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# A Comparison of Two Ventilator Systems Using an Infant Lung Model

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STANDARD adult circle systems (with adult ventilator bellows and carbon dioxide absorber) equipped with pediatric circuit hoses, rather than semiclosed partial rebreathing systems or specially designed pediatric circle systems (with small ventilator bellows and carbon dioxide canister), often are used to ventilate infants and children during administration of anesthesia.<sup>1-3</sup> If adult circle ventilator systems are used, it is important to understand the possible limitations and to make necessary modifications of adult techniques for use with infants. One limitation of this equipment for infant ventilation is the difficulty in determining how to set the tidal volume (TV) if using a time-cycled, volume-limited mode of ventilation to ensure that the patient receives the desired TV. The large compression volume of the circle

system relative to the infant's lung volume,<sup>4</sup> leaks around uncuffed endotracheal tubes, effects of fresh gas flow (FGF) on delivered TV, and the mechanical difficulty of setting a small TV using an adult bellows assembly contribute to a discrepancy between set and delivered TVs.

Recently, the Food and Drug Administration approved the use of a circle anesthesia system equipped with an electronic piston ventilator. This system is designed to accurately deliver small TVs by providing easy-to-use ventilator modes and controls, automatic system compliance compensation, and eliminating the interaction between FGF and TV. As a result, time-cycled, volume-limited ventilation of infants with a piston-driven ventilator may be more "user-friendly" and reliable compared with ventilation with most bellows-equipped ventilators. The purpose of our study was to compare the performance of the Drager Narkomed GS ventilator system (North American Drager, Telford, PA), equipped with a traditional ascending bellows ventilator, with the new Drager Narkomed 6000 ventilator system, which uses a circle anesthesia circuit, in ventilating an infant test lung model.

## Materials and Methods

A Drager Narkomed GS circle anesthesia system, equipped with a standard adult bellows and carbon dioxide absorber, and a Drager Narkomed 6000, which incorporates a Divan piston-driven ventilator (Dragerwerk, AG, Lubeck, Germany), were compared regarding delivery of minute ventilation ( $\dot{V}_E$ ) to an infant test lung. Both ventilator systems were equipped with a disposable pediatric circle circuit (Pediatric King; King Systems Corporation, Noblesville, IN). The test lung model used in this study has been described previously.<sup>5-8</sup>  $\dot{V}_E$  was measured using a test lung (Bio-Tek Ventilator Tester; Bio-Tek Instruments, Winooski, VT). The Bio-Tek test lung includes two wire wool-filled metal canisters that simulate lungs that have either normal compliance (0.003 l/cm H<sub>2</sub>O) or low compliance (0.001 l/cm H<sub>2</sub>O),

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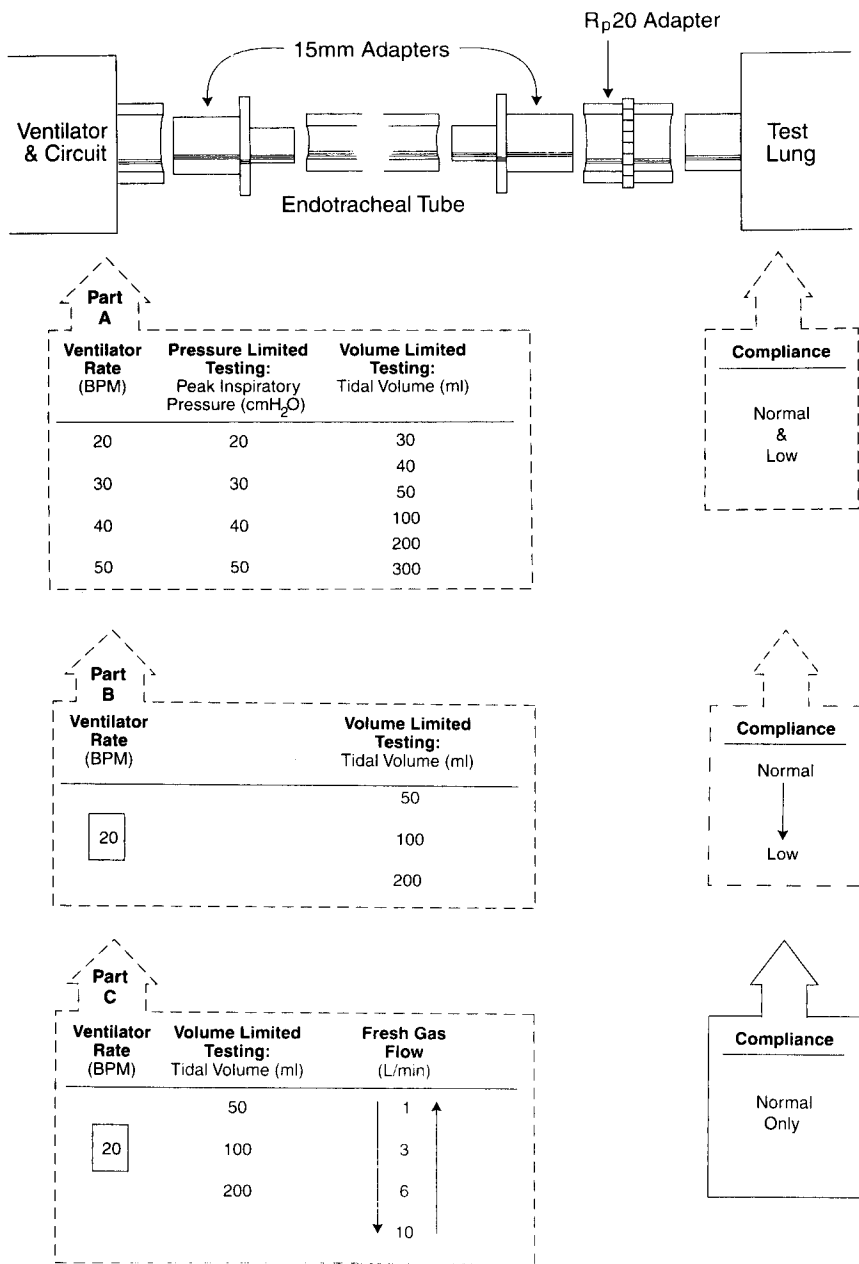


Fig. 1. The Narkomed GS and the 6000 ventilator systems were connected to the infant test lung by an endotracheal tube with a 3.5-mm inner diameter. The study consisted of 3 parts—part A: minute ventilation ( $\dot{V}_E$ ) during time-cycled, pressure-limited and time-cycled, volume-limited ventilation; part B: the effect on  $\dot{V}_E$  of an acute change in test lung compliance (changing from normal infant lung compliance [0.003 l/cm H<sub>2</sub>O] to low infant lung compliance [0.001 l/cm H<sub>2</sub>O]); and part C: the effect on  $\dot{V}_E$  of an increase or decrease in fresh gas flow. Variables tested in each part of the experiment are enclosed within boxes bounded by dotted lines. BPM = breath/min. (Modified with permission from Stevenson GW, Tobin MJ, Horn BJ, Sautel M, Chen EH, Hall SC, Coté CJ: The effect of circuit compliance on delivered ventilation with use of an adult circle system for time cycled volume controlled ventilation using an infant lung model. *Paediatr Anaesth* 1998; 8:139–44.)

as defined by the American National Standards Institute.<sup>9</sup> The test lung determines delivered  $\dot{V}_E$  by measuring peak inspiratory pressure (PIP) and multiplying by the calculated lung compliance to determine the TV.  $\dot{V}_E$  is calculated by multiplying the TV by the respiratory rate (RR). The accuracy of the test lung for  $\dot{V}_E$  is  $\pm 4\%$  for TVs of 5–300 ml in the infant mode. The test lung was connected to the ventilator systems by a 3.5-mm endotracheal tube (Mallinckrodt Medical, St. Louis, MO) cut

distally (removing the Murphy eye to prevent system leakage), with a 15-mm connector on each end (fig. 1). The test lung was set for ambient barometric pressure, temperature, and humidity before all testing. At the recommendation of the test lung manufacturer, the least restrictive adapter (parabolic restrictor R<sub>p</sub> 20) connected the endotracheal tube to the test lung. The study was divided into three parts (fig. 1). During all three parts of the study, an inspiratory-to-expiratory ratio of 1:2 was

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maintained. No significant leaks in either of the ventilator systems were detected before testing. For each condition tested,  $\dot{V}_E$  was measured three times. The average of these three  $\dot{V}_E$  measurements was used for subsequent data analysis.

*Part A:  $\dot{V}_E$  during Time-cycled Pressure-limited and Time-Cycled Volume-limited Ventilation*

The  $\dot{V}_E$  delivered by the ventilator systems to the test lung were compared during time-cycled, pressure-limited and time-cycled, volume-limited ventilation. To simulate a variety of pediatric conditions,  $\dot{V}_E$  was measured with both ventilator systems using a variety of RRs (20, 30, 40, and 50 breaths/min) and with the test lung set in both normal- and low-compliance infant modes. During time-cycled, pressure-limited trials the PIP was adjusted to 20, 30, 40, and 50 cm H<sub>2</sub>O. Using the GS ventilator system, the desired PIP was achieved by adjusting the drive gas flow to the bellows to medium, adjusting the bellows upward to the maximal setting, and adjusting the inspiratory pressure limit ("pop-off valve") to the target PIP. With the 6000 ventilator system, the desired PIP was achieved by direct entry of the desired PIP value into the operation control panel. During time-cycled, volume-limited trials, TVs of 30, 40, 50, 100, 200, and 300 ml were set. With the GS ventilator system this was achieved by visual adjustment of the bellows combined with adjustment of the drive gas flow to the bellows from its initial medium setting upward or downward (if needed) until the desired TV was indicated by the machine's spirometer. In the 6000 ventilator system, TV was adjusted by direct entry of the desired value into the operation control panel. An FGF of 3 l O<sub>2</sub>/min was used during all part A testing.

*Part B: Effect on  $\dot{V}_E$  of an Acute Change in Lung Compliance*

Minute ventilation was measured before and after an acute decrease in test lung compliance during time-cycled, volume-limited ventilation.  $\dot{V}_E$  was measured starting with an RR of 20 breaths/min and a TV of 50, 100, or 200 ml, with the test lung set to mimic normal-compliance infant lungs (0.003 l/cm H<sub>2</sub>O). Then, without changing any ventilator settings,  $\dot{V}_E$  was measured after the test lung compliance was decreased to 0.001 l/cm H<sub>2</sub>O. An FGF of 3 l O<sub>2</sub>/min was used during all part B tests. PIP limits of 80 cm H<sub>2</sub>O for the 6000 ventilator system and maximum for the GS ventilator system were set before all testing.

*Part C: Effect on  $\dot{V}_E$  of Changing Fresh Gas Flow.*

The test lung was set in the normal-compliance infant mode (0.003 l/cm H<sub>2</sub>O) for all testing. To test the effect of an increasing FGF, baseline  $\dot{V}_E$  measurements were made starting at an FGF of 1 l O<sub>2</sub>/min and a set TV of 50, 100, or 200 ml, with an RR of 20 breaths/min. Without changing ventilator settings,  $\dot{V}_E$  was measured after incremental increases of FGF to 3, 6, and 10 l/min. To test the effect of decreasing FGF, we reversed the procedure, obtaining baseline  $\dot{V}_E$  measurements starting with an FGF of 10 l O<sub>2</sub>/min, an RR of 20 breaths/min, and a set TV of 50, 100, or 200 ml. Without changing ventilator settings, the FGF was adjusted incrementally downward to 6, 3, and 1 l/min, and  $\dot{V}_E$  was again measured.

*Data Analysis*

The multiple regression technique was used to analyze the data for part A: The dependent variable was  $\dot{V}_E$ ; independent variables were the ventilator systems used (GS, 6000), lung compliance, RR, and PIP (pressure-limited data) or TV (volume-limited data). For parts B and C, the repeated-measures analysis-of-variance technique was used to analyze the data. The dependent variable was  $\dot{V}_E$ ; independent variables were the ventilator systems, TV, and lung compliance (part B) or FGF (part C).

## Results

*Part A:  $\dot{V}_E$  during Time-cycled Pressure-limited and Time-cycled Volume-limited Ventilation*

During time-cycled, pressure-limited ventilation both the GS and the 6000 ventilator systems generated nearly identical  $\dot{V}_E$  over the entire range of PIPs studied in both the compliant and noncompliant infant lung models ( $P = 0.77$  and  $P = 0.33$ , respectively; fig. 2). During time-cycled, volume-limited trials, the 6000 ventilator system could be set at all TVs; we were not able to set the GS ventilator system to achieve some higher TVs (especially at high RRs in the low-compliance lung model) or any TV less than 50 ml. Thus, no comparison data points were obtained for those TVs. Only TVs of 50, 100, and 200 ml were compared between the two ventilator systems. In the normal-compliance lung model, the 6000 ventilator system delivered slightly higher  $\dot{V}_E$  than the GS ventilator system, but this difference was not statistically significant ( $P = 0.18$ ). In the low-compliance lung model, the 6000 ventilator system delivered greater  $\dot{V}_E$  than the GS ventilator system (an average increase in  $\dot{V}_E$  of 18%;  $P = 0.024$ ; fig. 3).

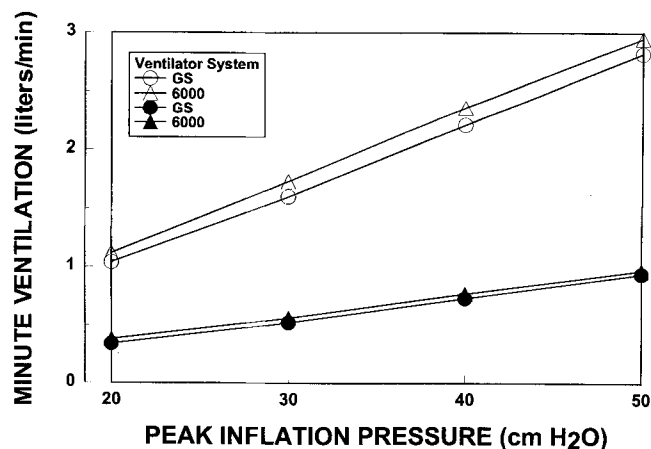


Fig. 2. Comparison of the Narkomed GS and 6000 ventilator systems during time-cycled, pressure-limited ventilation. Data shown are at a respiratory rate of 20 breaths/min; similar data were obtained at other rates studied. Open symbols = minute ventilation ( $\dot{V}_E$ ) with the test lung set to normal infant compliance; darkened symbols =  $\dot{V}_E$  with the test lung set to low infant compliance. Note the nearly identical  $\dot{V}_E$  over the entire range of peak inflation pressures, respiratory rates, and both test lung compliances tested.

#### Part B: Effect on $\dot{V}_E$ of an Acute Change in Lung Compliance

As lung compliance was decreased from normal to low, both ventilator systems delivered less  $\dot{V}_E$  (41–58% less) to the test lung at all TVs studied during time-cycled, volume-limited ventilation ( $P < 0.001$ ) (fig. 4). The 6000 ventilator system was better able to compensate for decreased lung compliance than the GS ventilator system ( $P < 0.001$ ).

#### Part C: Effect on $\dot{V}_E$ of Changing FGF

The GS ventilator system delivered progressively more  $\dot{V}_E$  to the test lung as FGF was increased from 1 to 10 l/min at all TVs studied ( $P < 0.001$  for FGF,  $P < 0.001$  for TV). The GS ventilator system delivered progressively less  $\dot{V}_E$  to the test lung as FGF was decreased from 10 to 1 l/min at all TVs studied ( $P < 0.001$  for FGF,  $P < 0.001$  for TV) (fig. 5A). The 6000 ventilator system maintained nearly identical  $\dot{V}_E$  as FGF was increased from 1 to 10 l/min at all three TVs studied ( $P = 0.14$  for FGF,  $P < 0.001$  for TV) or as FGF was decreased from 10 to 1 l/min at all three TVs studied ( $P = 0.07$  for FGF,  $P < 0.001$  for TV) (fig. 5B).

## Discussion

We observed nearly identical performance of the GS and 6000 ventilator systems during time-cycled, pres-

sure-limited ventilation over a wide range of RRs and PIPs and two test lung compliances. During time-cycled, volume-limited ventilation trials, at TVs that could be obtained in both systems being tested, the 6000 ventilator system delivered slightly greater  $\dot{V}_E$  than the GS ventilator system (an average increase of 18% as measured by the Bio-Tek test lung). This difference between systems may reflect in part how the TV was set on the GS ventilator as well as differences between the spirometers of the two systems. Smaller TVs (50 or 100 ml) were extremely difficult to set accurately with the GS ventilator system, requiring visual setting of the bellows (with 50-ml TV, the bellows was fully “seated” at the bottom of the bellows assembly) followed by adjustment of the driving gas flow to the bellows. TVs below 50 ml were not obtainable at all with the GS ventilator system (the machine’s digital spirometer display of TV does not register such low TVs). Substantial decreases in  $\dot{V}_E$  were observed with both ventilator systems as compliance decreased, at all TVs studied. The 6000 ventilator system was marginally better able to maintain  $\dot{V}_E$  with decreasing lung compliance. Changing FGF during time-cycled, volume-limited ventilation does not effect  $\dot{V}_E$  with the 6000 ventilator system but does influence  $\dot{V}_E$  with the GS system.

Based on our *in vitro* findings, what can we conclude about possible advantages or disadvantages of a piston-driven ventilator system compared with a traditional

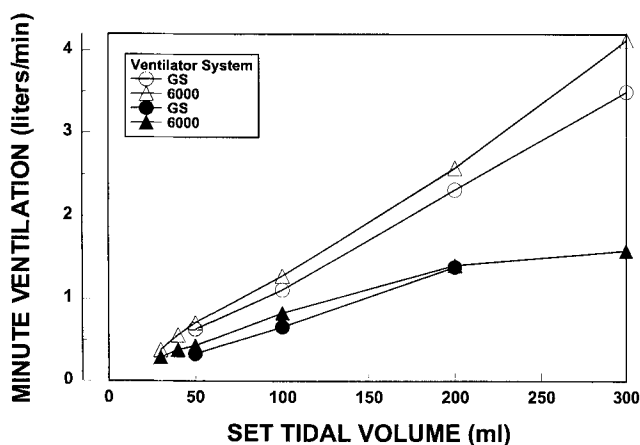


Fig. 3. Comparison of the Narkomed GS and 6000 ventilator systems during time-cycled, volume-limited ventilation. Open symbols = minute ventilation ( $\dot{V}_E$ ) with the test lung set to normal infant compliance; darkened symbols =  $\dot{V}_E$  obtained with the test lung set to low infant compliance. Note that no data points were obtainable in the GS system for tidal volumes less than 50 ml in either the normal or low compliance lung models. The data represented in this figure were obtained with a respiratory rate of 20 breaths/min; similar data were obtained at other rates tested.

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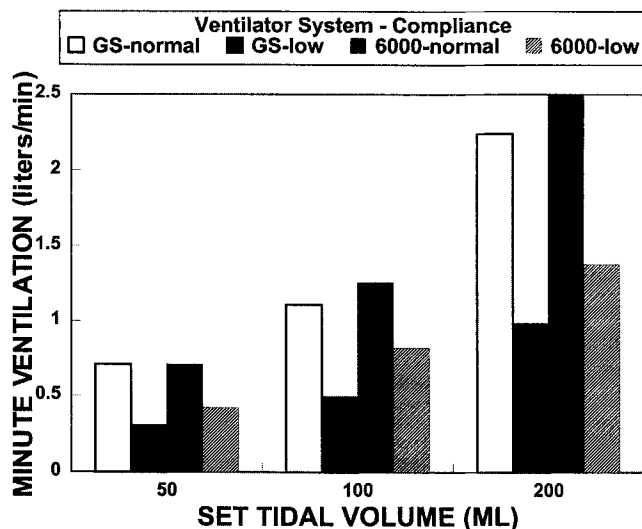


Fig. 4. Comparison of the performance of the Narkomed GS and 6000 ventilator systems during a time-cycled, volume-limited change from normal to low test lung compliance. Note that both ventilator systems delivered significantly lower minute ventilation ( $\dot{V}_E$ ) as the test lung compliance was decreased. The 6000 ventilator system partially compensated for change in lung compliance; the GS ventilator system did not compensate for changing compliance.

bellows ventilator system during infant ventilation? Pediatric anesthesiologists often use the ventilator of an adult circle system in the time-cycled, pressure-limited ventilation mode during infant anesthesia because of their familiarity with this type of ventilation and the mechanical ease of setting a target PIP limit with most ventilators. Our study indicates that during time-cycled, pressure-limited ventilation, it does not make a meaningful difference if one uses either a bellows-equipped ventilator or a piston-driven ventilator; the systems deliver equivalent volumes to the infant test lung over a wide range of RRs and PIPs. The near equivalence of the  $\dot{V}_E$  produced by the GS and 6000 ventilator systems during time-cycled, pressure-limited ventilation reinforces observations made in prior publications using this same lung model.<sup>5-8</sup> During time-cycled, pressure-limited ventilation,  $\dot{V}_E$  is dependent on lung compliance, PIP achieved, and RR, regardless of the compliance of the circuit used, the precise method of achieving a given PIP with the circle system, and the ventilator system used to achieve a given PIP (Mapleson system, circle system, or free-standing ventilator).<sup>5-8</sup> One potential disadvantage of time-cycled, pressure-limited ventilation is that if for whatever reason there were a sudden change in lung compliance or resistance in the system, such as a surgeon leaning on the chest of an infant or a kinked

endotracheal tube, there would be no change in the PIP, and there would be a decrease in delivered ventilation. Other means of monitoring respirations, however, such as auscultation of breath sounds and measured expired carbon dioxide (including the configuration of the wave form), likely would diagnose such problems. In the above scenario, with time-cycled, volume-limited ventilation there would be a sudden rise in peak inflation pressure as well as changes in breath sounds and the carbon dioxide waveform, but TV might be maintained better. Our study did not assess these clinically relevant means of assessing ventilation but rather just examined the performance of each ventilator system under extreme changes in lung compliance.

The GS and 6000 ventilator systems do not perform equally during time-cycled, volume-limited ventilation. The GS ventilator system cannot be used easily as a true volume-limited ventilator. Determination of an appropriate set TV based on patient weight is cumbersome. Badgwell *et al.*<sup>4</sup> have described the nonlinear relationship between patient weight and set TV required for time-cycled, volume-limited ventilation in infants using adult ventilator systems (150–200 ml/kg in a 1-kg infant *vs.* 25 ml/kg in infants more than 10 kg). Once calculated, the smaller TVs required for infants may be mechanically difficult to set because of the lack of precision of the adult bellows assembly. The lowest TV easily set during our study trials was 200 ml, which is the first mark on the bellows assembly. Thus, those who choose to use adult circle systems for infant ventilation often adjust the volume limit of the bellows slowly upward until the desired chest expansion or target PIP is achieved. An initial PIP of approximately 20 cm H<sub>2</sub>O usually is chosen, and further adjustment of the TV upward or downward is based on chest expansion, end tidal carbon dioxide concentration, and oxygen saturation. This type of time-cycled, volume-limited ventilation might be more accurately described as *time-cycled, volume-limited, pressure-guided* ventilation.

The 6000 ventilator system, in contrast to the GS system, is easily set for all TVs during time-cycled, volume-limited ventilation, including TVs less than 50 ml. The ability to set accurate infant TVs, along with the consistency in  $\dot{V}_E$  with changing FGF, would appear to be an advantage of the 6000 ventilator system for use with infants. Peters *et al.*<sup>10</sup> reported successful time-cycled, volume-limited ventilation of 20 infants between 2 and 6 kg with TVs of 10 ml/kg at RRs between 25 and 40 breaths/min, using a piston-driven ventilator system. Such low TVs are not easily obtainable using the GS

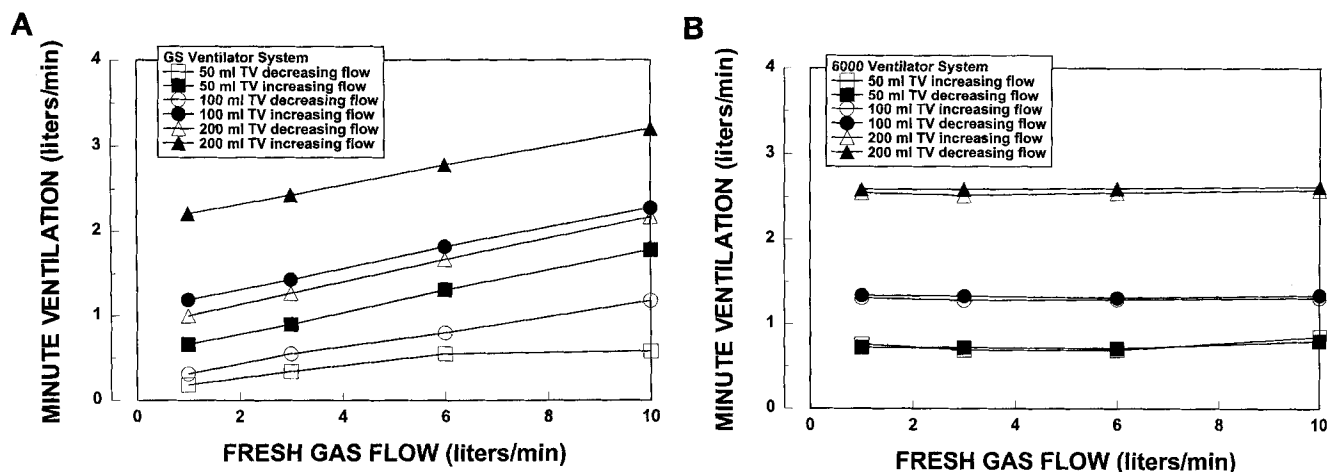


Fig. 5. (A) The effect on minute ventilation ( $\dot{V}_E$ ) of a changing fresh flow using the Narkomed GS during time-cycled, volume-limited ventilation. Note the dramatic increase in  $\dot{V}_E$  as fresh gas flow was increased (1–10 l/min), and the decrease in  $\dot{V}_E$  with decreasing fresh gas flow (10–1 l/min.). (B) The effect on  $\dot{V}_E$  of a changing fresh gas flow using the Narkomed 6000 during volume limited ventilation. Note that as fresh gas flow was varied from 1 to 10 l/min (both increasing and decreasing flow),  $\dot{V}_E$  was unaffected.

ventilator system. It is possible to set the GS ventilator to very low TVs by setting the bellows at the very lowest limit and then adjusting the drive gas flow to the bellows so that the desired TV is achieved; however, these low TV settings are below the technical limits of the GS spirometer and would necessitate assessment of efficacy purely on a clinical basis. Also, with any change in FGF, set TV would need to be readjusted (*i.e.*, if FGF were increased, set TV would need to be decreased to maintain constant  $\dot{V}_E$ ; if FGF were decreased, set TV would need to be increased to maintain constant  $\dot{V}_E$ ). The consistency in  $\dot{V}_E$  over a wide range of FGFs we observed using the 6000 ventilator system is similar to results reported by Schirmer *et al.*<sup>11</sup> in a test lung study using a piston-driven ventilator: TVs ranging from 20–200 ml were delivered reliably during time-cycled, volume-limited ventilation over a range of FGFs (1–6 l/min). When using the 6000 ventilator system, once an appropriate set TV has been achieved, FGF can be adjusted over a wide range without risk of inadequate ventilation (with a decrease in FGF) or overventilation or barotrauma (with an increase in FGF).

Another design difference between the GS and 6000 ventilator systems as used for time-cycled, volume-limited ventilation is the response to a changing lung compliance. Our results show that the 6000 ventilator system has some ability to compensate for compliance changes; the GS ventilator system does not. Because the compensation for a decrease in lung compliance by the 6000 ventilator system is incomplete, the clinical advantage of this compliance feature needs further evaluation; a set

TV may require significant upward adjustment to maintain  $\dot{V}_E$  as lung compliance decreases, regardless of the ventilator system used. The conclusion we have reached based on our *in vitro* study is consistent with results reported by Schirmer *et al.*<sup>11</sup> using a piston-equipped ventilator in an animal model. In that study, using newborn piglets, decreased lung compliance was induced by creation of a tension pneumothorax. Although the piston-equipped ventilator had an improved ability to maintain constant ventilation after induction of the pneumothorax, it was not able to maintain normal ventilation in several piglets.<sup>12</sup> The actual lung compliance of the piglets may have been different from the compliance settings we studied, so that direct comparison of results is not possible. Further studies would be required to examine the clinical importance of the compensation provided by the 6000 ventilator because the acute changes in compliance that we studied may have been more extreme than those that would be observed in most clinical settings.

Our study indicates that the piston-equipped Drager Narkomed 6000 ventilator system performs in a manner similar to the traditional ascending bellows-equipped Drager Narkomed GS ventilator system during time-cycled, pressure-limited ventilation. During time-cycled, volume-limited ventilation, however, the 6000 ventilator system can be set easily to achieve small TVs, but the GS ventilator system cannot. More importantly, the 6000 ventilator system allows maintenance of a constant TV during a wide range of FGFs, without further adjustment. Regardless of the ventilator system used, or the type of

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ventilation that is chosen (time-cycled, pressure limited *vs.* time-cycled, volume-limited), significant adjustment of ventilator parameters is required to maintain ventilation if lung compliance changes.

It is important to emphasize that this study evaluated only the ability of each ventilator system to deliver  $\dot{V}_E$  to a test lung; our study did not address other potential issues related to clinical use of these ventilator systems. Further studies are warranted to evaluate the clinical role of the 6000 ventilator system during infant anesthesia compared with other available systems.

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