Performance of Transport Ventilator With Patient-Triggered Ventilation*

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Objectives: Transport ventilators with inspiratory triggering functions and pressure support-control modes have recently become commercially available. We evaluated these ventilators in comparison with a standard ICU ventilator.

Study design: Laboratory study with a mechanical lung model.

Methods: We compared the performance of four transport ventilators (model 740, Mallinckrodt, Pleasanton, CA; TBird, Bird Products Corp, Palm Springs, CA; LTV1000, Pulmonetic Systems, Colton, CA; Esprit, Respironics, Vista, CA) with a standard ICU ventilator (model 7200ae; Mallinckrodt) using a test lung that simulated spontaneous breathing (compliance, 46.8 mL/cm H₂O; resistance, 5 cm H₂O/L/s). The settings of ventilators were positive end-expiratory pressure (PEEP) of 0 or 5 cm H₂O, and pressure support (PS) of 0 or 10 cm H₂O. The settings of the test lung were inspiratory time of 1 s, respiratory rate of 10/min, peak inspiratory flow of 40, 60, and 80 L/min. To evaluate inspiratory function at each setting, we measured the inspiratory delay time (DT), inspiratory trigger pressure (P-I), and the time for airway pressure to rise from the baseline pressure to 90% of the end-inspiratory pressure (T90%); for expiratory function, supraplateau expiratory pressure (P-E) and the time constant (τₑ) for pressure decrease during exhalation were evaluated. Oxygen requirement was assessed as the time required to empty a 3.5-L oxygen tank.

Results: For inspiratory triggering, four transport ventilators had DT < 100 ms, which is considered clinically satisfactory, in all the settings except for PS 0 cm H₂O, PEEP 0 cm H₂O, and inspiratory flow of 80 L/min with LTV1000. P-I increased only in LTV1000 when PEEP was increased from 0 to 5 cm H₂O. τₑ for the transport ventilators was > 50% shorter than for the ICU ventilator except for PS 0 cm H₂O and PEEP 5 cm H₂O with TBird. Oxygen requirement was lowest for the Esprit, followed by the 740, LTV1000, and TBird.

Conclusion: The newer Food and Drug Administration–approved transport ventilators have performance indexes comparable to the ventilator currently used in ICUs and can probably be recommended for clinical use. (CHEST 2000; 118:1109–1115)

Key words: ARDS; transport; ventilator performance; work of breathing

Abbreviations: DT = inspiratory delay time; FIO₂ = fraction of inspired oxygen; P-E = supraplateau expiratory pressure change; PEEP = positive end-expiratory pressure; P-I = inspiratory trigger pressure; PS = pressure support; RR = respiratory rate; T₉₀% = time taken for airway pressure to rise from baseline pressure to 90% of end-inspiratory pressure; TI = inspiratory time; τₑ = time constant of expiration
should be performed by experienced staff. The use of a transport ventilator can reduce risk when only less experienced staff are available.

Although a number of studies of ventilator performance have been published, they have generally been concerned with ICU ventilators and home-care ventilators. Since the advent of pressure-support ventilation, ICU ventilators have provided improved synchrony with patient breathing and increased patient comfort during mechanical ventilation. The basic requirements for transport ventilators include physical ease of portability, an independent power source, and low oxygen utilization; these design considerations have technically limited the performance of transport ventilators. The transport ventilators that provide inspiratory triggering functions and pressure support–control modes to preserve spontaneous breathing have recently become commercially available. In this study, we evaluated these ventilators in comparison with a standard ICU ventilator, using a lung model simulating spontaneous breathing.

**Materials and Methods**

*Lung Model and Ventilators*

A custom-made bellows-in-a-box model lung was used to simulate spontaneous breathing (Fig 1). The space between the rigid box and the bellows simulated the pleural space. The upper bellows was connected to a metal T-tube through which gas flow was injected to create negative pressure owing to the Venturi effect in the pleural space. Source gas (air at 50 lb/square inch) was connected to a custom-made pressure regulator and a proportional solenoid valve (SMC 315; SMC Co; Tokyo, Japan). Opening of the solenoid valve was controlled by a function generator (H3BF; Omron; Tokyo, Japan). Inspiratory flow demand, inspiratory time, and respiratory rate (RR) were controlled by setting the regulator. A register of 5 cm H2O/L/s (Michigan Instruments Inc; Grand Rapids, MI) was connected to the model lung, the compliance of which was adjusted to 46.8 mL/cm H2O. When attached to each ventilator, using the ventilator's standard circuit without a humidifier, the model lung was set as follows: spontaneous breathing, RR, 10 breaths/min; inspiratory time, 1.0 s; and peak inspiratory flow, 40, 60, or 80 L/min.

Table 1 shows the basic characteristics of the following single ICU ventilator and four transport ventilators that we evaluated: (1) Mallinckrodt 7200ae (Pleasanton, CA); (2) Mallinckrodt 740; (3) TBird (Bird Products Corp; Palm Springs, CA); (4) LTV1000 (Pulmonetic Systems; Colton, CA); and (5) Esprit (Respironics Inc; Vista, CA).

**Measurements**

A pneumotachometer (model 4700 [0–160 L]; Hans-Rudolph Inc; Kansas City, MO), calibrated using a precision flowmeter, was placed at the airway opening of the model lung (Fig 1). Pressure transducers (model TP603T; [± 50 cm H2O]; Nihon Kohden; Tokyo, Japan), which had been calibrated at 20 cm H2O using a water manometer, were used to monitor the pressure differential across the pneumotachometer, or pressure at the airway opening. The data signals from these devices were amplified, digitized, and recorded at 200 Hz/signal using data analysis software.
acquisition software (WINDAQ; Dataq Instruments Inc; Akron, OH). Three breaths were analyzed, and average values were used.

Experimental Protocol and Data Analysis

Experiment 1: Each ventilator was set at positive end-expiratory pressure (PEEP) of 0 or 5 cm H2O and pressure support (PS) of 0 or 10 cm H2O, and used to ventilate the model lung, which was set to require inspiratory flow rates of 40, 60, and 80 L/min. Except for the 7200ae (−1 cm H2O), flow triggering was used in all transport ventilators. Sensitivity was set at 1 L/min except for the Esprit (0.5 L/min) as the most sensitive setting without self-triggering.

Figure 2 shows the variables that we analyzed to evaluate ventilator performance. The time between the start of inspiration to the point of minimum airway pressure was recorded as inspiratory delay time (DT). Inspiratory trigger pressure (P-I) records the difference between the baseline pressure and the maximum subbaseline pressure established during triggering of inspiration. T90% values represent the time for airway pressure to rise from the baseline pressure to 90% of the end-inspiratory pressure. Supraplateau expiratory pressure change (P-E) expresses the pressure change from the end-inspiratory value after the onset of exhalation. The rate of airway pressure decrease during exhalation was evaluated from the time taken for airway pressure to decrease from the peak value to 37% of peak value (time constant (τe)).

Experiment 2: Except for the 7200ae, a tank containing 3.5 L of O2 pressurized to 150 kg/cm² was connected to the oxygen inlet of each ventilator. The model lung (Training Test Lung; Michigan Instruments Inc) was ventilated using volume-controlled ventilation: tidal volume, 500 mL; RR, 20; fraction of inspired oxygen (FIO2), 1.0; and PEEP, 5 cm H2O. In the TBird, base flow was set at 10 L/min. The time taken for the O2 tank to empty, thus setting off the ventilator supply pressure alarm, was measured.

Results

Figure 3 shows typical waveforms for airway pressure plotted against time for each ventilator when the lung model was set to an inspiratory flow rate of 40 L/min with PEEP set to 5 cm H2O and PS at 10 cm H2O.

For each of the ventilators in this study, Table 2 presents data for the variables shown in Figure 2. The Esprit showed intractable self-triggering at inspiratory flow of 60 and 80 L/min, and results that were affected by this were excluded from analysis.

During inspiration, DT at inspiratory phase was not affected by different PEEP or PS levels with any of the ventilators (Table 2). All four transport ventilators had DT < 100 ms in all the settings except for PS 0 cm H2O, PEEP 0 cm H2O, and inspiratory flow of 80 L/min with the LTV1000. P-I increased with increasing inspiratory flow in all ventilators (Table 2 and Fig 4, top, A); however, the LTV1000 was least affected by inspiratory flow. Figure 4, bottom, B shows the ratio of P-I at PEEP 5 cm H2O to that at PEEP 0 cm H2O. Four ventilators were not affected by the PEEP level, and only the LTV1000 was affected. For the LTV1000, when PEEP was 5 cm H2O, the P-I value was double the value obtained at PEEP 0 cm H2O. The values of T90% for the four transport ventilators were less than for the 7200ae (Fig 5).

During expiration, for all ventilators, P-E increased with increasing flow rates; P-E values with the LTV1000 were especially high except when PEEP was 5 cm H2O, PS was 10 cm H2O, and flow was 80 L/min. τe was not affected by increasing flow,
and all four transport ventilators showed >50% shorter values than the 7200ae except for PS 0 cm H$_2$O and PEEP 5 cm H$_2$O (Table 2).

The time taken for the tested ventilators to empty the O$_2$ tank was 25 min 18 s for the TBird, 44 min 40 s for the 740, 57 min 19 s for the Esprit, and 31 min 8 s for the LTV1000.

**DISCUSSION**

The major findings of this study are that (1) the transport ventilators we evaluated trigger inspiration well enough to synchronize with the breathing of patients; (2) the transport ventilators had even lower expiratory resistance than a standard ICU ventilator; and (3) the Esprit had the lowest oxygen requirement, followed by the 740, the LTV, and the TBird.

Mechanically ventilated critically ill patients often require transport to perform diagnostic or therapeutic procedures that cannot be conducted in the ICU. Outside of the ICU, patients are ventilated manually or mechanically with a transport ventilator. Braman et al have reported that clinically significant hemodynamic and blood gas changes occurred in 16 of 20 patients receiving manual ventilation during transport. They concluded that patients should be ventilated with a volume ventilator during transport. Weg and Haas, however, could not discern any hemodynamic and blood gas change in 20 patients during transport and concluded that mechanical portable transport ventilators should not replace well-trained personnel. Hurst et al and Gervais et al have reported respiratory alkalosis in patients ventilated manually during transport. Gervais et al also showed that the unintended respiratory alkalosis during manual ventilation could be avoided when minute ventilation was monitored using a spirometer. There has been no evidence that transport ventilators outperform manual ventilation. In previous reports, the transport ventilators studied were volume or time-cycled ventilators lacking the ability to synchronize with the breathing of patients.

By contrast, the ventilators that we evaluated in this study feature sophisticated pressure support-control modes and are able to synchronize with the patient’s breathing. Using a model lung, we have found that they performed as well as the modern ICU ventilator. In this model lung study, we followed the methodology of a previously published report. As the inspiratory function, we evaluated
DT as the representative value of inspiratory triggering and T90% as the representative value of flow delivery. The DTs of all ventilators were < 100 ms, which is considered satisfactory except for in one setting (PS, 0 cm H2O; PEEP, 0 cm H2O, and inspiratory flow of 80 L/min) with the LTV1000. The performance of inspiratory triggering of the LTV1000 declined with increasing PEEP (Table 2 and Fig 4). This was probably because the exhalation valve attached to the circuit did not work as well as those in the other ventilators. Small T90% values in the four transport ventilators show their capacity to meet the inspiratory flow demand in critically ill patients. The Esprit that we tested was still a prototype at the time of evaluation, and we could not apply some of the test lung settings because of intractable self-triggering. This problem may have been corrected in the commercial version.

Ventilator performance during expiration also correlates to the work of breathing and comfort in mechanically ventilated patients. As an expiratory factor, we evaluated P-E as the representative value of expiratory triggering function. The resistance of the expiratory system is reflected as the combination of P-E and te. With the LTV1000, the P-E values were greater than those with the other ventilators. In this study we set the expiratory trigger sensitivity of each transport ventilator at 25%. P-E can be minimized by adjusting expiratory trigger sensitivity in the LTV1000 and the Esprit (Table 1). Proper adjustment is not easy, however, because none of the transport ventilators in this study comes with a display to monitor waveform in the standard configuration. All four transport ventilators outperformed the 7200ae with regard to te. We do not conclude, however, that these transport ventilators have better expiratory performance than other ICU ventilators, because the 7200ae is known to have a high expiratory resistance. Recent recommendations for ARDS patients include keeping the lungs open by adding sufficient levels of PEEP, with limitations for peak alveolar pressure to avoid additional lung injury by mechanical ventilation. It is difficult to accomplish this sophisticated ventilation technique with manual ventilation. Furthermore, Zakynthinos et al reported that early ARDS patients ventilated with PS showed better oxygenation than with controlled ventilation probably owing to alveolar recruitment augmented by active diaphragmatic contraction. These new transport ventilators not only save the labor of the person who would otherwise have to administer manual ventilation, but they also provide the same quality of mechanical ventilation during transport as ventilators in the ICU.

The basic practical requirements, in addition to the ability to synchronize with the breathing of patients, for transport ventilators are: (1) compact form, (2) low oxygen requirement, and (3) a built-in independent power source. The most compact ventilator that we

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<th>DT</th>
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*Only mean values are shown.
†Data at peak inspiratory flow rates of 60 and 80 L/min were not available because of intractable self-triggering.

Table 2—Measurements of Inspiratory and Expiratory Variables for Each Ventilator
tested in this study was the LTV 1000 (Table 1). In our findings, the order of oxygen requirement grossly followed that of constant flow rate during the expiratory phase. Transport ventilators that more sensitively detected inspiration (740 and Esprit) are bulkier than the other two, possibly because of more complex detection systems. The oxygen requirement of the Esprit can be changed by adjusting the flow sensitivity setting. We set flow sensitivity of the Esprit at 0.5 L/min in this study, which corresponds to a total base flow of 3.5 L/min (Table 1). Reducing the flow sensitivity of the Esprit will cause an increase in the oxygen requirement. To evaluate the oxygen requirement, we used an $F_{\text{io}_{2}}$ of 1.0 to avoid the effects of inaccurate $F_{\text{io}_{2}}$ values. We did not test the capacity of the batteries used in these units. According to the manufacturers' information, however, each of these transport ventilators provide sufficient battery capacity.

The use of a model lung limited the usefulness of this study. First, it is impossible to evaluate gas exchange or the comfort of patients. Second, performance may be dependent on the model lung. At least it can be concluded from our results that the transport ventilators tested in this study can provide the same quality of mechanical ventilation during transport. The performance of these new transport ventilators requires further evaluation in a clinical setting before being recommended for critical care patients. Judging from our findings, we hypothesize that they may be able to do away with the need for manual ventilation during transport.

In conclusion, the newer US Food and Drug Administration–approved transport ventilators available for clinical use have specific performance indexes comparable to ventilators currently used in ICUs. Toward that end, they can probably be recommended for clinical use, specifically for the transport of critically ill patients.

**REFERENCES**