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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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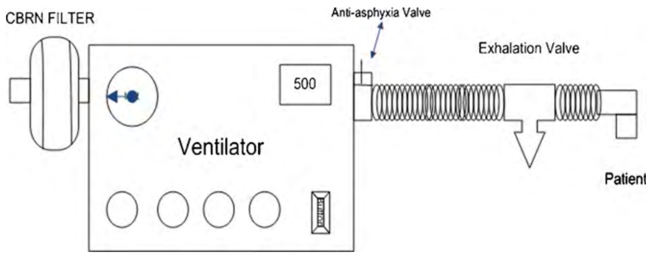

Fig. 1. CBRN filter placement.

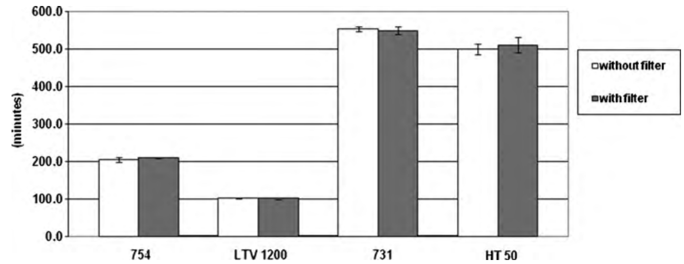

Fig. 2. Battery duration with and without CBRN filter.

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.