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Clinical paper

Mechanical ventilators in the hot zone: Effects of a CBRN filter on patient protection and battery life[☆]

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ABSTRACT

Objective: In a contaminated environment, respiratory protection for ventilator dependent patients can be achieved by attaching a chemical, biological, radiological, or nuclear (CBRN) filter to the air intake port of a portable ventilator. We evaluated the effect of the filter on battery performance of four portable ventilators in a laboratory setting.

Methods: Each ventilator was attached to a test lung. Ventilator settings were: assist control (AC) mode, respiratory rate 35 bpm, tidal volume 450 ml, positive end-expiratory pressure (PEEP) 10 cm H_2O, inspiratory time 0.8 s, and FIO_2 0.21. Ventilators were operated until the battery was fully discharged. We also evaluated the ventilators' ability to deliver all the gas through the CBRN filter and analyzed the pressures required to breathe through the anti-asphyxiation valve of a failed device.

Results: The range of battery life varied widely across different ventilator models (99.8–562.6 min). There was no significant difference in battery life ($p < 0.01$) when operating with or without the CBRN filter attached. Only the Impact 731 routed all inspired gases through the CBRN filter. The pressure required to breathe though the failed device was -4 cm H_2O to -9 cm H_2O.

Conclusions: Duration of operation from the internal battery was not altered by attachment of the CBRN filter. The use of a CBRN filter is necessary for protection of ventilator dependent patients when environmental contamination is present, although conditions exist where all gas does not pass through the filter with some ventilators under normal operating conditions.

1. Introduction

Lung damaging chemicals have been used in warfare since World War I when chlorine gas was released on a Belgium battlefield producing 5000 casualties. Mustard gas was later added to the chemical weapon arsenal. Throughout the 20th century these agents continued to be used as weapons of war.[1] More recently, nerve agents such as Sarin gas released in the Tokyo subway by terrorists have been reported. Over 5000 people required medical care and 11 died as a result of the Tokyo attack.[2] Airborne biological organisms also have the potential to infect and kill many people. A terrorist attack against civilians or war fighters using any of these or other chemical or biological agents remain a possibility.[3]

Civilian and military personnel require respiratory protection if the potential exists for exposure to hazardous airborne chemical and biological contaminants as well as radiological and nuclear agents. Similar provisions must be made to provide respiratory protection for patients that are dependent on mechanical ventilation and have the potential for exposure. A chemical, biological, radiological, and nuclear (CBRN) filter provides respiratory protection for caregivers and patients from these potential contaminants.

CBRN filter media is composed of a fiberglass layer for particulate contaminants and an activated carbon layer for gaseous contaminants. The CBRN filter's multiple layers have an air flow resistance of approximately 4 cm H_2O/L/s. We hypothesized that increasing resistance could cause the ventilator compressor to work harder therefore reducing battery duration. We evaluated the effect of the addition of a CBRN filter on battery performance of four portable ventilators. We also evaluated the anti-asphyxiation valve of the ventilators to determine the position of the CBRN filter and ability to filter all the patients inspired gas, as well as the effort required to breathe through a failed device.

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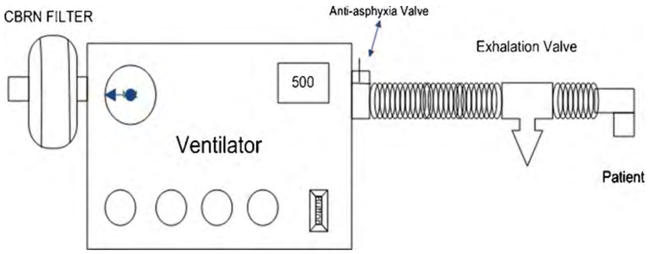

Fig. 1. CBRN filter placement.

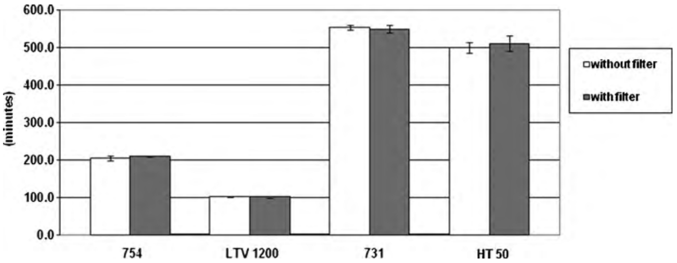

Fig. 2. Battery duration with and without CBRN filter.

2. Methods

We evaluated four portable ventilators which have been purchased around North America for disaster management. This included the Impact Univent 754 and Impact EMV 731 (Impact Instrumentation, Caldwell, NJ), Newport HT 50 (Newport Medical, Costa Mesa, CA), and Pulmonetics LTV 1200 (CareFusion, San Diego, CA). At present, the Impact 754 and LTV-1200 are part of the Centers for Disease Control Strategic National Stockpile. Each ventilator was attached to a Michigan Instruments Training Test Lung (TTL, Michigan Instruments, Grand Rapids, MI) via the supplied ventilator circuit. Lung compliance was set at 0.02 L/cm H_2O and resistance was set at 5 cm H_20/L/s. Ventilator settings were: A/C mode, respiratory rate 35 bpm, tidal volume 450 ml, PEEP 10 cm H_2O, inspiratory time 0.8 s, and FIO_2 0.21. Ventilator settings were chosen to approximate the mean settings from day 1 of patients in the ARDSnet trial.[4] We placed a pneumotachograph (PF 301 Flow-Analyser, IMT Medical, Buchs, Switzerland) between the ventilator and test lung and output was recorded to a PC to verify tidal volume. Volume recordings were used to document the start and stop time of each test to calculate battery duration. Ventilators chosen for the testing were either compressor or turbine driven and were operated with 0.21 FIO_2 to fully engage the driving mechanism, placing maximum load on the battery. Of note, the battery duration of the LTV 1200 decreases using FIO_2 1.0.[5] Testing was accomplished by operating the ventilator without the CBRN filter and then again after placing the filter on the air inlet (Fig. 1) and operating the ventilator at the pre-defined settings until the battery was discharged. Adaptation of the CBRN filter to the HT-50, and Impact 754 ventilator was accomplished with a commercially available adapter. The Impact 731 has an external thread which allows direct connection of the CBRN filter. We created a stereolithography adapter to allow connection of the CBRN filter to the air inlet of the LTV-1200. The order of the testing was done in a random fashion. Full discharge was defined as the inability of the ventilator to deliver breaths. Testing was performed on each ventilator a minimum of three times both with and without the CBRN filter attached. A single unit of each ventilator model was utilized for the testing. We tested only factory installed internal batteries with all ventilators being charged a minimum of 24 h initially and between tests.

We also evaluated the ability of the ventilator to assure all gas delivered to the patient passes through the CBRN filter. This was evaluated by connecting the ventilator to a model simulating spontaneous breathing. For this test we placed a lift-bar between the two chambers of the TTL such that one chamber driven by a ventilator would simulate a patient and trigger the ventilator attached to the other chamber. Identical settings were used with both ventilators except that inspiratory flow was set at 40 lpm in the test ventilator and 80 lpm on the driving ventilator. The driving ventilator initiated a breath triggering the test ventilator which delivered a breath with twice the inspiratory flow demand as delivered by the driving ventilator. To demonstrate extra flow comes from the anti-asphyxiation valve, the test ventilator FIO_2 was set at 1.0, and inspired gas was continuously measured by a fast response O_2/CO_2 analyzer (Oxigraf, Mountain View, CA) placed at the ventilator outlet. If gas was entrained through the anti-asphyxiation valve (FIO_2 0.21), the measured FIO_2 would fall as room air at 0.21 mixed with oxygen. To verify gas was entrained through the anti-asphyxiation valve we created a CO_2 rich environment around the valve. A cylinder of 100% CO_2 was fitted with a regulator and flow meter. Flow was set at 5 lpm and gas directed down a 48 in. long piece of oxygen connecting tubing two inches from the anti-asphyxiation valve. A rise in CO_2 would indicate that gas was being entrained through the anti-asphyxiation valve. Continuous measurements of FIO_2 and CO_2 were downloaded to a PC for later analysis.

For the final test we simulated a device failure by turning each test ventilator off and having the driving ventilator deliver a breath, simulating a patient breathing through the test ventilator's anti-asphyxiation valve. We placed a fixed orifice pneumotachometer (COSMO, Phillips Respironics, Andover, MA) between the test ventilator and the TTL, and the pressure data produced during the breath was downloaded to a PC to analyze the peak negative pressure produced by breathing through a failed device.

3. Results

The range of battery duration varied widely across all ventilator models (99.8–562.6 min). The shortest duration was from the LTV 1200 and longest duration was from the Impact 731. Results were compared using Student's *t*-test with a $p < 0.01$considered significant. The *p* values for each ventilator: Impact 745, $p = 0.15$; Impact 731, $p = 0.28$; Newport HT 50, $p = 0.32$; Pulmonetics LTV 1200, $p = 0.39$; show that there was no significance difference in battery duration with any of the individual ventilators tested while operating with and without the CBRN filter attached. Fig. 2 shows the mean battery duration (±SD) for all ventilators at both conditions.

The flow demand testing demonstrated that if a patient's inspiratory demand exceeds the ventilator flow capability, gas would be entrained through the anti-asphyxiation valve therefore lowering the FIO_2 and potentially exposing the patient to contaminated room air. Fig. 3 shows the degree of decrease in FIO_2 was 10–20% due to air entrainment through the anti-asphyxiation valve. To ensure that air was entrained through the anti-asphyxiation valve, a CO_2 rich environment was created around the valve. Fig. 4 illustrates that as gas is entrained, the fraction of inspired carbon dioxide ($FICO_2$) increased, and FIO_2 decreased proving that the entrained gas came through the anti-asphyxia valve. We also noted that even at a set FIO_2 of 1.0 the LTV-1200 delivered an FIO_2 of 0.93–0.95.

The triggering evaluation showed that pressure generated while breathing through a failed device varied between ventilator models, suggesting work of breathing under this condition differed among ventilators. Fig. 5 shows the Impact 731 generated the greatest pressure change from base line suggesting the highest work of breathing among the test devices. The CareFusion LTV 1200 demonstrated the lowest peak negative pressure.

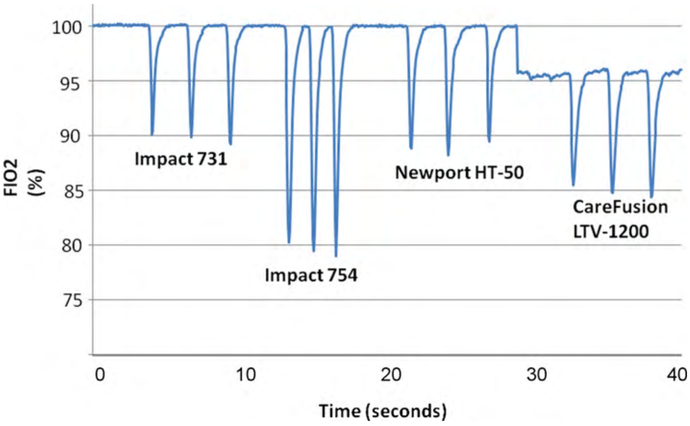

Fig. 3. Air entrainment through anti-asphyxiation valve and effect on FIO_2.

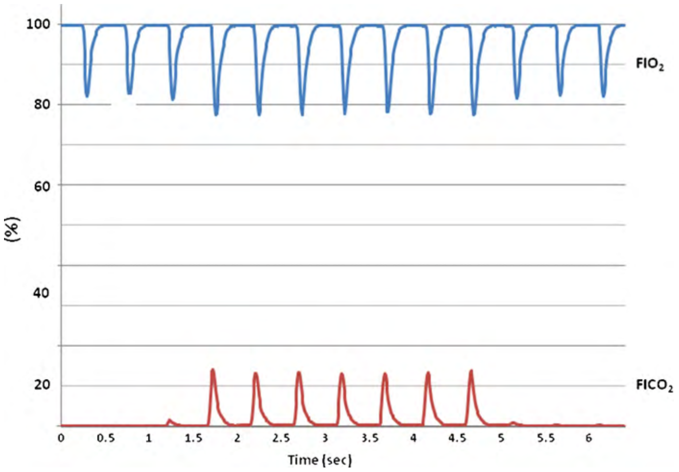

Fig. 4. Entrained CO_2 through anti-asphyxiation valve.

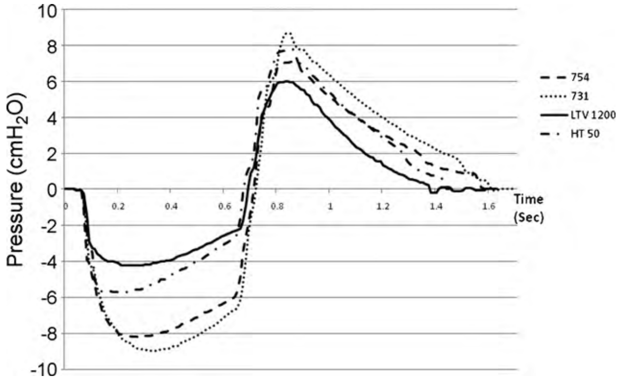

Fig. 5. Peak negative pressure when breathing through a failed device.

4. Discussion

Concerns over biologic and chemical warfare and more recently flu, have resulted in the stockpiling of ventilators by Federal and State Governments. In both military and civilian tenders, the ability to connect a CBRN filter is considered desirable. A CBRN filter is necessary for the protection of the ventilator dependent patient in the presence of lung damaging environmental contamination. Placing such a filter on the air inlet of the ventilator in theory could provide a certain amount of resistance to airflow, increasing the load on the ventilator driving system and increasing power consumption.[6] Assuring maximum battery life is crucial to safe transport of the mechanically ventilated patent. To our knowledge, this is the first paper to examine the effect of a CBRN filter on the operating duration from the battery of portable ventilators.

Our results showed that while battery duration varied greatly between portable ventilator models, which is consistent with work by Campbell et al.[6] placing a new CBRN filter on the air intake port did not decrease battery duration of any of the ventilators tested. The CBRN filter canister contains both a particulate filter, which filters 99.9% of particles down to 0.3 μm, and a granulated carbon bed capable of absorbing a wide range of chemical warfare agents.[7] Entraining gas through this filter media causes an increase in airflow resistance. We measured the pressure drop across the filter to approximate airflow resistance using the RT-200 Calibration Analyzer (Timeter Instrumentation Corporation, Lancaster, PA). The resistance measured approximately 4 ml/cm H_2O at a flow of 60 lpm.

A description of the battery type, battery weight, and reported maximum operating duration is provided here and in Table 1. The Impact 731 has a lithium-ion battery weighing 1.4 lbs., and an operating duration of 10 h. The Impact 754 has a sealed lead acid battery weighing 4.35 lbs., and an operating duration of 3 h. The LTV 1200 has a sealed lead acid battery weighing 3.5 lbs., and an operating duration of 1 h. The HT 50 has both a sealed lead acid and a nickel metal hydride (NiMH) internal battery. The sealed lead acid battery weighs 4.41 lbs and has an operating duration of 10 h. The NiMH battery weighs 0.89 lbs. and has an operating duration of 1 h. The lead acid battery discharges first leaving the NiMH battery as the emergency power source. Portable ventilator battery duration is a product of battery type, drive mechanism, and ventilator operating characteristics.[6]

Portable ventilators require a mechanism through which a patient can entrain gas in the event of device failure. An anti-asphyxiation valve provides this mechanism. However, the simple use of a one-way valve in the inspiratory limb of the ventilator circuit also allows ambient gas to be entrained if a pressure differential exists. In volume control mode, setting the inspiratory demand of the test ventilator at twice the demand of the driving ventilator resulted in entrainment of room air through the anti-asphyxiation valve. To demonstrate the entrained gas came through the valve, we created an environment where CO_2 would

Table 1
Portable ventilator battery specifications.

	Impact 731	Impact 754	HT 50	CareFusion LTV 1200
Battery type	Lithium-ion	Sealed lead acid	1-Sealed lead Acid 1-NiMH[a]	Sealed lead acid
Battery dimensions (in.)	5.9 × 2.75 × 1.6	8.5 × 1.9 × 2.8	3.54 × 2.75 × 4.17 (lead acid) 1.19 × 2.27 × 3.4 (NiMH)	8.25 × 2.8 × 4.62
Battery weight	1.4 lbs	4.35 lbs	4.41 lbs (lead acid) 0.89 lbs (NiMH)	3.5 lbs
Battery duration[b]	10 h	3 h	10 h (lead acid) 1 h (NiMH)	1 h

[a] Nickel metal hydride.

[b] Maximum operating time reported in operator's manual.

be the gas entrained (Fig. 4). Although this valve is a requirement for patient safety, the consequences are twofold. Entraining room air through the valve in our test model effectively lowered the FIO_2 by 10–20% (Fig. 3). If the ratio of patient inspiratory demand to ventilator flow delivery is greater that in our test model, the FIO_2 could further decrease, potentially creating hypoxemia in a critically ill patient. Additionally, entraining gas through the anti-asphyxiation valve defeats the purpose of using a CBRN filter which is designed to protect the patient from a contaminated environment. Of note, the Impact 731 utilizes an internal anti-asphyxia valve that directs all entrained air through the compressor and therefore through the CBRN filter. Although the patient is able to inspire additional gas through the anti-asphyxiation valve, the consequences could prove to be detrimental to an already critically ill patient. In intensive care unit ventilators, the anti-asphyxiation valve is kept closed by the electronic control of the device which only becomes functional when electronic failure occurs. Portable ventilators utilize a simple one-way valve. If pressure inside the circuit falls below ambient pressure, ambient gas enters the circuit. This reduces FIO_2 and during operation in a hazardous environment defeats the CBRN filter.

We also simulated a patient breathing through a failed device with the driving ventilator aggressively triggering a breath through each test ventilator while turned off, and measuring pressure changes from baseline. The positive and negative pressures produced indicate the amount of patient effort required to breathe solely through each ventilator's anti-asphyxiation valve.[8] The Impact 731 generated the greatest pressure change during this maneuver (Fig. 5), due to the anti-asphyxiation valve directing entrained gas through the internal compressor. This design ensures that all gas delivered to the patient passes through the CBRN filter providing complete protection from lung damaging contaminants. The design and location of the anti-asphyxiation valve on the remaining test ventilators explain the lower negative pressures. These ventilators' anti-asphyxiation valves are located near the ventilator outlet, between the ventilator and patient, resulting in lower opening pressures. The pressure differences among these ventilators can be attributed to the size of the anti-asphyxia valve orifices, creating differences in resistance. Although breathing through these anti-asphyxiation valves would require less patient effort, the gas entrained would not flow through the CBRN filter, leaving the patient vulnerable to inhaled contaminants.

The limitations of this study include the fact that we only used one unit of each ventilator model in our testing. Each ventilator employed a new battery. The intent was to eliminate any variability in operation and battery duration within ventilator models. We used a new CBRN filter for our study. Ventilator battery operating duration may be affected by the use of a CBRN filter that has absorbed contaminants into the filter media. Finally, the wisdom of using a $6000–$12,000 ventilator in a hazardous environment remains in question. Clearly, the appropriate treatment of these patients includes removal from the hazardous environment. The ability to decontaminate ventilators for re-use is unknown. However, since ventilators can be used with CBRN filters, we believe understanding the effects and limitations justify this investigation.

5. Conclusions

A CBRN filter is a potentially important addition to a portable ventilator in providing clean gas to the ventilator dependent patient in the event of intentional or accidental environmental contamination. Our study showed that the use of a CBRN filter does not decrease battery duration of four portable ventilators, although the longer the filter is used in a contaminated environment the possibility exists that battery duration may be affected. Additionally, even though patients can entrain gas through the anti-asphyxiation valve in the event of inadequate inspiratory flow or device failure, the benefit of the CBRN filter may be lost due to the entrainment of contaminated room air. Clinicians must be aware of these caveats in order to provide safe care for ventilator dependent patients in a contaminated environment.

Conflict of interest

GE Healthcare has provided monetary research support to our institution, the University of Cincinnati. Mr. Branson has received honoraria from Newport and CareFusion. Mr. Blakeman, Mr. Toth, and Mr. Rodriquez have no conflicts of interest to disclose.

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