Battery Performance of 4 Intensive Care Ventilator Models

Thomas C Blakeman RRT, Bryce RH Robinson MD, and Richard D Branson MSc RRT FAARC

BACKGROUND: Hospital electrical power failure represents an important challenge in the intensive care unit. Despite the presence of backup generators, total electrical power failure may still occur. Life-support equipment should have a reliable internal battery to ensure patient safety. We tested the duration of operation of the internal battery of 4 intensive care ventilators. METHODS: In our laboratory we evaluated one each of 4 ventilator models available in our facility (Evita XL, Puritan Bennett 840, Avea, and Servo 300), with volume-control and pressure-control ventilation, and with positive end-expiratory pressure (PEEP) of zero and 20 cm H_2O. We then randomly selected and tested 6 Evita XL and 4 Servo 300 ventilators from our inventory to determine the variability of internal battery duration among ventilators of the same model. The ventilator settings were identical to the previous tests, other than fraction of inspired oxygen, which was set at 0.6, and PEEP was 5 cm H_2O. RESULTS: The battery-duration range of the tested ventilators was 20.5−170.5 min, and the mean ± SD battery duration was 80.4 ± 49.3 min. Changes in breath type and PEEP did not significantly impact battery duration. Among the ventilators of the same model, the battery-duration range was 5–69 min and the mean ± SD battery duration was 28.9 ± 21.4 min. Use of a compressor significantly shortened battery duration. There was no correlation between battery duration and battery age ($r = -0.263$). CONCLUSIONS: The duration of ventilator operation on internal battery ranged widely among the tested devices. Clinicians need to be aware of these differences in the event of power failure. *Key words: ventilator; power failure; backup battery.*
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Introduction

Electrical power failure in the hospital represents an important challenge in the intensive care unit (ICU). Ventilator-dependent patients are at particular risk during a power outage. Although unlikely, total electric power failure can occur, even if an emergency power system is in place. Clinicians rely on electrically powered devices to provide patient care, with ventilators and intravenous infusion pumps being 2 critical devices.[1] The life-support nature of these devices dictates that they have internal batteries to address the risk of hospital-wide power failure.

Older-generation ICU ventilators were electrically powered and did not have internal batteries and, as a consequence, would fail during a power outage. Many of these ventilators are still in use.[1-3] Most newer-generation ICU ventilators have an internal backup battery system, or the option is available. To ensure patient safety, a reliable internal backup battery system is needed if power failure occurs. We tested the internal backup battery systems of 4 ICU ventilator models: Evita XL (Dräger Medical, Telford, Pennsylvania), Puritan Bennett 840 (Covidien, Mansfield, Massachusetts), Avea (Carefusion, San Diego, California), and Servo 300 (Siemens/Maquet, Bridgewater, New Jersey).

The Evita XL and Avea have an external battery system available as an option. Additionally, we tested the variability of internal backup battery duration among multiple units of the Evita XL and Servo 300.

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Methods

This study involved 2 separate evaluations. The first evaluation determined the impact of various ventilator settings on battery duration. We used a single unit of each ventilator model to avoid any variation in individual ventilator performance. Each ventilator battery was charged per the manufacturer's instructions. The Evita XL has an internal battery and an optional external battery, and we tested the internal and external batteries separately.

Of the ventilators available from our inventory, the Avea was the only ventilator we tested that has an internal compressor. We tested the Avea with the compressor (fraction of inspired oxygen [F_{IO_2}] 0.6) and without the compressor operating (F_{IO_2} = 1.0).

The Puritan Bennett 840 was equipped with an optional external compressor, but that compressor does not operate from the backup battery, so we did not test the Puritan Bennett 840's battery performance with the compressor on. In that situation the F_{IO_2} defaults to 1.0 during battery operation.

The Evita XL has an external compressor available as an option, but the Evita XL units in our inventory were not so equipped.

The Servo 300 does not have the option for a compressor.

In each test the ventilator was attached to one chamber of a test lung (Training and Test Lung, Michigan Instruments, Grand Rapids, Michigan). Lung compliance was set at 0.04 L/cm H_2O and resistance at 5.0 cm H_2O/L/s. We placed a pneumotachograph (3700, Hans-Rudolph, Shawnee, Kansas) between the ventilator and the test lung and recorded the output (Hans-Rudolph Pneumotach System, RSS 100, Hans-Rudolph, Shawnee, Kansas) to document the start and stop time of each trial, to calculate duration of operation. We used an oxygen analyzer (Miniox, MSA Catalyst Research, Mars, Pennsylvania) to verify the F_{IO_2}.

We evaluated 4 different combinations of ventilator settings to assess the effect of breath type and positive end-expiratory pressure (PEEP) combinations on battery duration. Each test was done in continuous mandatory ventilation mode, with a respiratory rate of 20 breaths/min, F_{IO_2} of 0.6, and an inspiratory time of 1.0 second. In the volume-controlled mode we set the tidal volume at 0.5 L. We also tested the pressure-control continuous mandatory ventilation mode, during which the peak pressure setting was 14 cm H_2O above PEEP, to deliver approximately a 0.5 L tidal volume.

Testing was performed in duplicate with each combination of ventilator settings. Each test was considered complete when the ventilator ceased to operate.

The second evaluation determined the range of battery duration among a group of a given brand of ventilator. We randomly chose 6 Evita XL and 4 Servo 300 ventilators from our respiratory care department's inventory, which includes 57 Evita XL, 4 Servo 300, 2 Puritan Bennett 840, and one Avea ventilator.

We charged all the batteries per the manufacturer's instructions. Preventive maintenance had been performed on all the ventilators within the previous 3 months. All these tests were done on the same settings: volume control in the continuous mandatory ventilation mode, with a respiratory rate of 20 breaths/min, tidal volume of 0.5 L, inspiratory time of 1.0 second, F_{IO_2} of 0.6, and PEEP of 5 cm H_2O. The compliance and resistance on the test lung were unchanged from the previous tests. Measurements of airway pressure and flow were recorded as previously described. Each test was done in duplicate.

Volume control versus pressure control and zero PEEP versus 20 cm H_2O PEEP in the first evaluation, and the mean battery duration of the Servo 300 and the Evita XL in the second evaluation, were compared with Student's *t* test. $P < .05$ was considered significant. All data are represented as mean ± SD. Statistical analysis was done with spreadsheet software (Excel, Microsoft, Redmond, Washington).

Results

In the initial evaluation the battery-duration range across all ventilators was 20.5–170.5 min; the mean ± SD battery duration was 80.4 ± 49.3 min. The shortest duration was with the Evita XL internal battery, and the longest duration was with the Evita XL external battery. Figure 1 compares the mean tested battery lives to the manufacturer's reported battery lives. The mean tested battery duration of all the ventilators exceeded the manufacturer's reported battery duration, by 29–118%. There were no significant differences in battery duration between volume control and pressure control, or between zero PEEP and 20 cm H_2O PEEP. There was a significant difference ($P < .05$) in battery duration with the Avea when the internal compressor was activated (F_{IO_2} = 0.60) versus when the compressor was not in use (Fig. 2).

Battery performance variability of various units of the same model of ventilator was part 2 of the evaluation. The battery-duration range was 5–69 min among those 10 ventilators (Fig. 3); the mean ± SD battery duration was 28.9 ± 21.4 min. Battery duration was not related to battery age in these tests (r = −0.263) All but one of the Evita XL ventilators had the battery changed at the last regularly scheduled preventive maintenance. The battery that had not been changed had the shortest battery duration (5.5 ± 0.7 min). The Servo 300 ventilator with the shortest battery duration (5.5 ± 0.7 min) had been in service for only 7 months. Two other Servo 300 ventilator batteries had been in service for 25 months. The battery duration in those 2 ventilators ranged from 34 ± 2.8 min to

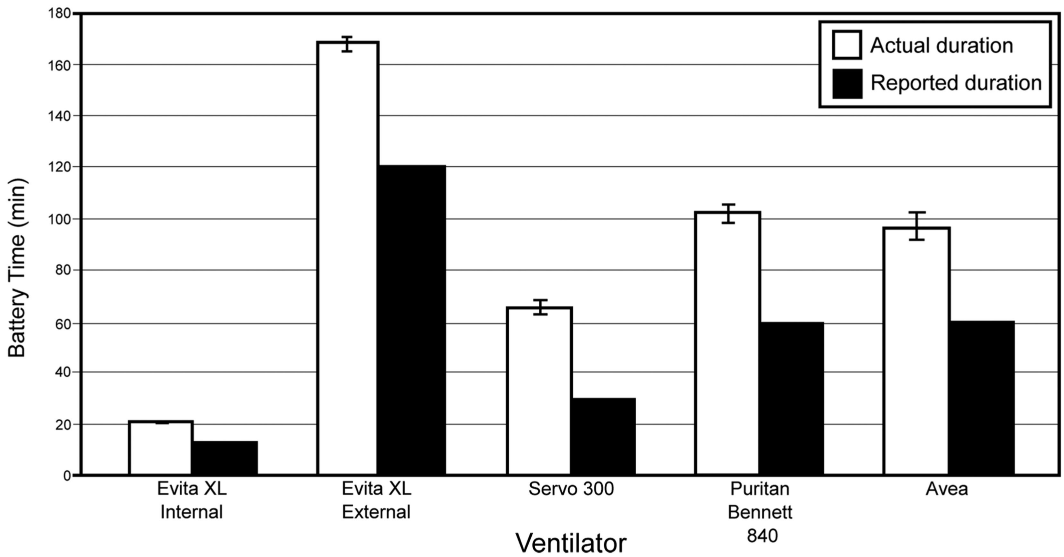

Fig. 1. Duration of ventilator operation on the battery. Data are mean ± SD.

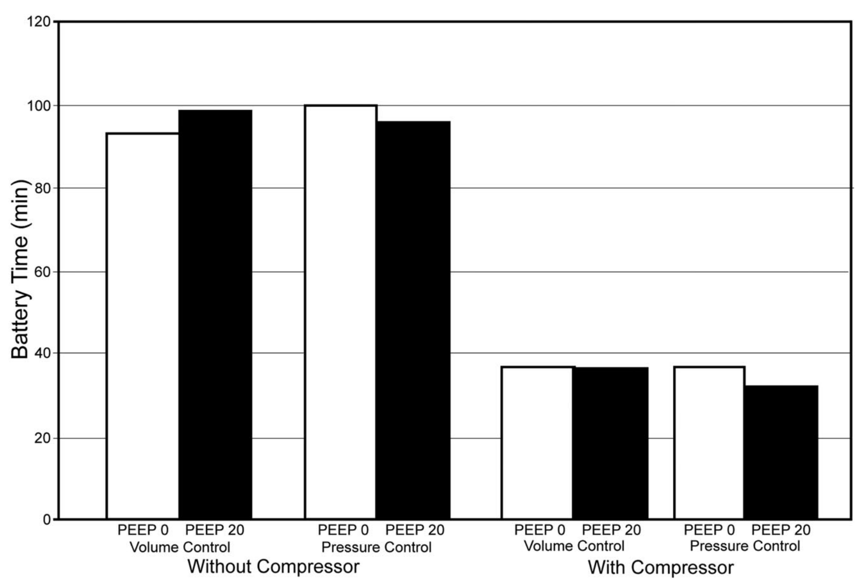

Fig. 2. Duration of Avea ventilator operation on the internal battery, with and without the compressor; with pressure control or volume control; and at positive end-expiratory pressure (PEEP) of zero or 20 cm H_2O. The battery-duration differences with and without the compressor were statistically significant ($P \leq .001$).

68 ± 1.4 min. The battery in the remaining Servo 300 had been in service for 2 months and had a duration of 66.5 min.

Discussion

To our knowledge, this is the first systematic study of battery duration of ICU ventilators. Our main findings demonstrate that battery duration is shortened by operation of an internal compressor, but not by PEEP or breath type. We also found wide variations in battery duration among ventilators of the same model and that had undergone similar use and maintenance. Whereas some of the batteries failed to provide the manufacturer's reported operation duration, many operated longer than the manufacturer's reported duration.

Interruption of the power supply can present a serious problem for mechanically ventilated patients. Hospitals have emergency backup power in the event of commercial power failure, but the ventilator must be plugged into the emergency power outlet to benefit from the backup power system.[1] Despite the ventilator's being connected to emergency power, problems may still arise. When commercial power is interrupted, the system is automatically switched to emergency power, but there is a brief period (usually

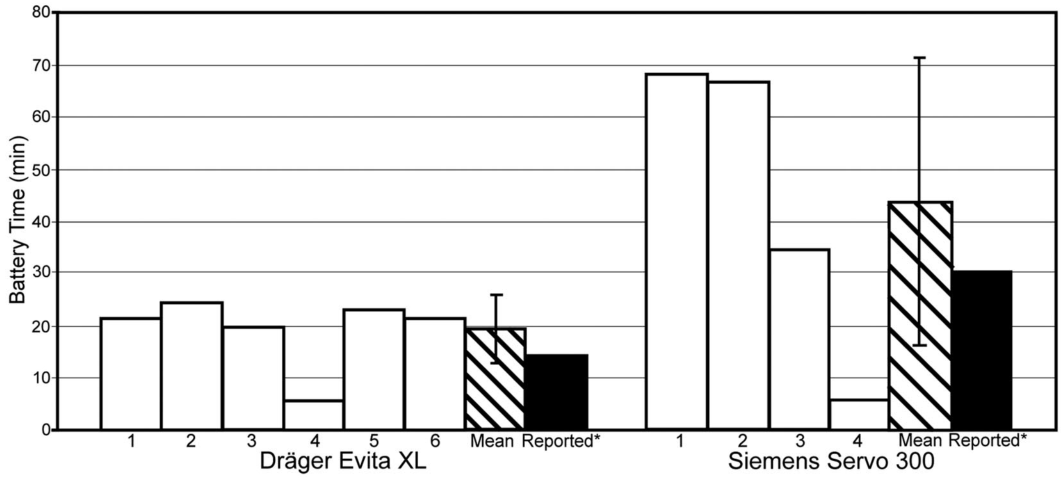

Fig. 3. Duration of ventilator operation on the internal battery with 6 Evita XL and 4 Servo 300 ventilators. The hatched bars indicate the mean ± SD value for that group of ventilators. The mean battery-duration difference between the Evita XL and Servo 300 was statistically significant (P = .008). *Manufacturer's reported battery duration.

less than one second) when there is no power to the emergency plugs.[1] A ventilator that does not have a backup battery system may stop operating due to that power interruption. The ventilator must reset and will therefore fail to provide ventilation, which could be detrimental to the ventilator-dependent patient.[3]

Backup power systems can fail or be unavailable, as was seen during the aftermath of hurricane Katrina in New Orleans,[4] and the recent ice storms in western Kentucky.[5] Those types of emergencies necessitate evacuation of patients to other hospitals.

Another risk is that a ventilator without a backup battery system can be accidentally unplugged from the wall or the back of the ventilator, causing it to shut down. An alarm will sound but no message will be displayed, and the patient will not be ventilated, at least for a short period, even if a clinician is present.[6] A reliable backup battery would prevent that problem. There have been descriptions of battery systems for ICU ventilators, to aid in transport, but not as a backup in the case of power failure.[7]

Since ICU ventilators utilize the power of compressed gas from the wall, changes in PEEP or breath type do not affect battery duration. This is in contrast to portable ventilators that use an internal compressor (turbine or piston), with which increasing PEEP or using pressure control reduces battery duration.[8] Any variable that requires the power source to work against increasing back-pressure (eg, increasing lung compliance or higher PEEP) reduces battery duration. Pressure-control ventilation requires higher initial flow, resulting in greater power consumption.

The duration of ICU ventilator operation from the battery is a function of battery type and size, energy density, type of display, and operation of a compressor. The compressor has the greatest power demand in the ventilator. Operation of the compressor from the battery shortens battery duration, but maintains consistent F_{IO_2}. Another option is always to default to an F_{IO_2} of 1.0 during battery operation, to maximize battery duration. In adults, these F_{IO_2} changes are safe, but in neonates they may have deleterious consequences. Clearly, a trade-off of duration of operation and compressor operation to maintain F_{IO_2} has to be made.

Table 1 describes the batteries tested.

The Evita XL has 2 batteries: an internal dual, sealed, lead-acid battery, with a manufacturer-reported duration of 10–14 min, and an external lead-acid gel battery with a manufacturer-reported duration of 2 hours. The Evita XL was not equipped with a compressor, and operates from a color touch screen.

The Puritan Bennett 840 has an internal sealed lead-acid battery, with a manufacturer-reported battery duration of 1 hour minimum. The 840 we tested was not equipped with a compressor, and operates from a color touch screen.

The Servo 300 has an internal sealed lead-acid battery, with a manufacturer-reported battery duration of 30 min. The Servo 300s we tested were not equipped with a compressor. When the battery is operating, the monochrome waveform display is disabled and the ventilator is operated with control dials.

The Avea has an internal nickel metal hydride battery, with a manufacturer-reported duration of 30 min with the integral internal compressor activated, and 1 hour without. We tested the battery duration with and without the compressor in operation. The Avea operates from a color touch screen.

All the ventilators we tested, except the Avea, use a sealed lead-acid backup battery. The Avea uses a nickel metal hydride battery. Of those 2 battery types, the sealed lead-acid battery has the lower energy density (weight to energy ratio). The energy density of the nickel metal hy-

Table 1. Ventilator Batteries in the Present Study

Ventilator	Type	Volts	Dimensions (cm)	Weight (kg)	Energy Density (min/kg)
Evita XL internal battery	Sealed lead-acid	12	13.5 × 6.7 × 17.1	1.5	13.9
Evita XL external battery	Sealed lead-acid	12	18.3 × 7.6 × 16.8	6.3	26.7
Puritan Bennett 840	Sealed lead-acid dual battery pack	24	15.2 × 6.7 × 19.7	5.5	18.6
Avea	Nickel metal hydride battery pack	24	3.3 × 9.9 × 14.0	0.9	106.5
Servo 300	Lead-acid (2-pack)	12	17.8 × 3.5 × 6.4	2.0total	32.7

* Energy density = mean battery life divided by battery weight.

dride battery was 70% higher than the best-performing sealed lead-acid battery.

Sealed lead-acid batteries are widely used because they are reliable, durable, and inexpensive. The disadvantage of these batteries is their lower energy density, slower charging time, and greater weight. Nickel metal hydride batteries are more expensive but have higher energy density, shorter charging time, and lower weight.

At our institution, regularly scheduled maintenance is performed on all ventilators every 6 months. The Evita XL batteries are changed every 2 years, and the Servo 300 batteries are changed every 3 years, as recommended by the manufacturers. There was no correlation between battery age and duration of operation in our evaluations, as demonstrated by the Pearson's correlation coefficient ($r = -0.263$). Although regularly scheduled preventive maintenance is performed on ventilators at all institutions, problems with the backup battery system can still occur.

We noted one area of potential improvement of ventilators that operate on batteries. Most ventilators use a light emitting diode (LED) display to signal if the device is charging or operating from battery power. The level of battery charge can be ascertained from the color of the LED (green, yellow, red). Only the Avea provides a graphical display of the battery charge. A display that alerts the user to battery charge in 10% increments would assist clinicians in decision making.

Limitations

We used only one ventilator of each model in part one of the study. Our reasoning was to avoid variability among individual ventilators. It is possible that we chose a ventilator with a battery that was at its optimum performance level and one that was performing at less than optimum, despite charging according to the manufacturer's specifications. Although the second evaluation demonstrated battery variability within ventilator models, Figure 1 shows that each ventilator exceeded the manufacturer's specifications, which suggests that we had well charged batteries.

A limitation in part 2 of our study was the number of ventilators studied. We tested all four of the Servo 300s available and 6 Evita XLs. We tested more Evita XLs because we have more of them in stock, and attempted to more accurately represent the entire inventory. Further evaluations of battery variability could test more ventilators. We limited our evaluation to 6 Evita XLs to be more comparable to the number of Servo 300 ventilators evaluated.

Conclusions

Backup battery duration of ICU ventilators ranges widely between ventilators, and even among the same ventilator model. Despite regular preventive maintenance, battery performance may still be less than predicted. Battery performance is a function of battery type, size, energy density, type of ventilator display, and the use of a compressor. ICU ventilators utilize the power of compressed gas to ventilate the patient. Changes in PEEP and breath type did not affect battery duration, as seen with portable ventilators that utilize an internal compressor. Clinicians must be aware of the potential differences in ventilator battery duration and of the characteristics that alter battery duration.

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