

In vitro investigation of the Flusso™ Bypass adapter efficiency upon ventilator circuit disconnect in a clinical simulated environment

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Rationale: Mechanically ventilated patients must be disconnected from the ventilator during intra-facility transfers. Intentional and accidental circuit disconnections represent a potential hazard to patients (sudden collapse and re-expansion of the alveoli) as well as to clinical staff (exposure to patient's unfiltered exhalation). Therefore, avoiding abrupt circuit disconnections could better protect the patient's health and reduce or eliminate contamination risks around clinical staff.

Objective: The purpose of this in-vitro work was to investigate and evaluate the potential for environmental exposure of Nitric Oxide (NO, as an indicator of any contamination exposure) before and after implementing the novel Flusso™ Bypass adapter during the disconnect procedure of a mechanical ventilator system.

Methods: A mechanical ventilator delivering NO was connected to a breathing simulator with and without the Flusso™ Bypass adapter. The ambient NO concentration was measured when the circuit was briefly disconnected (3 s) during inhalation and exhalation. Both volume and pressure ventilation modes were used.

Measurements and main results: Disconnecting the standard ventilator circuit (pressure-controlled mode) without the Flusso™ Bypass adapter produced higher NO escape to the surroundings (compared with the volume-controlled mode), leading to a longer NO dissipation time. No ambient NO traces were detected when the Flusso™ adapter was used.

Conclusion: The usage of the Flusso™ adapter drastically decreases the unwanted exposure among clinical staff dealing with potentially hazardous airborne biological aerosols emanating from the circuit. Avoiding abrupt disconnection in the ventilator circuit could reduce lung injuries and alveolar over distension and collapse.

Key Words: *Flusso™ Bypass adapter; mechanical ventilation; nitric oxide; circuit disconnection*

INTRODUCTION

Transportation of mechanically ventilated patients is a common procedure in an intensive care unit for routine tests and patient care. During the transport, the patient is required to be briefly disconnected from the mechanical ventilator [1]. While this can pose some risks (including an increased risk of ventilator-associated-pneumonia [2]), they can be mitigated by carefully following the appropriate safety procedures, such as constant patient care and monitoring by trained staff while using appropriate user-friendly equipment [3]. These disconnects occur during normal patient care and are considered routine by health care professionals. Patient disconnection is often required to transport patients needing computed tomography or magnetic resonance imaging. Katira et al. [4] investigated the effect of abrupt discontinuation of the positive end-expiratory pressure (PEEP) on the lungs in mechanically ventilated rats to assess lung function via scanning electron microscopy and microvascular leak using Evans blue dye. The authors demonstrated that a sudden deflation of the lung after a sustained inflation, such as during an abrupt ventilator disconnection, causes a mismatch in the left ventricle load while increasing the lung hydrostatic pressure resulting in potential lung edema and acute cor pulmonale. Kubiak et al. [5] investigated the hemodynamics and lung function of four pigs with acute respiratory distress syndrome (ARDS)

under continuous high-frequency oscillatory ventilation (two pigs) and after brief disconnection (two pigs). The authors showed that following disconnection, the pigs suffered from a permanent loss of lung function, whereas the pigs that remained connected to the ventilator maintained a steady improvement in lung function. Disconnects often require physician attention, which typically causes an increase in unnecessary workload [6].

The disconnection also introduces the risk of airborne contamination, which can pose a significant risk to the safety of both the patients and staff. When the ventilator is disconnected, it continues to deliver air (in some cases at an accelerated rate), thus dispersing it into the atmosphere, increasing the probability of health care workers and other patients being exposed to biological aerosols from the ventilator [7, 8]. While the largest risk factor for contamination is direct contact with patients [9], airborne contamination is still prevalent and a recognized hazard to the hospital as a whole [10], since airborne contaminants can easily spread away from the source to many different areas of the hospital [10, 11]. This is also a matter of interest when using Nitric Oxide (NO) therapy via mechanical ventilation. In fact, inhaled NO is commonly used for invasively ventilated patients as a pulmonary vasodilator used for treatment of ARDS and acute lung injury [12] and persistent pulmonary hypertension for adults and newborn infants [13]. However, NO

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delivered via mechanical ventilation was shown to react with the delivered oxygen, producing nitrogen oxide compounds [13, 14], which may irritate the respiratory tract. Thus, it can be concluded that avoiding disconnects can improve patient health, improve staff safety, and reduce the risk of infections by reducing the risk of contamination.

The Flusso™ Bypass (MMSI Inc., Rockton, ON) adapter was designed and developed by one of the authors (FF) to reduce the frequency of these circuits disconnects. In particular, the design features a swivel to reduce torque on the endotracheal tube, a common source of disconnects [7]. It also features a tethered port-cover (cap) to keep the ports clean. Finally, it allows for the process to be visualized (to verify that the patient's positive pressure ventilation has been secured) by using a transparent housing with a distinguishable colored valve [15].

In this paper, the binary classification (pass/fail: with pass meaning “no control-gas leakage” and fail representing detection of “control-gas leakage”) was used to investigate experimentally, in an in vitro setup at a local hospital (Children's Hospital of Eastern Ontario, Ottawa, Ontario), the performance of the Flusso™ Bypass adapter by evaluating NO leakage with and without the Flusso™ Bypass adapter. This experimental setup attempts to replicate clinical settings with a planned patient disconnection (not an accidental one) where a patient (under mechanical ventilation) is briefly disconnected and reattached to a portable mechanical ventilator to be transported or disconnected for transition of therapy (e.g., changing dry ventilator circuit to heated wire circuit). For this purpose, a mechanical ventilator delivering NO (the selected control gas) was connected to a breathing simulator (spontaneously breathing patient) both with and without the Flusso™ Bypass adapter. The NO gas was used in this study to provide a measurable airborne substance, mimicking, for example, extremely small respiratory droplets (diameter with less than 2.5 µm). The circuit was briefly disconnected in both cases to measure the NO gas detected in the environment.

METHODS

Ethics approval was not required for this study.

Flusso™ Bypass adapter

The Flusso™ Bypass adapter (MMSI Inc., Rockton, ON, Figure 1) was designed to safely facilitate planned disconnection of mechanically

ventilated patients during patient's transportation or circuit change. Due to its minimal dead space (7cc) and the standard International Organization for Standardization connections [16] designed for the different ventilator circuit ports, it can be used for standard circuits and ventilators currently available in hospitals. Using the Swing Valve Technology™ and a transparent housing, a constant closed circuit can be ensured thus minimizing potential staff exposure to hazardous airborne contaminants.

Experimental setup

The in vitro experimental setups are shown in Figures 2 and 3, detailing the different testing scenarios with and without the Flusso™ Bypass adapter. A mechanical ventilator (Servo I, Maquet Getinge, Germany), with an inspiratory flow range of 0–3.3 L/s, is used to deliver 100% oxygen with a tidal volume of 500 mL with an inspiratory length of 1 s and a positive end expiratory pressure (PEEP) of 12 cm H₂O for volume-controlled ventilation. The peak inspiratory pressure for the pressure-controlled mode of ventilation was set to 28 cm H₂O. During each test performed, a constant dose of NO (40 ppm) was delivered into the inspiratory ventilator circuit via a NO dosing unit (INOMax DSIR, Mallinckrodt Pharmaceuticals, USA).

Two different experimental setups were used to compare the performance of the Flusso™ Bypass adapter. In the first experimental setup without the Flusso™ adapter (Figure 2), simulating standard protocols for patient transport in clinical settings, the inspiratory and expiratory lines of the ventilator circuits were connected directly to a breathing simulator (Active Servo Lung, ASL 5000, IngMar Medical, USA), via a bacterial filter (Inter-guard filter, Intersurgical, UK), with the profile of a spontaneously breathing patient with a respiratory rate of 14 breaths per minute and an inspiratory muscle pressure of 12 cm H₂O.

To test the Flusso™ adapter within the same conditions, in a second experimental setup (Figure 3) the inspiratory and expiratory lines of the ventilator circuits were connected to the ventilation port of the Flusso™ adapter while the patient port of the adapter was connected to the ASL 5000, via a filter. A resuscitation bag (Spur II, Ambu, USA) with a filter (Inter-guard filter, Intersurgical, UK) is connected to the bypass port in place of a standard disconnection. Within this configuration, the swing valve of the adapter allows transition of gas flow movement from the ventilator port to the bypass port.

To measure NO concentration from the patient during patient disconnection, an NO gas detector (GAXT-N-DL GasAlert Extreme Single Gas Detector, NO, BW by Honeywell, USA), with a resolution of 1 ppm and sampling rate of 5 s, was placed within a 5 inch radius from the disconnection site as shown in Figures 2 and 3. This distance from the disconnection site was chosen as it was shown to provide the optimal reading for the NO gas detector. The bacterial filters used in this study do not alter the NO delivery to the measurement site (disconnection site).

Experimental procedure

The experiments were performed under ambient relative humidity. To investigate the impact of the Flusso™ Bypass adapter, multiple baseline experiments without the adapter were performed. To assess the effectiveness of the Flusso™ Bypass adapter, the binary classification (pass/fail: with pass meaning “no control-gas leakage” and fail representing detection of “control-gas leakage”) was used.

Without Flusso™ Bypass adapter

Using the first experimental set up, four experiments were performed varying the ventilation mode (volume-controlled or pressure-controlled) and breathing phase of disconnection (during inhalation or exhalation). Once all the components connected to the ventilator circuit as described above, the inspiratory and expiratory lines are disconnected for 3 s from the ASL 5000, releasing the NO in the ambient air, during inhalation and exhalation. The NO gas detector was used to monitor the amount of NO released after disconnection until no gas was detected. Five repeats of each test were performed.

FIGURE 1
Flusso™ Bypass Adapter and associated components.

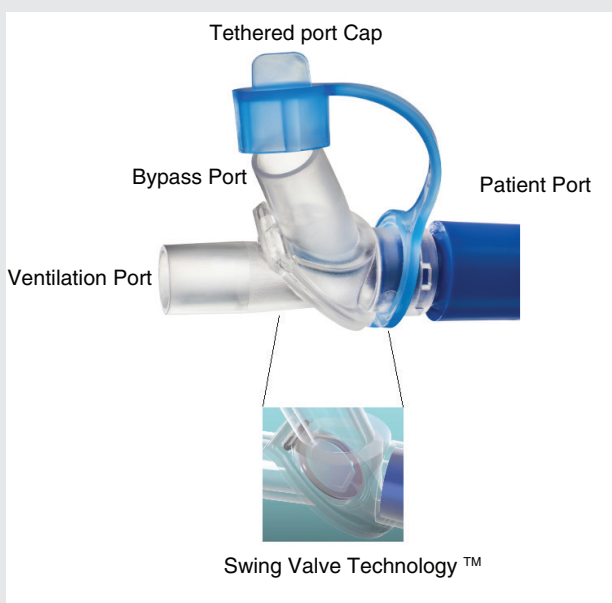


FIGURE 2
Experimental setup without the Flusso™ Bypass Adapter.

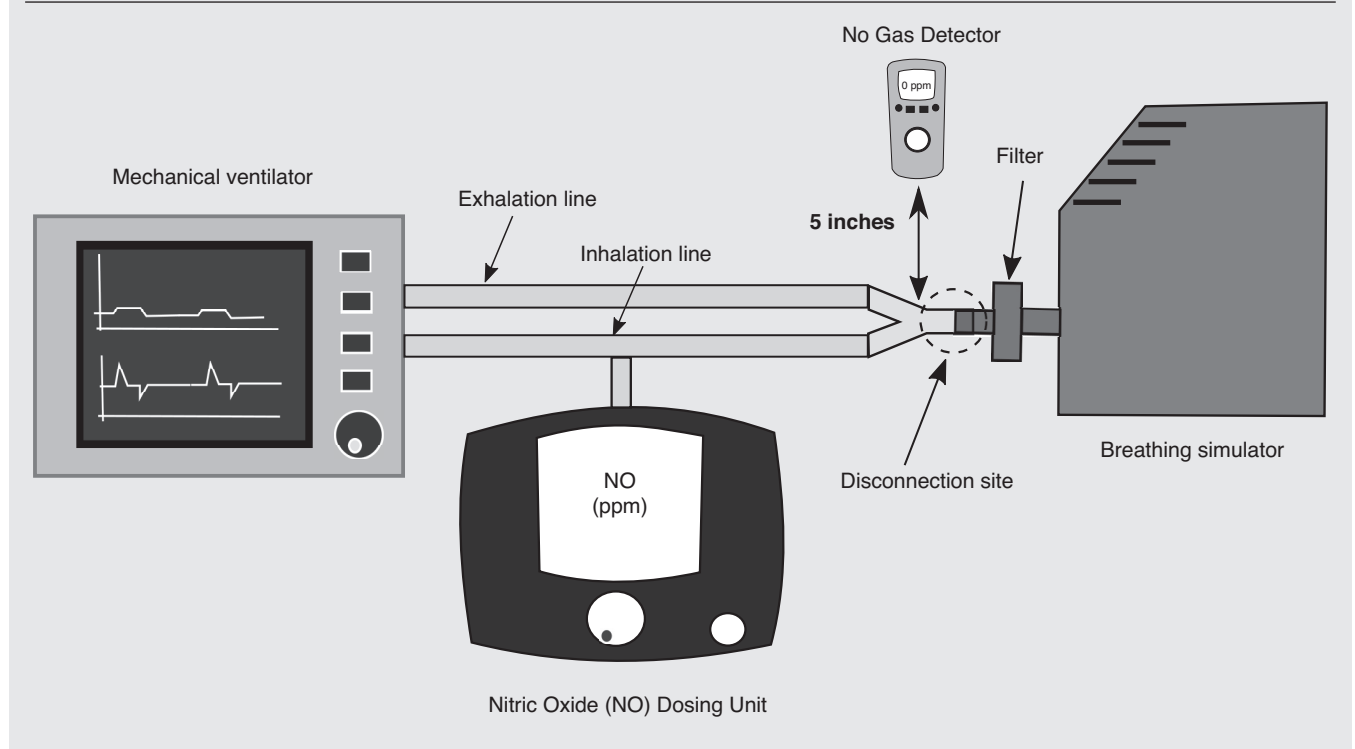
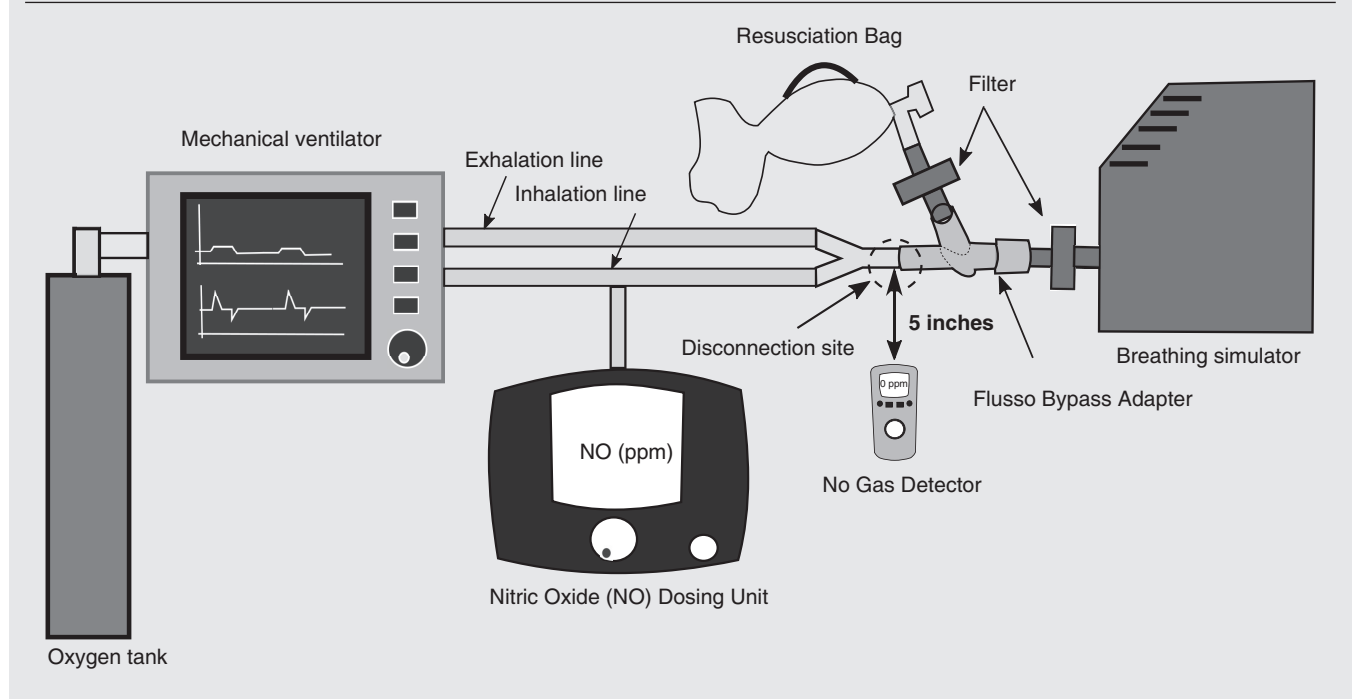


FIGURE 3
Experimental setup with the Flusso™ Bypass Adapter.



With Flusso™ Bypass adapter

Using the second experimental setup, using the Flusso™ adapter, four tests were also performed varying the ventilation mode and breathing phase of disconnection as for the previous setup. When the bypass port is not in use, the swing valve of the adapter allows flow movement between the ventilator port and patient port, hence blocking the bypass port. Before circuit disconnection, the resuscitation bag or transport ventilator is attached and activated. Upon pressurization of the bypass port, this pressure change relocates the location of the swing valve, allowing flow between the bypass port and the patient port, hence blocking the ventilation port. The ventilator is then placed. The circuit is then disconnected while the resuscitation bag is providing oxygen to the ASL 5000 for 30 s. The NO was also monitored using the gas detector after disconnection until no gas was detected. Five repeats of each test were performed. During disconnection, the ventilator was set on standby mode, following the standard procedure for patient transport in hospitals.

RESULTS

The results obtained from the eight tests performed are presented in Table 1, in terms of the average nitric oxide detected in parts per million (ppm), the duration of NO detection in seconds and the maximum NO detected in parts per million with and without Flusso™ Bypass adapter, for the volume and pressure-controlled modes for circuit disconnections during inhalation and exhalation. The results are shown as average values ± standard deviation (SD).

Figure 4 shows the comparison of average NO in parts per million for the volume and pressure-controlled ventilation modes for the circuit disconnection during inhalation and exhalation without the Flusso™ Bypass adapter. The average NO detected was found to vary between 10.2 ± 1.6 and 11.5 ± 1.3 ppm to a maximum exposure of 18.4 ± 1.2, indicating leakage (“fail” classification). In fact, no significant difference was found for the average NO detected for the different ventilation modes during inhalation or exhalation.

Figure 5 shows the comparison of the duration of NO detection for both ventilator modes for circuit disconnections during inhalation and exhalation without the Flusso™ Bypass adapter. Comparing the results obtained for the volume-controlled ventilation mode, the time until a null NO reading was found to be 37.2 ± 14.4 s and 33.4 ± 18.8 s, during inhalation and exhalation, respectively, whereas for the pressure-controlled ventilator mode, the duration of NO detection was found to be 79.2 ± 21.0 s and 103.2 ± 11.0 s, during inhalation and exhalation, respectively. No significant difference was found for the volume-controlled or the pressure-controlled ventilation mode comparing the inhalation and exhalation tests performed. However, a significant difference

was found in NO dissipation time comparing both modes of ventilation during inhalation ($p < 0.05$) or exhalation ($p < 0.05$).

Figure 6 presents a comparison of the maximum NO detected for both ventilator modes for circuit disconnections during inhalation and exhalation without the Flusso™ Bypass adapter. Higher NO amounts were detected for the pressure-controlled mode (16.8 and 17.4 ppm during inhalation and exhalation, respectively) compared with the volume-controlled mode (18.2 and 18.4 ppm during inhalation and exhalation, respectively). However, no significant difference was found.

DISCUSSION

The findings of this study were used to evaluate the impact of the Flusso™ Bypass adapter in a hospital environment. These results presented in the previous section indicate a longer dissipation time for the NO (Nitric Oxide) released for the disconnection during exhalation especially for the pressure-controlled ventilation mode (as compared to

FIGURE 4

Comparison of the average Nitric Oxide (NO) detected in parts per million (ppm) for the volume and pressure-controlled ventilation modes during inhalation and exhalation disconnection without the Flusso™ Bypass adapter.

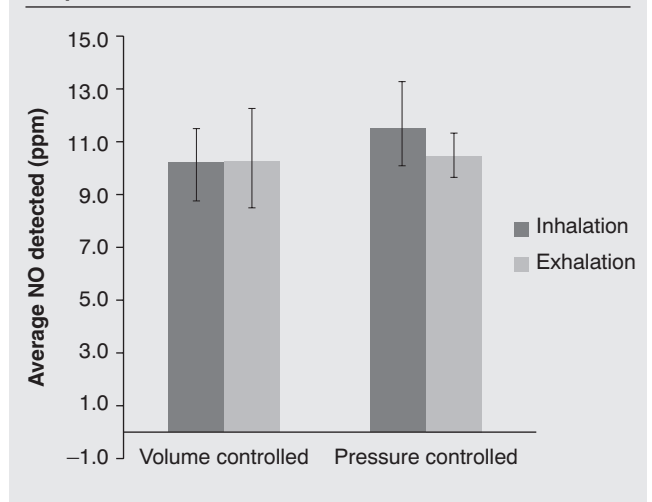


TABLE 1

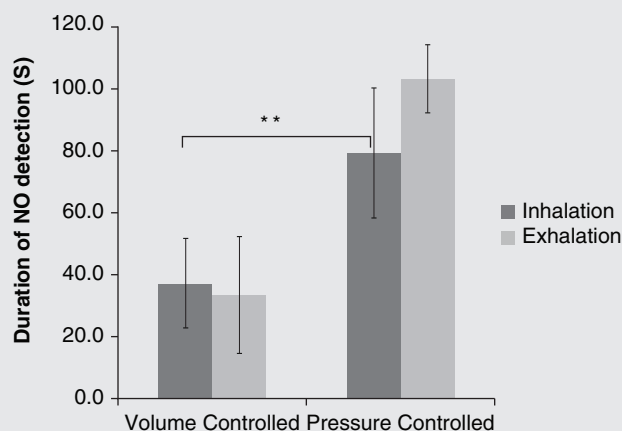
Summary of results of detected NO with and without Flusso™ Bypass adapter, for the volume controlled and pressure-controlled ventilator modes for a circuit disconnection during inhalation and exhalation

	Volume controlled		Pressure controlled	
	Without Flusso™ Bypass adapter		Without Flusso™ Bypass adapter	
	Inhalation Average ± SD	Exhalation Average ± SD	Inhalation Average ± SD	Exhalation Average ± SD
Average NO detected (ppm)	10.2 ± 1.6	10.3 ± 1.8	11.5 ± 1.3	10.5 ± 0.8
Duration of NO detection (s)	37.2 ± 14.4	33.4 ± 18.8	79.2 ± 21.0	103.2 ± 11.0
Maximum NO detected (ppm)	16.8 ± 1.5	17.4 ± 3.0	18.2 ± 0.7	18.4 ± 1.2
	With Flusso™ Bypass adapter		With Flusso™ Bypass adapter	
	Inhalation Average ± SD	Exhalation Average ± SD	Inhalation Average ± SD	Exhalation Average ± SD
Average NO detected (ppm)	0 ± 0	0 ± 0	0 ± 0	0 ± 0
Duration of NO detection (s)	0 ± 0	0 ± 0	0 ± 0	0 ± 0
Maximum NO detected (ppm)	0 ± 0	0 ± 0	0 ± 0	0 ± 0

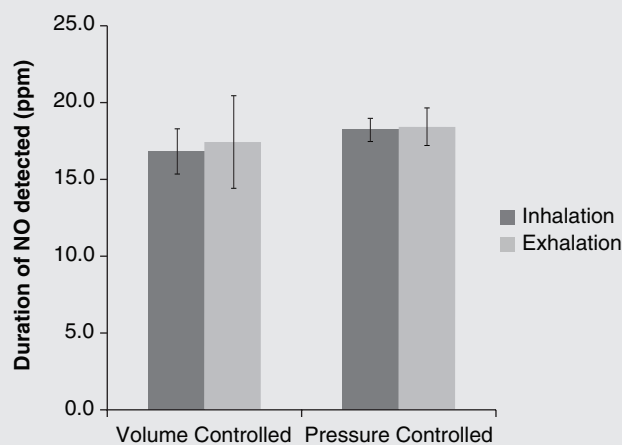
The results are shown in terms of the average Nitric Oxide (NO) detected in parts per million (ppm), the duration of NO detection in seconds and the maximum NO detected in parts per million. The results are presented as an average ± standard deviation (SD).

FIGURE 5

Comparison of the duration of Nitric Oxide (NO) detection in seconds (s) for the volume and pressure-controlled ventilation modes during inhalation and exhalation disconnection without the Flusso™ Bypass adapter.

**FIGURE 6**

Comparison of the maximum Nitric Oxide (NO) detected in parts per million (ppm) for the volume and pressure-controlled ventilation modes during inhalation and exhalation disconnection without the Flusso™ Bypass adapter.



during inhalation and volume-controlled mode). A significant difference in the duration of NO detection was also found when comparing both ventilation modes for the circuit disconnection during inhalation ($p < 0.05$). The same findings were noted for circuit disconnection during exhalation ($p < 0.05$). In fact, disconnection of the circuit during the pressure-controlled ventilation mode causes the ventilator to over-compensate for the pressure loss and hence an increase in flow and volume was noted. Therefore, a large volume of NO was delivered in the room, causing a long dissipation time to a null NO reading. These results can also be seen when looking at the results obtained for the maximum NO detected (Figure 6), where higher NO was detected for the pressure-controlled mode compared with the volume-controlled

mode. However, no significant difference was found in the maximum NO values detected for all the tests performed.

It can be noted, that no Nitric Oxide was detected (binary “pass” classification) when using the Flusso™ Bypass adapter. These results indicate that using the Flusso™ adapter, no gas leakage was detected, despite the ASL 5000 still providing 14 breaths per minute, simulating a spontaneously breathing patient’s behaviour in a clinical setting where the patient is not completely paralyzed consisting of a potential hazardous exposure to the clinical staff. Therefore, it is determined that using the Flusso™ adapter minimizes the probability of staff exposure to NO and potentially to hazardous airborne droplets emanating from the patient. It is also important to note that using the Flusso™ adapter, no abrupt disconnection of the patient was experienced due to Swing Valve Technology™ and the use of the resuscitation bag, which could reduce lung injuries and alveolar over distension and collapse.

Study limitations

The results presented in this study are solely pertaining to the gas used (NO), which would not behave similarly to biological aerosols. However, it is conjectured that extremely small respiratory droplets (with aerodynamic diameters less than 2.5 μm) may be dispersed in the room similarly to NO due to their low inertia and low settling velocities (typically below 0.2 mm/s) [17, 18], but further investigation is required. It is also important to note that some of the biological droplets would be blocked by bacterial filters, hence further reducing staff exposure.

The use of NO in this study was intended as a gas marker to measure quantitatively the effect of ventilation disconnection. One concern using inhaled NO is its reaction with the oxygen delivered through the ventilator, producing nitrogen dioxide (NO_2) [13, 14]. At the point of delivery, the concentration of NO_2 was detected at 0.3 ppm. The concentration of NO_2 was not monitored throughout the study. However, this concentration is expected to be below the recommended safety limit of 5 ppm [19] since the NO is introduced in the inspiratory line of the ventilator near the lung simulator and the measurement point [12]. In fact, it was shown that inhaled NO delivered at 80 ppm was not associated with significant dose of nitrogen dioxide [13].

Using the Swing Valve Technology™ ensures continuous ventilation to the patient. However, its performance could be altered under certain conditions. High relative humidity was used for the multiple tests performed. However, no visible water droplet buildup was noted during the experiments performed and therefore did not affect the valve performance during the study. It was also believed that the type of medication delivered could affect the valve functioning, since patients under mechanical ventilation could receive different viscous drugs (steroids, antibiotics, or anticoagulants). For this purpose, the Flusso™ Bypass adapter was tested using a solution of Acetylcysteine (20 mg/mL) for three consecutive disconnection cycles and repeated after 24 h and showed no diminishing performance of the valve (no significant change in tidal volume). However, a buildup of medication was noted on the adapter’s walls, which, in time, could affect the valve’s performance. This adapter is recommended to be replaced every 7 days. Therefore, medication buildup would not affect the adapter’s proper functioning.

CONCLUSIONS

With this work, an in vitro study was performed demonstrating the impact of the Flusso™ Bypass adapter in a hospital environment where a patient, under mechanical ventilation, is briefly disconnected and reattached to a portable mechanical ventilator to be transported. It was found that following the current standard procedures for patient transportation, with a three second disconnect, a leakage of particles delivered to the patient were dispersed in the room to which the clinical staff will be exposed. It was shown that this leakage was avoided when using the Flusso™ Bypass adapter therefore decreasing the risk of potential exposure to the clinical staff.

DISCLOSURES

Contributors

RM, AA, NO, and FF contributed to the conception design of the work, the acquisition, analysis and interpretation of data. RM, EM, and FF were involved in drafting and commenting on the paper and have approved the final version.

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Competing interests

All authors have completed the ICMJE uniform disclosure form at www.icmje.org/coi_disclosure.pdf and declare: FF owns the intellectual property for the Flusso™ device. However, Carleton University was the study lead with unrestricted rights to publish any and all findings at their discretion.

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