Evaluation of 4 New Generation Portable Ventilators

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BACKGROUND: Portable ventilators are increasingly utilized in the intra- and inter-hospital transport of patients. We evaluated 4 portable ventilators, Impact EMV, CareFusion LTV 1200, Newport HT70, and Hamilton T1, in terms of triggering, delivered tidal volume (V_T) accuracy, battery duration, delivered F_{IO_2} accuracy, and gas consumption. METHODS: Triggering was tested using a microprocessor controlled breathing simulator that simulated a weak, normal, and aggressive inspiratory effort using muscle pressures of −2, −4, and −8 cm H_2O respectively. Delivered V_T and F_{IO_2} accuracy were evaluated across a range of operation. To determine gas consumption, the ventilators were attached to an E type oxygen cylinder and operated at an F_{IO_2} of 1.0 until the tank was depleted. Battery duration was tested by operating each ventilator at an F_{IO_2} of 0.21 until the device ceased to operate. RESULTS: Differences remain among devices in several aspects of the testing protocol. Gas consumption ranged from 9.2 to 16 L/min. Battery duration ranged from 101 to 640 min. Triggering performance varied among devices but was consistent breath to breath within the same device, using the fastest and slowest rise time settings. F_{IO_2} accuracy varied at the low range on the 50 mL V_T setting with one device, and at the high range on both the 50 mL and 500 mL V_T settings with another. CONCLUSIONS: Manufacturers continue to improve the performance of portable ventilators. All the ventilators we tested performed well on V_T delivery across a range of settings, using both the internal drive mechanism (F_{IO_2} 0.21) and compressed oxygen (F_{IO_2} 1.0). Two of the ventilators were unable to deliver accurate F_{IO_2} across the range of V_T. None of the devices was clearly superior to the others in all aspects of our evaluation. *Key words: portable ventilators; triggering; battery duration; gas consumption.* [Respir Care 2013;58(2):264–272. © 2013 Daedalus Enterprises]

Introduction

The use of portable ventilators for intra- and inter-hospital transport of patients has steadily increased over the past 2 decades. Critically ill patients with variable levels of respiratory dysfunction often must be transported within the hospital, across town, or, in the case of military medical transport, across continents, to receive specialized treatment or diagnostic procedures.[1–4] Safe transport of these patients requires the use of a reliable ventilator capable of supporting their ventilatory needs. As technology has advanced, the performance of portable ventilators has improved.[5,6] Devices are also smaller, lighter, and have many of the features traditionally available only with ICU ventilators. We evaluated 4 new generation portable ventilators with respect to delivered tidal volume (V_T) accuracy, triggering, battery duration, gas consumption, and F_{IO_2} stability in a laboratory setting.

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The authors have disclosed relationships with General Electric, Impact Instrumentation, CareFusion, Hamilton Medical, and Newport Medical Instruments, which provided the studied ventilators. Mr Branson has also disclosed relationships with Advanced Circulatory Systems, Ikaria, Covidien, and Breathe Technologies.

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Methods

Ventilators

We evaluated 4 new generation portable ventilators with an internal air source that meets the national disaster management recommendations: LTV 1200 (CareFusion, San Diego, California), EMV (Impact Instrumentation, West Caldwell, New Jersey), HT70 (Newport Medical, Costa Mesa, California), and T1 (Hamilton Medical, Reno, Nevada). The LTV 1200 and HT70 are portable ventilators designed for transport and home care use, while the EMV and T1 are portable ventilators designed for transport. All ventilators were set up and had operational verification tests performed per manufacturer instructions. Ventilator circuits were supplied by the manufacturers.

Tidal Volume Accuracy

Devices were evaluated to determine their ability to accurately deliver V_T across a range of 3 V_T/breathing frequency combinations simulating pediatric and adult volumes. Each ventilator was attached to a lung model (Training and Test Lung, Michigan Instruments, Grand Rapids, Michigan). We placed a Fleisch pneumotachograph (Hans Rudolph, Shawnee, Kansas) between each ventilator and the lung model, with the output recorded with the pneumotachograph's software (RSS 100, Hans-Rudolph, Shawnee, Kansas) for analysis. Each ventilator was tested in volume control ventilation, in 3 ventilation scenarios:

- Set V_T 50 mL, breathing frequency 50 breaths/min, inspiratory time 0.3 s, set compliance 0.025 L/cm H_2O, set resistance 20 cm H_2O/L/s
- Set V_T 100 mL, breathing frequency 50 breaths/min, inspiratory time 0.3 s, set compliance 0.025 L/cm H_2O, set resistance 20 cm H_2O/L/s
- Set V_T 400 mL, breathing frequency 30 breaths/min, inspiratory time 0.5 s, set compliance 0.05 L/cm H_2O, set resistance 10 cm H_2O/L/s

Testing was done at each scenario with an F_{IO_2} of 0.21 and 1.0. In each scenario, after a 1-min stabilization period, 1 min of continuous ventilator operation was recorded. We averaged the data from 50 breaths in the V_T 50 mL and V_T 100 mL scenarios, and from 30 breaths in the V_T 400 mL scenario.

Triggering

A microprocessor controlled breathing simulator (ASL 5000, Ingmar Medical, Pittsburgh, Pennsylvania) was used to evaluate each ventilator's triggering response to varying inspiratory efforts. Muscle pressure settings of −2, −4, and −8 cm H_2O were used to simulate weak, normal, and aggressive inspiratory efforts, respectively, with a lung compliance of 0.05 L/cm H_2O and airway resistance of 5 cm H_2O/L/s. Ventilators were evaluated using 0 and 10 cm H_2O pressure support above 5 cm H_2O PEEP, utilizing the slowest and fastest rise times available on each device and the lowest sensitivity setting that did not produce auto-triggering. After a 1-min stabilization period, 5 breaths were recorded for later analysis. Triggering performance was evaluated using 3 criteria (Fig. 1).

- P_{Imax}, in cm H_2O, was defined as the peak negative pressure change generated during a simulated inspiratory effort. A lower value indicates a lower inspiratory effort required to trigger the ventilator.
- Time delay, in ms, is defined as the time during which airway pressure remains below baseline. Time delay is dependent on the triggering and pressurization responses.
- Rise time, in ms, is defined as the time from baseline after triggering to 90% of the peak pressure produced. Rise time is the indication of the ventilator's ability to recover from the negative pressure phase of triggering and to begin gas delivery.

Battery Duration

Battery duration was evaluated during operation in volume control, with a breathing frequency of 20 breaths/min, V_T of 500 mL, inspiratory time of 1.0 s, PEEP of 5 cm H_2O, F_{IO_2} of 0.21, and lung model parameters of 0.05 L/cm H_2O compliance and 5 cm H_2O/L/s resistance. Devices were equipped with a new, manufacturer supplied, integrated internal battery, and operated on battery power to exhaus-

QUICK LOOK

Current knowledge

Portable ventilators are increasingly utilized in the intra- and inter-hospital transport of patients. The performance of these ventilators has been shown to vary widely with respect to triggering, accuracy of delivered tidal volume, battery duration, accuracy of F_{IO_2}, and gas consumption.

What this paper contributes to our knowledge

Portable ventilators used for transport have similar triggering characteristics and volume delivery accuracy. Gas consumption, battery duration, and F_{IO_2} accuracy of devices tested demonstrated a wide range of characteristics and performance. Understanding the performance of devices allows informed decisions regarding device selection for a given environment.

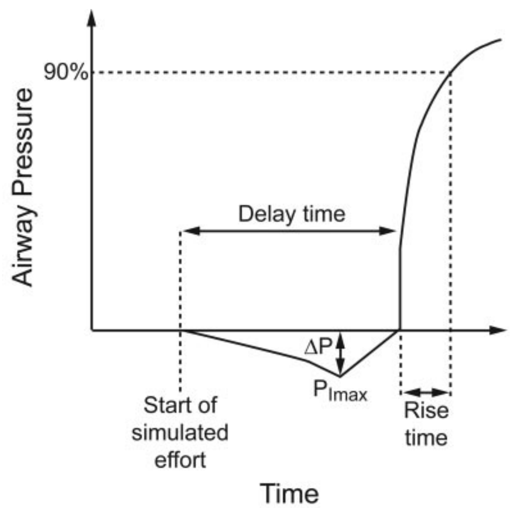

Fig. 1. Triggering evaluation diagram showing maximum inspiratory pressure (P_{Imax}), delay time, and rise time.

tion. The display screen of each device was set to go to "sleep" as quickly as possible, or if that option was not available, the display resolution was set at the lowest setting, to conserve power. Batteries were charged a minimum of 24 hours before testing. Battery duration of each ventilator was tested a minimum of 2 times. Ventilators were attached to the lung model and continuous pressure, volume, and flow measurements were recorded for later analysis of V_T consistency at the end of battery duration. Battery exhaustion was determined by failure of the device to deliver breaths.

Gas Consumption

Gas consumption was accomplished at a breathing frequency of 20 breaths/min, V_T of 500 mL, PEEP of 5 cm H_2O, inspiratory time of 1.0s, and F_{IO_2} of 1.0, using a lung compliance and airway resistance of 0.05 L/cm H_2O and 5 cm H_2O/L/s, respectively. Ventilators were attached to the lung model and pneumotachograph, and continuous airway pressure, volume, and flow were recorded. F_{IO_2} was measured continuously and recorded using a fast response laser diode oxygen analyzer (O_2Cap, Oxigraf, Mountain View, California). Each device was attached to a full E-cylinder (679 L) gas source and operated until the low oxygen alarm was activated and the operating time was recorded. Gas consumption was calculated using the following formula:

$$\text{Inspiratory volume (mean } V_T \times 20 \text{ breaths/min} \times \text{operation time)} + \text{expiratory volume (bias flow} \times \text{expiratory time} \times \text{operation time)/operation time}$$

Table 1. Tidal Volume Accuracy

V_T/F_{IO_2} Settings	Ventilator Model			
	731	HT70	LTV 1200	T1
50/0.21	51.0 ± 1.1	57.9 ± 1.9*	58.2 ± 1.2*	56.3 ± 1.6*
50/1.0	48.7 ± 1.2	52.5 ± 1.4	54.4 ± 1.1	55.7 ± 1.4*
100/0.21	95.5 ± 1.0	105.3 ± 2.6	96.1 ± 1.7	114.5 ± 1.4*
100/1.0	92.3 ± 2.4	101.5 ± 1.8	95.1 ± 1.4	107.8 ± 1.2
400/0.21	387.1 ± 2.1	399.9 ± 1.6	385.3 ± 2.5	439.6 ± 5.9
400/1.0	382.9 ± 5.8	370.5 ± 2.3	381.9 ± 2.1	415.5 ± 1.5

Values are mean ± SD.
* Greater than 10% difference from set tidal volume (V_T).

F_{IO_2} Stability

Ventilators were evaluated on the ability to deliver a stable and accurate F_{IO_2}, particularly at the low and high range, at low V_T (50 mL, breathing frequency 30 breaths/min) and high V_T (500 mL, breathing frequency 20 breaths/min). Lung compliance and airway resistance were set at 0.025 L/cm H_2O and 20 cm H_2O/L/s, respectively, at low V_T, and 0.05 L/cm H_2O and 10 cm H_2O/L/s at high V_T. Each ventilator was attached to the lung model and oxygen analyzer. F_{IO_2} of 0.22–0.3 and 0.9–1.0 were tested in increments of 0.02. We also tested the devices at an F_{IO_2} of 0.6. These values were chosen to represent the range of operation of the oxygen blending systems from a ratio of 1:1 at 0.60 to greater precision at low and high F_{IO_2}. After a 5 min stabilization period at each F_{IO_2} and V_T setting, 1 min of data was recorded for analysis.

Results

Tidal Volume Accuracy

Table 1 shows the mean ± SD V_T delivered by each ventilator at the 3 ventilation scenarios, using F_{IO_2} of 0.21 and 1.0. The mean delivered V_T range was 48.7–58.2 mL on the 50 mL setting, 92.3–114.5 mL on the 100 mL setting, and 381.9–439.6 mL on the 400 mL setting. The HT70 and LTV 1200 produced V_T that were greater than the ± 10% ASTM International standard of the set volume on the 50 mL setting, as did the T1 on the 50 and 100 mL settings. On the 400 mL setting, all the devices were within the 10% ASTM standard.

Triggering

Triggering characteristics varied greatly among devices on both the slowest and fastest rise time settings, and across weak, normal, and aggressive efforts. The P_{Imax} range was 0.32–1.72 cm H_2O with the fastest rise time, and 0.34–3.29 cm H_2O with the slowest rise time. The

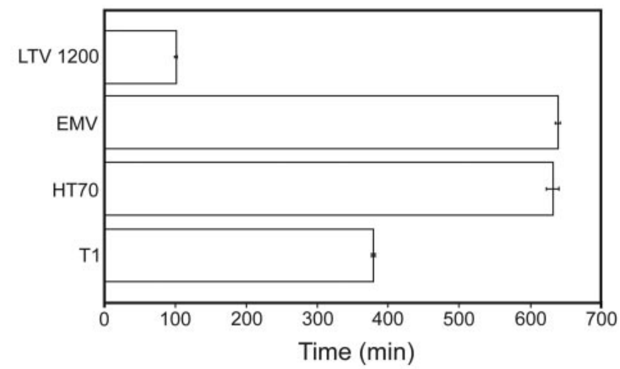

Fig. 2. Mean ± SD battery duration of all tests.

delay time range was 89–405 ms with the fastest rise time, and 93–513 ms with the slowest rise time. The rise time range was 266–765 ms using the fastest rise time setting, and 310–1,180 ms using the slowest rise time setting.

Battery Duration

Battery duration ranged widely among the devices (Fig. 2). The LTV 1200 had the shortest duration (101.3 ± 1.5 min) and the EMV had the longest duration (639.5 ± 3.5 min). The delivered V_T was consistent throughout the entire evaluation with each device.

Gas Consumption

Gas consumption varied among devices and was affected by the use of bias flow and flow-triggering (Fig. 3). The range was 9.2–16.0 L/min at a set minute ventilation of 10 L/min.

The highest gas consumption was with the LTV 1200 with the bias flow on, and the lowest was with the T1 with the bias flow off. The EMV is pressure triggered and there is no bias flow. The delivered V_T differed among ventilators, which had an effect on gas consumption.

F_{IO_2} Stability

Tables 2 and 3 show the mean delivered F_{IO_2} during the 2 ventilation scenarios. Using a threshold of ± 5% set-to-delivered F_{IO_2} accuracy, the HT70 and T1 were able to deliver the F_{IO_2} within the threshold criteria throughout the range of both ventilator setting scenarios. The LTV 1200 was unable to meet the threshold on the high F_{IO_2} settings with both ventilation scenarios. The EMV was unable to meet the threshold on the 0.26–0.30 F_{IO_2} settings and did not have F_{IO_2} settings of 0.22, 0.24, and 0.98 available during the low V_T scenario. The delivered F_{IO_2} was stable throughout each breath cycle with all the devices at every F_{IO_2} setting (standard deviation ≤ 0.01).

Discussion

The main findings of this study demonstrated significant performance differences among devices across the spectrum of operation. The P_{Imax} and delay time were comparable among the devices during the triggering evaluation, but the time to pressurization (rise time) differed

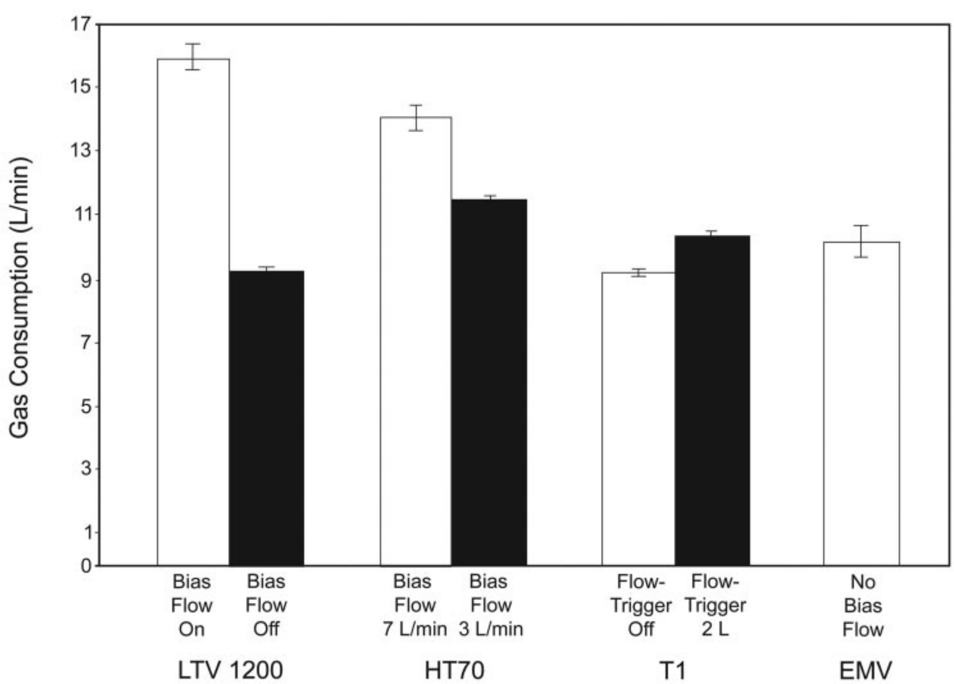

Fig. 3. Mean ± SD gas consumption with and without bias flow.

Table 2. Delivered F_{IO_2} at 30 Breaths/Min and Tidal Volume of 50 mL

	F_{IO_2} Setting											
	0.22	0.24	0.26	0.28	0.30	0.60	0.90	0.92	0.94	0.96	0.98	1.0
LTV 1200	0.215	0.231	0.247	0.263	0.280	0.540	0.811	0.828	0.845	0.878	0.892	0.919
EMV	NA	NA	0.363*	0.383*	0.396*	0.634	0.876	0.910	0.931	0.961	NA	0.998
HT70	0.224	0.243	0.260	0.277	0.298	0.591	0.905	0.925	0.944	0.967	0.989	0.997
T1	0.222	0.238	0.256	0.276	0.293	0.610	0.868	0.897	0.919	0.949	0.980	0.997

* Not within ASTM International standards.
NA = not applicable

Table 3. Delivered F_{IO_2} at 20 Breaths/Min and Tidal Volume of 500 mL

	F_{IO_2} Setting											
	0.22	0.24	0.26	0.28	0.30	0.60	0.90	0.92	0.94	0.96	0.98	1.0
LTV 1200	0.214	0.230	0.248	0.266	0.283	0.565	0.843	0.864	0.883	0.901	0.925	0.944
EMV	0.232	0.256	0.266	0.285	0.305	0.604	0.900	0.921	0.940	0.962	0.983	0.999
HT70	0.224	0.240	0.259	0.281	0.294	0.599	0.909	0.919	0.936	0.961	0.981	0.996
T1	0.221	0.241	0.265	0.286	0.309	0.603	0.910	0.925	0.944	0.964	0.979	0.999

greatly. The devices that had the fastest rise time also produced the largest pressure overshoot. There was a large disparity in gas consumption and between the shortest and longest battery duration. With a few exceptions, the F_{IO_2} and V_T accuracy were comparable among the devices.

Portable ventilators can be grouped into one of 3 categories: automatic resuscitator, simple portable ventilator, and sophisticated portable ventilator. An automatic resuscitator is typically gas powered, provides a set breathing frequency and pressure, and the only alarm is for high pressure. A simple portable ventilator provides a set rate and V_T, and usually has some safety systems. A sophisticated portable ventilator provides a set rate and volume with various modes, including those that allow spontaneous breathing, and has alarms and monitoring capabilities.[4,7,8] This laboratory evaluation allowed a comparison of 4 of the most recent generation of portable ventilators. All the ventilators included in this evaluation are considered sophisticated portable ventilators. All the devices are currently FDA cleared.

The V_T accuracy reported in the operator's manual varied somewhat between ventilators. The EMV and HT70 use the ASTM standard[9] of ± 10% of set V_T, whereas the LTV 1200 and T1 use the same ± 10%, but also includes ± 10 mL, whichever is greater. We chose to use the ASTM standard in our evaluation. All the devices were within 10% of the set V_T at the 400 mL setting. Four of the 5 V_T that were outside of the ASTM standard were at the 50 mL setting, and one was at the 100 mL setting. Four of these 5 V_T were on an F_{IO_2} of 0.21 and produced by both turbine and piston driven devices (see Table 1). The greater V_T accuracy utilizing an F_{IO_2} of 1.0 demonstrates that, even though technology is much improved, volume delivery at low V_T and high breathing frequencies tends to be more accurate when delivered pneumatically rather than by the ventilator's internal drive system. Alternatively, if the ± 10 mL standard, as utilized by 2 of the manufacturers, was used in our analysis, only one V_T would have been outside both standards.

Minimizing the patient's work of breathing is an important goal of mechanical ventilation. Maintaining spontaneous breathing during a transport is desirable, and the ease with which the patient can initiate breaths plays an important role in decreasing work of breathing. Work of breathing is traditionally calculated by creating a pressure-volume curve, measuring the area below baseline pressure, and expressing the work in joules/L.[10,11] Measuring work of breathing in this fashion is technically difficult, not easily duplicated, and often not meaningful to the bedside clinician.

More recently, several studies have evaluated trigger performance of ICU and portable transport and home care ventilators[6,12–16] in terms of the triggering and pressurization portions of the spontaneous breath in pressure support ventilation. The triggering (P_{Imax}, delay time) and pressurization (rise time) measurements we evaluated varied widely among the devices, with both the fastest and slowest rise time setting. The difference was more marked between ventilators with the slowest rise time setting (Fig. 4). The rise time ventilator setting, also called ramp or slope, determines the time it takes to reach full inspiratory pressure. The rise time setting is set by choosing a

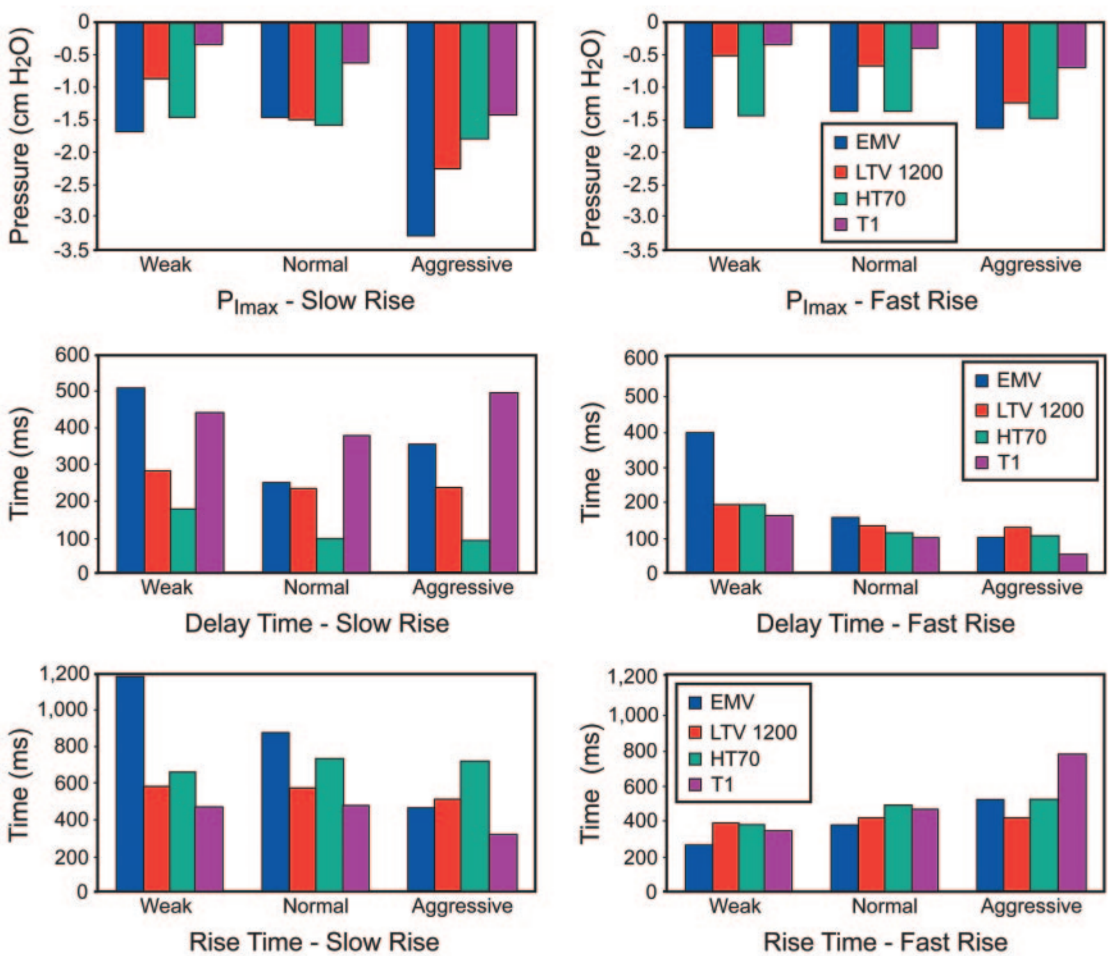

Fig. 4. Triggering evaluation components utilizing fastest and slowest rise time setting. P_{Imax} = peak negative pressure change generated during a simulated inspiratory effort.

numerical value that indicates either a rise time profile or a specific time in seconds or milliseconds. An overly aggressive rise time can result in overshoot, which is defined as the difference between the pressure support setting and the actual airway pressure.[10,17,18] In our evaluation, each ventilator had pressure overshoot when utilizing the fastest rise time setting. The devices with the fastest rise time profile (steepest slope) produced the greatest overshoot (Fig. 5). Conversely, when using the slowest rise time with the same pressure support setting, the T1 did not reach the set pressure, and the EMV produced an extremely long delay time using the same inspiratory time profile on the ASL 5000 and aggressive effort as when testing the fastest rise time setting (Fig. 6). Clinically, this may be important because setting the rise time too fast may result in "ringing" in the ventilator circuit producing pressure overshoot, which may be uncomfortable for the patient. Setting the rise time too slow may result in the set pressure not being delivered or delivered too slowly, resulting in air hunger,

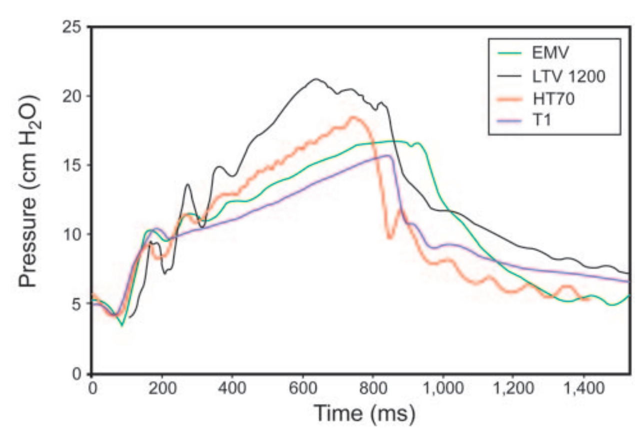

Fig. 5. Representative breaths from each device with aggressive effort, fast rise time, and pressure support of 10 cm H_2O.

increased work of breathing, and patient-ventilator asynchrony.[19–21]

Battery duration is an important function of portable ventilators. These devices are often used in environments

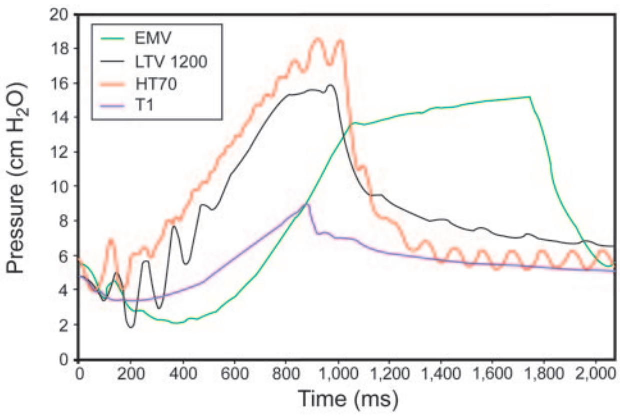

Fig. 6. Representative breaths from each device with aggressive effort, slow rise time, and pressure support of 10 cm H_2O.

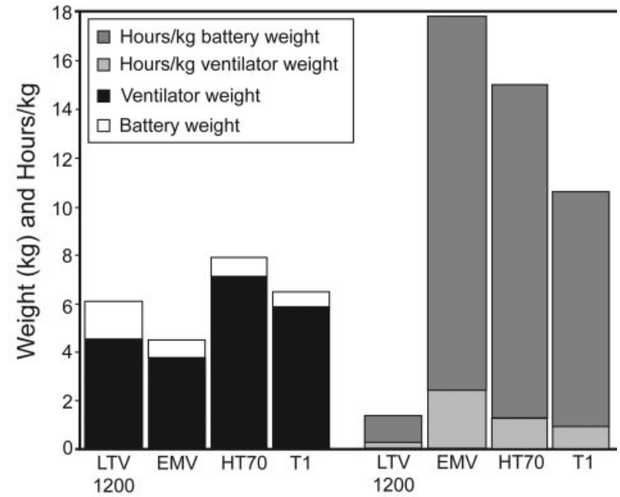

Fig. 7. Battery weight and proportion to ventilator weight, and battery operating time/kg of battery weight and ventilator weight.

where electricity is not immediately available. No industry guidelines currently exist for battery duration. The American Association for Respiratory Care recommended guidelines for portable ventilator minimum battery duration of 4 hours at nominal settings.[19] We chose to test battery duration using only the ventilators' internal air source (F_{IO_2} 0.21) to address the likely scenario of no 50 psi oxygen source in a disaster scenario. The Centers for Disease Control and Prevention task force for mass casualty care recommends the same duration, but based on ventilator settings requirements for ARDS.[19] Several variables affect battery duration, including ventilator settings, battery type and size, and ventilator operating characteristics and drive systems.[14] Prior evaluations have shown that typically turbine-driven ventilators have a shorter battery duration than do piston-driven ventilators, and that constant-speed turbines use the most energy.[14,21,22] Our results showed that, indeed, ventilators that utilize constant-speed turbines have the shortest battery duration, followed by variable-speed turbines and then piston-driven (see Fig. 2).

The LTV 1200 and T1 use a constant-speed turbine and a variable-speed turbine, respectively. The EMV and HT70 are piston-driven. The LTV 1200 uses a lead-acid battery, whereas the other devices use lithium batteries. Additionally, the T1 has dual hot-swappable batteries, and the HT70 has an additional integrated lithium battery that reportedly provides 30 min of power after the main battery is exhausted. These differences may explain the large discrepancy in battery duration among the devices. Campbell et al further quantified battery duration in terms of time of operation in relation to ventilator weight.[21] Figure 7 shows this relationship as well as operation time in relation to battery weight. With their evaluation there was a loose correlation between ventilator weight and operation time. The lightest devices most often had the longest operating time/kg. Figure 7 shows that in our evaluation there was no correlation between device weight and operating time, but the device with the heaviest battery did have the shortest operating time/kg. Battery duration is a function of the battery type (lithium, NiMh, lead-acid, et cetera), battery size, the driving system (turbine, piston, et cetera), and other features (display, touch screen, et cetera). These factors can be optimized for longer battery duration.

In a previous evaluation of portable ventilators we found that V_T decreased toward the end of battery duration with some devices.[23] Clinically, this could promote hypercarbia and respiratory acidosis. In this evaluation the V_T remained consistent from the beginning of the test until complete battery exhaustion with each device.

Gas consumed by the ventilator is another important component of its operation. A major part of planning for patient transport is determining the amount of oxygen to have available. Oxygen cylinders are heavy, cumbersome, and may become projectiles if dropped. Having adequate oxygen supplies without transporting excess cylinders is the goal. Attempts have been made to develop a nomogram to estimate gas consumption for a given cylinder size and duration of use.[24] Unfortunately, ventilator settings, operating characteristics, patient-ventilator interaction, and inconsistent volumes of oxygen in cylinders confound the problem of determining oxygen usage.[25]

To our knowledge, measurements of gas consumption have been limited to determining how long in minutes a cylinder will last on given ventilator settings.[8,22,25] We chose to determine the actual gas usage in L/min, but several variables clearly affected the measurements. One operating characteristic influencing gas consumption is delivered V_T accuracy. The mean inspired V_T varied widely among ventilators during this portion of the testing. The EMV delivered V_T was closest to the set V_T (508 ± 29 mL). The measured V_T delivered by the T1, LTV 1200, and

HT70 were less than the set V_T (range 454–474 mL). Although the V_T delivered with all the devices was within the industry standards, the differences affect the gas consumption results. Quite obviously, a larger V_T results in more gas consumption, whereas a smaller V_T results in using less gas. The other operating characteristic affecting gas consumption is bias flow. Manufacturers utilize this continuous gas flow through the ventilator circuit to facilitate triggering and stabilize PEEP, but it greatly increases gas consumption (see Fig. 3). The LTV 1200 and HT70 provide bias flow of 10 L/min and 7 L/min respectively during the expiratory phase. Bias flow can be turned off with the LTV 1200, and the HT70 has the option of decreasing the bias flow to 3 L/min when placed in NIV mode, which decreases gas consumption. The T1 provides 2 L/min bias flow during the last portion of the expiratory phase of the respiratory cycle, instead of the entire expiratory phase. Utilizing this technique minimizes the increase in gas consumption (1.2 L/min) associated with bias flow use, as opposed to increases of 6.7 L/min with the LTV 1200 and 2.6 L/min with the HT70. The EMV does not utilize bias flow.

For the F_{IO_2} stability portion of the evaluation we used a more rigorous threshold than the ASTM standards for F_{IO_2} accuracy. We used ± 5% threshold for all F_{IO_2} measurements, whereas the ASTM standards are ± 10% of the set F_{IO_2} above 0.30 and ± 3% absolute F_{IO_2} at ≤ 0.30. The EMV was unable to provide an F_{IO_2} within the ASTM standards on the 50 mL setting and F_{IO_2} of 0.26–0.30. The measured F_{IO_2} was approximately 10% higher than set. The EMV was the only device that did not utilize bias flow, which could explain the inaccuracy and unavailability of some of the F_{IO_2} settings on the 50 mL setting. Bias flow provides a continuous flow of gas at a stable F_{IO_2} through the ventilator circuit, which can be readily delivered at virtually any breathing frequency and V_T combination available on a given ventilator. The EMV relies on precise opening and closing of valves to regulate the F_{IO_2}, and with the combination of low V_T, high breathing frequency, and short inspiratory time, the accuracy of this system is diminished.

Limitations

The main limitation of this evaluation is that only one ventilator of each model was used. We assume that additional devices would perform in a similar manner. We did not test devices for suitability in deployed environments, for ease of use, or evaluate ruggedness. The evaluation of a device for purchase should include an assessment of cost, cost of ownership, ease of use, and suitability for the intended environment. All of these are important considerations.

Conclusions

Over the past 2 decades the performance and capabilities of portable ventilators have greatly improved, often incorporating many of the features of ICU ventilators. Overall, the devices included in this evaluation performed well, according to the ASTM standards, although differences remain. While some of the ventilators we tested performed better on triggering or battery duration, others performed better on F_{IO_2} stability, gas consumption, or V_T accuracy. None of the devices was clearly superior to the others in all aspects of our evaluation. Clinicians must consider the desired features and the environment in which the portable ventilator will be used when determining which device to purchase.

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