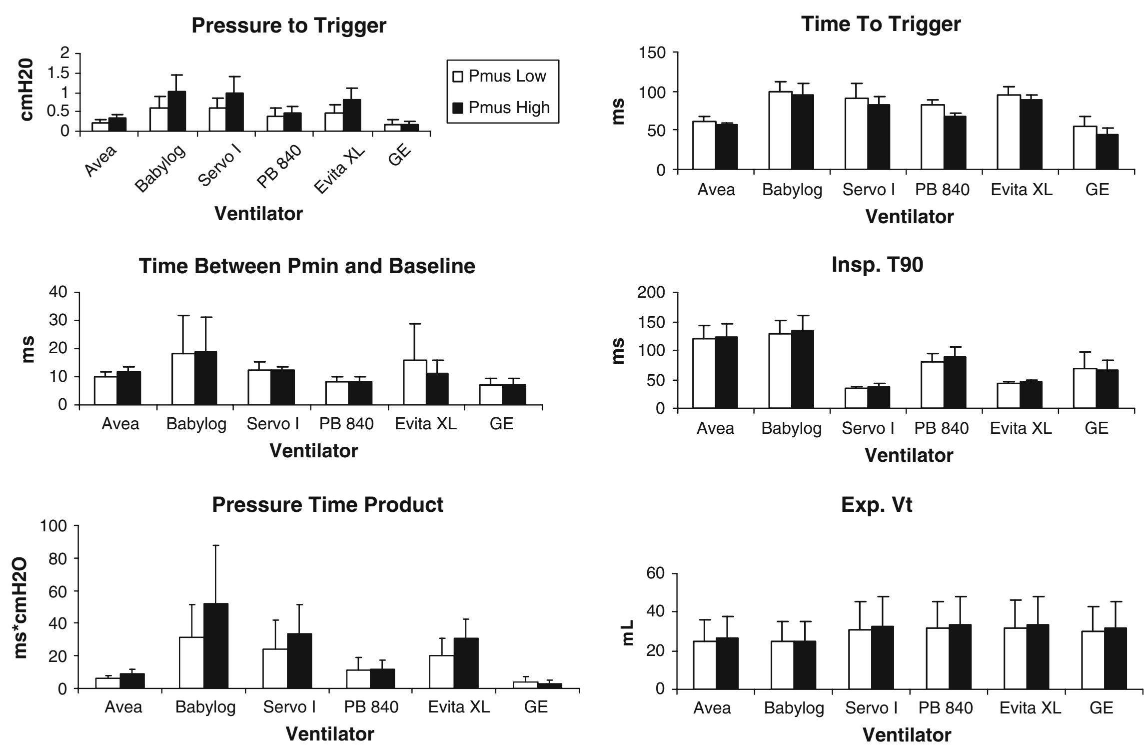

Fig. 4 The effect of changing simulated patient muscle effort on all evaluated variables. The *white bar* represents the lower muscle effort (4 cmH_2O) and the *black bar* represents the higher muscle effort (7 cmH_2O). The *error bars* show standard deviation

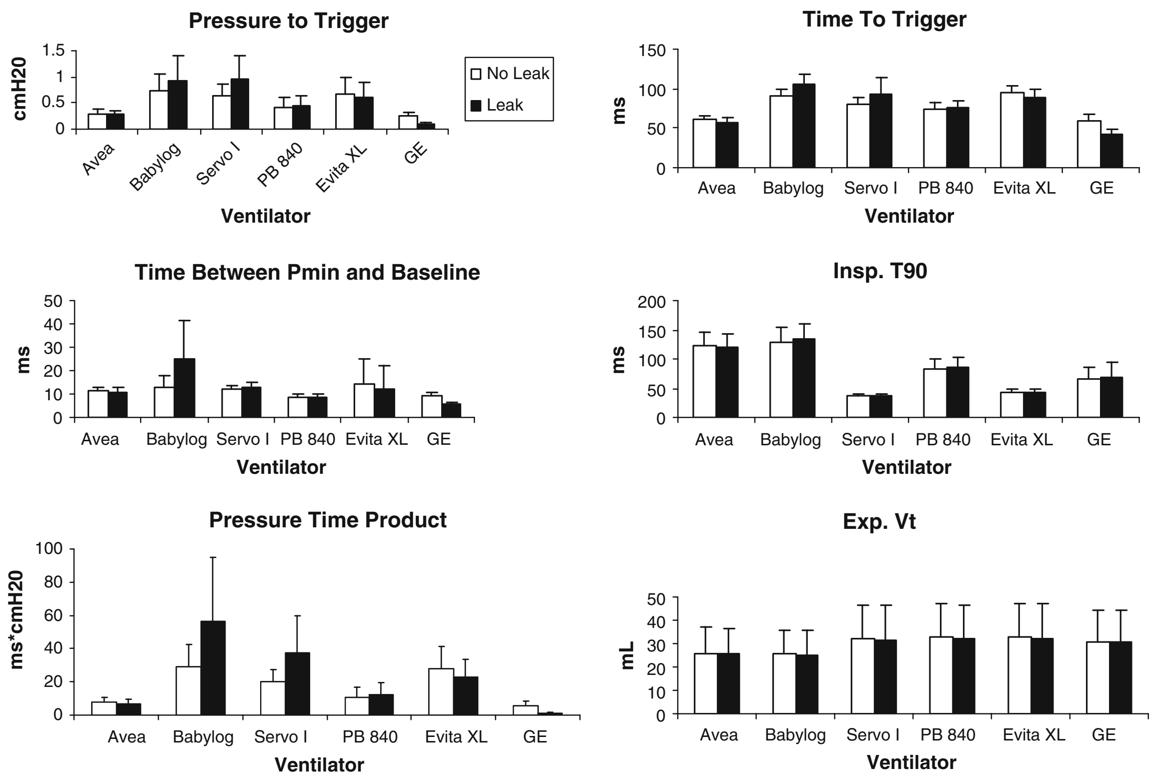

Fig. 5 The impact of a leak on all evaluated variables. The *white bar* represents no leak and the *black bar* represents a leak of 0.3 L/min at a constant pressure of 5 cmH_2O. The *error bars* show standard deviation

Discussion

The findings of this study can be summarized as follows; (1) The ICU ventilators evaluated are capable of responding to neonatal inspiratory efforts and providing initial gas delivery at least as well as the Babylog. (2) The variable where differences were greatest was the triggering PTP, with all ICU ventilators exceeding the Babylog's PTP by at least 30%. (3) Changes in PEEP, leak, and muscular effort had minimal effects on triggering and initial gas delivery of all ventilators evaluated.

We were surprised at these findings and our hypothesis was proven false, since all ICU ventilators performed at least equivalent to the Babylog. Although it is impossible to determine details of each manufacturer's gas delivery system, it does seem reasonable to conclude that the technology in the ICU ventilators evaluated allows them to effectively vary gas delivery over a very large range of compliances and airways resistances. These ICU ventilators have processors that allow a large range of variability in gas delivery as the size of the patient varies.

The variable where the difference between these two types of ventilators was greatest was trigger PTP. This variable is affected by a number of the individual variables evaluated, the PT, TT, and T to B. The single control on all of the ICU ventilators that affected this response, the rise time, was not available on the Babylog. The setting of rise time at its maximum level insured that the post trigger phase of ventilator activation (T to B) and time to 90% of peak flow (T90) were minimized reducing the PTP. The difference in flow acceleration (T to B) of the Babylog post trigger compared to the ICU ventilators was second only to the PTP. This coupled with a more responsive demand system as illustrated by the lower pressures to trigger and times to trigger accounted for the large differences in trigger PTP between these groups of ventilators. The setting of continuous flow on the Babylog may have affected these variables, however the settings used (8 and 10 L/min) were consistent with the settings we use daily in patients. However, we did not evaluate the effect of increasing continuous flow on trigger PTP. Some of the ventilators tested included a bias flow. However, the presence of a bias flow did not appear to affect ventilator response, since most ventilators were flow triggered. The ventilator with the greatest bias flow, the Babylog (our setting of 8 or 10 l continuous flow) is triggered by the inspiration of a given volume of gas. At our sensitivity setting this amounted to about 0.5 ml without the leak and about 2.0 ml with the leak.

Alteration in lung mechanics across all ventilators resulted in predictable changes in PT, PTP, T90 and tidal volume. As the compliance decreased and the resistance increased, inspiratory effort decompressed the system more rapidly allowing a more rapid divergence of flow or volume to trigger. This resulted in a smaller PTP and a more rapid attainment of T90 since the system could be rapidly pressured. The decrease in tidal volume was also expected because of the increased impedance of the system. Increasing PEEP resulted in larger tidal volumes and T90 s on most ventilators as a result of stabilization of the lung model similar to what might be expected with the appropriate application of PEEP in patients. Increased muscle effort increased PT and subsequently PTP because the more rapidly the model inspired the more difficult it became for the ventilator to respond and begin to pressurize the system. Surprisingly the leak had minimal effect on the performance of all ventilators except the Babylog and the Servo i where PT and PTP increased. These ventilators, it would appear, had a more difficult time adjusting to the leak in spite of our adjustment of the sensitivity. In addition, adding a leak did not increase the number of missed or rejected breaths.

Comparison with other studies

A number of others investigators have evaluated the performance of neonatal ventilators [3–8]. In general the performance of the Babylog in these evaluations was consistent with our data [9–14]. Time to trigger, pressure to trigger and ability to function in the presence of a leak in these studies was consistent with our data. The most recent of these evaluations was preformed by Sharma et al. [14], who evaluated the peak pressure, inspiratory time, mean airway pressure and tidal volume delivered by the Babylog, SLE 5000 (SLE systems, UK), Stephaine pediatric ventilator (F. Stephan Biomedical, Germany) and the VIP Bird Gold (Viasys Healthcare, US). They found that at the same settings these four variables were different among the ventilators evaluated. They, however, did not evaluate trigger and initial gas delivery. No previous group compared infant ventilators to adult ICU ventilators.

See online supplement for greater details.

The use of a lung simulator

A lung simulator, no matter how complex and detailed its programming, can never simulate the complexities of the variability in ventilatory pattern of a spontaneously breathing dys-synchronous patient! But what a lung simulator can do is insure that the evaluations performed on a series of ventilators are carried out under the exact same set of circumstances. This is what we were able to accomplish in this evaluation. This data allows prediction of the performance of these ventilators in the same clinical setting but can not precisely define how a ventilator will respond to the stressed patient. It is because of the variability that is observed in patients that these types of evaluations should not be performed in patients. It would be impossible to guarantee that the inspiratory effort of a neonate generated exactly -7 cmH_2O or that the total system leak in a patient with a 2 mm ID uncuffed endotracheal tube was always 0.3 L/min at a constant pressure of 5 cmH_2O.

There is no question that additional data from patients assists in the evaluation of mechanical ventilators. However, with no benefit and considerable risk it must be considered inappropriate to subject infants to the multitude of scenarios created in this evaluation across six ventilators.

Clinical implications

This data supports the current trend in the manufacture of ventilators, ability to ventilate infants to adults. At least when considering the variables of triggering and initial gas delivery, all of the ICU ventilators evaluated can be used with confidence on near term infants. However, there are many other aspects of ventilator function that should be taken into consideration, which we did not evaluate, before a decision is made on a specific ventilator.

Limitations

As discussed above the primary limitation of any study of this nature is the fact that it was not performed on patients. In addition, we did not evaluate every possible gas delivery scenario and there may be situations where these ICU ventilators perform poorly in the neonatal setting. Specifically, we did not design our evaluation to assess ventilation of a 500 g premature neonate and as a result can not comment on the ventilators' performance on these infants. Finally, we did not evaluate all operational aspects of the individual ventilators. It may be that alarm functions, monitoring capabilities or available modes and adjuncts of these ventilators favor the use of a ventilator designed specifically for neonatal use.

Conclusion

All tested ICU ventilators triggered and initially delivered gas flow at least as well as the Drager Babylog 8000 Plus. Under all varying lung mechanics regardless of leak, PEEP, or muscular pressure, the five ICU ventilators ventilated the lung model at least as well as the Babylog. There were considerable differences among all tested ventilators. The evaluated variable showing on average the greatest difference across ventilators was the trigger pressure time product.

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