Bench Study on Active Exhalation Valve Performance

Guang-Yu Jiao MD and John W Newhart RRT

BACKGROUND: Ventilator exhalation-valve performance during the expiratory phase has been studied in depth. An active exhalation valve uses servo-control technology that allows gas to be released from the exhalation valve during the inspiratory phase if the patient makes an expiratory effort. We conducted a bench study of active exhalation valve response to expiratory effort during the inspiratory phase. METHODS: We studied 4 ventilators that have active exhalation valves (Maquet Servo-i, Newport e500, Puritan Bennett 840, and Evita XL) and one that does not (Puritan Bennett 7200ae). With an active test lung we simulated various magnitudes of expiratory effort during the middle of the inspiratory phase. We measured the exhalation resistance and pressure over-shoot during the expiratory effort, and we measured the pressure under-shoot after the expiratory effort. The exhalation resistance of the 7200ae could not be determined because this ventilator did not allow any gas-release through the exhalation valve during the expiratory effort. RESULTS: The exhalation resistance of the Evita XL (6.6 ± 1.8 cm H_2O/L/s) was higher than that of the Servo-i (3.0 ± 1.3 cm H_2O/L/s), e500 (2.6 ± 0.8 cm H_2O/L/s), and 840 (3.5 ± 0.8 cm H_2O/L/s) (all $P < .001$). The magnitude of pressure over-shoot during the expiratory efforts was not significantly different among the 4 ventilators with active exhalation valves. Pressure over-shoot was significantly higher with the 7200ae than with any of other ventilators (all $P < .001$). CONCLUSIONS: There was a significant difference in exhalation resistance between the Evita XL and the other 3 ventilators with active exhalation valves. All 4 ventilators with active exhalation valves had lower exhalation resistance than the 7200ae. *Key words: exhalation valve, expiratory resistance, mechanical ventilation, bench study.* [Respir Care 2008;53(12):1697–1702. © 2008 Daedalus Enterprises]

Introduction

During the inspiratory phase of mechanical ventilation, the exhalation valve closes to force the delivered gas to enter the patient's respiratory system. When the expiratory phase starts, the exhalation valve opens to release gas from the patient's respiratory system. Traditionally, the exhalation valve is *fully* closed during the inspiratory phase, and gas can be released from the patient's respiratory system only during the expiratory phase. This means that the patient cannot exhale freely until the ventilator switches to the exhalation phase. If the inspiratory phase is longer than the patient's neural inspiratory time or the patient coughs before the end of the inspiratory phase, airway pressure can rise to a high level in the lungs and cause discomfort or even barotrauma.[1] It may also disrupt breath delivery if the high-pressure alarm is triggered.

To address the problem of patient exhalation during the inspiratory phase of a pressure-controlled breath, most currently available ventilators have a servo-controlled "active" exhalation valve that the ventilator controls during both the inspiratory and expiratory phase. If a patient exhales or coughs prior to the completion of the ventilator's inspiratory phase, the ventilator tries to avoid pressure over-shoot above the set target pressure by partially opening the exhalation valve and releasing the excess pressure. As the patient's expiratory effort or cough pressure diminishes, the active exhalation valve quickly moves toward the closed position to avoid pressure under-shoot below the target pressure.

Guang-Yu Jiao MD is affiliated with the Respiratory Department and Respiratory Intensive Care Unit, Shengjing Hospital, China Medical University, Shenyang, Peoples Republic of China. John W Newhart RRT is affiliated with the Department of Respiratory Care Services, University of California, San Diego Medical Center, San Diego, California.

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Correspondence: Guang-Yu Jiao MD, Respiratory Department, Shengjing Hospital, China Medical University, Shenyang, Postal Code 110004, Peoples Republic of China. E-mail: guangyujiao@yahoo.com.

Although there have been many studies of exhalation valve performance during the ventilator's expiratory phase,[2-4] there have been no studies of active exhalation valve performance during the ventilator's inspiratory phase. We evaluated exhalation resistance, pressure over-shoot, and pressure under-shoot with a simulated expiratory effort during the inspiratory phase with 5 commercially available ventilators: 4 with and 1 without an active exhalation valve.

Methods

Ventilators

The 4 ventilators with active exhalation valves were Evita XL (Dräger, Telford, Pennsylvania), Servo-i (Maquet, Bridgewater, New Jersey), e500 (Newport, Newport Beach, California), and 840 (Puritan Bennett, Pleasanton, California). The modes we used were: airway pressure-release with the Evita XL, "Bi-Vent" with the Servo-i, biphasic pressure release with the e500, and Bilevel with the 840. We also tested a ventilator that does not have an active exhalation valve (7200ae, Puritan Bennett, Pleasanton, California), and we used its pressure-control mode.

We tested all the ventilators at set target inspiratory pressures of 15 cm H_2O and 25 cm H_2O, and positive end-expiratory pressure of 5 cm H_2O, which resulted in inflating pressures of 10 cm H_2O and 20 cm H_2O, respectively. The inspiratory and expiratory phases were both set at 2.0 s. Pressure support, automatic tube compensation, and other additional ventilator features were turned off or set to their minimum values. Other settings relevant to the study but not common to all ventilators were set to the manufacturers' recommended default value whenever applicable. Specifically: with the Evita XL the pressure slope was set at 0.20; with the Servo-i the inspiratory cycle-off setting was 25% and the inspiratory slope was 0.2 s; with the e500 the slope and cycle-off were both set to "auto"; with the 840 the slope was 50%, the pressure support was zero, and the cycle-off setting was 25%.

Test Lung and Settings

We connected the test lung (ASL5000, software version 2.2, IngMar, Pittsburgh, Pennsylvania) to the test ventilator with a standard breathing circuit. Calibrations of internal transducers and system leak test of the test lung were conducted by the manufacturer prior to the study. No bacterial filters or humidifiers were used (Fig. 1).

The respiratory muscle pressure profile for the test lung was programmed per the test lung's user's manual,[5] to generate an expiratory effort during the middle of the ventilator's inspiratory phase of each ventilator breath. This was done by generating 2 connecting segments (Fig. 2).

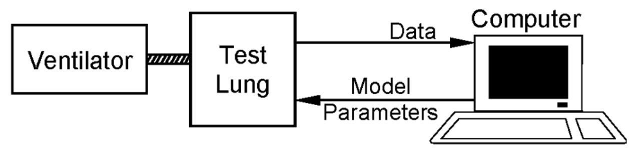

Fig. 1. Test setup.

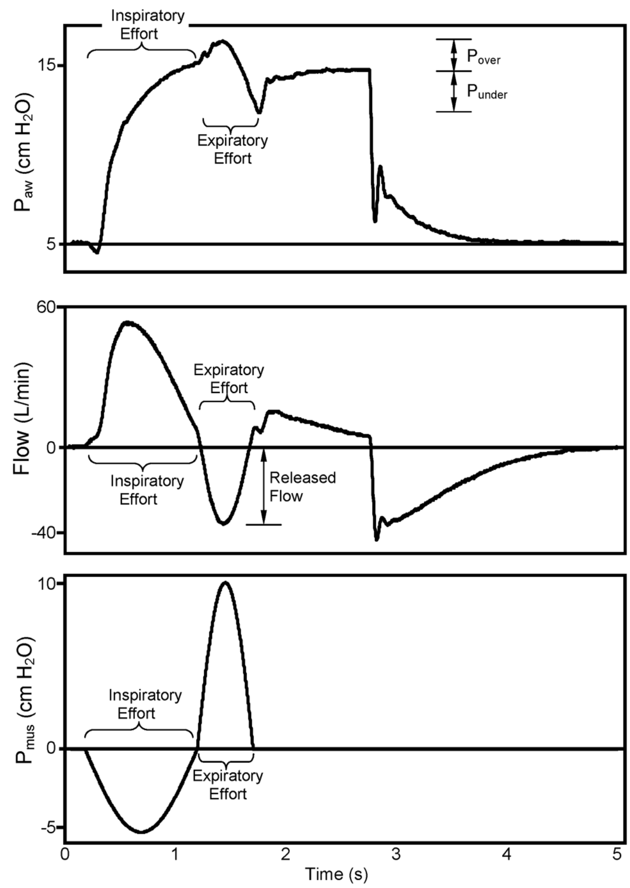

Fig. 2. Airway pressure (P_{aw}), flow, and respiratory-muscle-pressure (P_{mus}) in a test-lung model of a patient making an expiratory effort during the inspiratory phrase of a ventilator breath. To simulate patient respiratory efforts with P_{mus}, each breath is composed of an active inspiratory effort (a negative P_{mus}) followed immediately by an expiratory effort (a positive P_{mus}) during the ventilator's inspiratory phase, which causes a pressure over-shoot above the target pressure (P_{over}) and pressure under-shoot below the target pressure (P_{under}). Resistance to the expiratory effort is computed from the P_{over} and the released flow rate.

The first segment was a negative sine waveform to simulate a typical spontaneous inspiratory effort of 1.0 s at a maximum magnitude of –5 cm H_2O. The first segment was immediately followed by the second segment, which was a positive sine waveform to simulate a 0.5-s expiratory effort, at either 5, 10, or 15 cm H_2O, to simulate 3 different expiratory efforts.

Table 1. Pressure Over-Shoot

	Pressure Over-Shoot (cm H_2O)							
	P_{target} 15 cm H_2O P_{mus} 5 cm H_2O	P_{target} 15 cm H_2O P_{mus} 10 cm H_2O	P_{target} 15 cm H_2O P_{mus} 15 cm H_2O	P_{target} 25 cm H_2O P_{mus} 5 cm H_2O	P_{target} 25 cm H_2O P_{mus} 10 cm H_2O	P_{target} 25 cm H_2O P_{mus} 15 cm H_2O	Mean ± SD	*P**
Evita XL	2.3	3.7	5.5	2.0	2.3	4.3	3.4 ± 1.3	Servo-i: .18 e500: .15 840: .34 7200: < .001
Servo-i	0.3	1.4	2.7	0.4	1.7	2.7	1.5 ± 1.0	Evita XL: .18 e500: .99 840: .99 7200: < .001
e500	0.7	1.4	2.3	0.7	1.4	2.3	1.5 ± 0.7	Evita XL: .15 Servo-i: .99 840: .99 7200: < .001
840	0.7	1.8	3.4	0.7	1.5	2.9	1.8 ± 1.1	Evita XL: .34 Servo-i: .99 e500: .99 7200: < .001
7200	4.5	8.3	13.3	2.8	6.3	10.4	7.6 ± 3.9	Evita XL: < .001 Servo-i: < .001 e500: < .001 840: < .001

* Comparison of the mean pressure over-shoot of each ventilator to the other ventilators.
P_{target} = target pressure
P_{mus} = respiratory muscle pressure, which represents the expiratory effort

Other test-lung settings were: single-compartment model, linear airway resistance of 10 cm H_2O/L/s, and linear compliance of 50 mL/cm H_2O.

Measurements

The pressure and flow at the airway opening were measured by the transducers in the test lung, and digitized at 512 Hz. We measured:

- Pressure over-shoot: the maximum pressure over the target pressure during the expiratory effort
- Exhalation resistance during the expiratory effort: pressure over-shoot divided by the corresponding flow rate released from the exhalation valve
- Pressure under-shoot: the maximum pressure dip below the target pressure immediately after the expiratory effort

In each test condition we calculated the mean value from 3 consecutive breaths, after the 2-min stabilization period.

Statistical Analysis

With statistics software (SPSS 15.0, SPSS, Chicago, Illinois) we analyzed the differences in resistance, pressure over-shoot, and pressure under-shoot with 2-way analysis of variance and Tukey's Honest Significant Difference test for post-hoc analysis. A *P* value of < .05 was considered significant.

Results

Pressure Over-Shoot

With all the ventilators, the expiratory effort caused pressure over-shoot (Table 1 and Fig. 3). Among the 4 ventilators with active exhalation valves there was no statistical difference in pressure over-shoot; the largest pressure over-shoot was 5.5 cm H_2O above the target pressure. The pressure over-shoot was significantly higher with the 7200ae than all other ventilators ($P < .001$). This reflects the significant impact of active-exhalation-valve capability on minimizing pressure over-shoot.

Exhalation Resistance

The airflow waveform showed that no flow was released from the 7200ae's exhalation valve during the expiratory effort. Although this was expected, because the 7200ae's exhalation valve system is designed not to release gas during the inspiratory phase, it made it im-

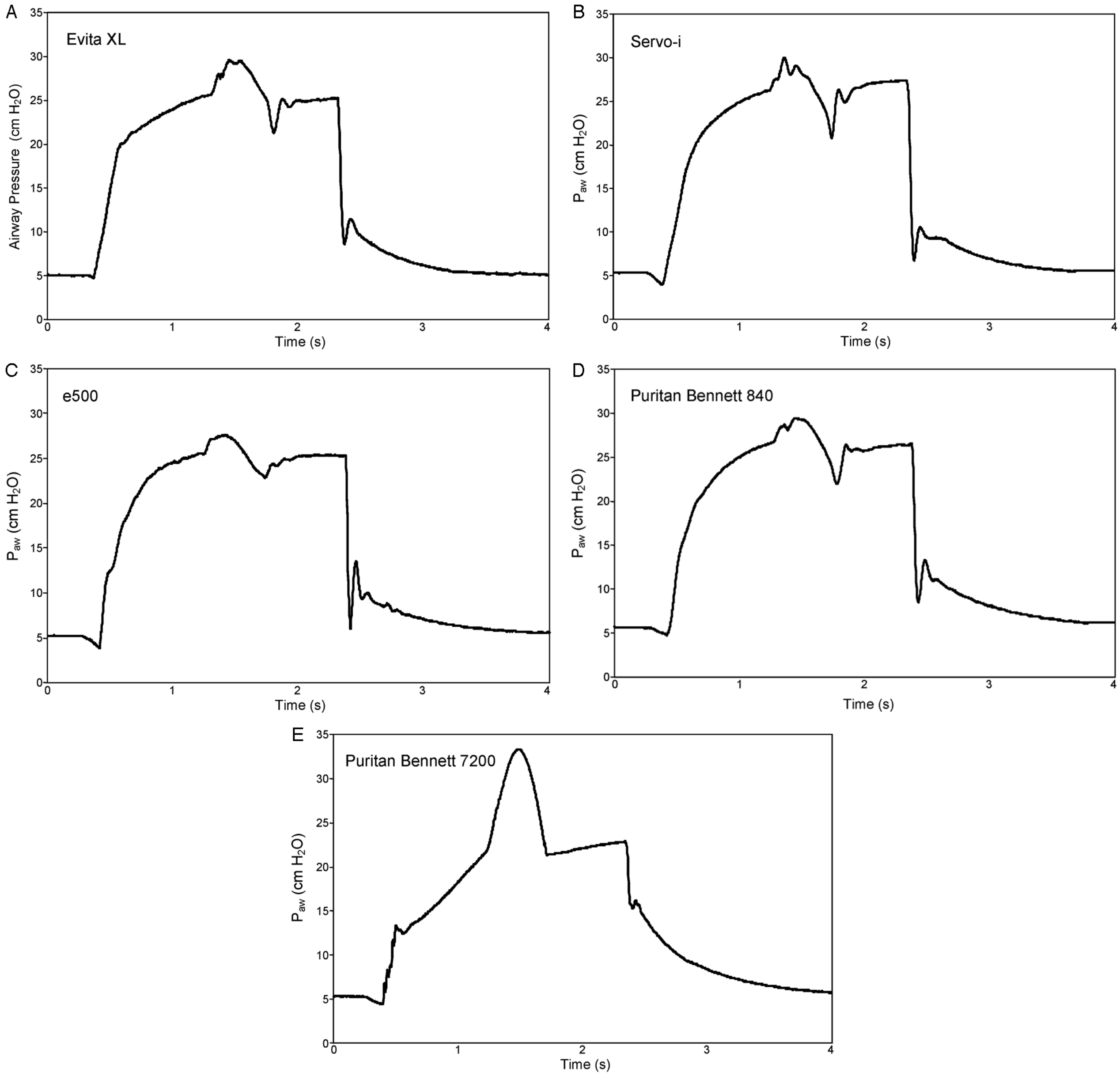

Fig. 3. Airway pressure waveforms from the 5 ventilators at a set target pressure of 25 cm H_2O and expiratory muscle pressure of 15 cm H_2O.

possible to compute the exhalation resistance with the 7200ae, so we could only compare the exhalation resistance of the 4 other ventilators (Table 2).

Among the 4 ventilators with active exhalation valves, Evita XL had the highest mean exhalation resistance (see Table 2) ($P < .001$ for Evita XL compared to Servo-i, e500, and 840). There was no statistical difference in mean exhalation resistance among the Servo-i, e500, and 840 ventilators.

Pressure Under-Shoot

The 7200ae had no pressure under-shoot following the expiratory effort, because the 7200ae's exhalation valve is fully closed during the ventilator's inspiratory phase, so we could only make statistical comparisons of pressure under-shoot among the 4 ventilators with active exhalation valves (Table 3). The Servo-i had a bigger pressure under-shoot than the 840, Evita XL, or e500 (all $P < .001$). And the 840 had a bigger pressure under-shoot than Evita XL or e500 (both $P < .001$).

Discussion

Among the 4 ventilators with active exhalation valves, Evita XL had the highest exhalation resistance. The magnitude of pressure over-shoot was not statistically different

Table 2. Exhalation Resistance

	Resistance (cm H_2O/L/s)							
	P_{target} 15 cm H_2O P_{mus} 5 cm H_2O	P_{target} 15 cm H_2O P_{mus} 10 cm H_2O	P_{target} 15 cm H_2O P_{mus} 15 cm H_2O	P_{target} 25 cm H_2O P_{mus} 5 cm H_2O	P_{target} 25 cm H_2O P_{mus} 10 cm H_2O	P_{target} 25 cm H_2O P_{mus} 15 cm H_2O	Mean ± SD	*P**
Evita XL	7.4	6.0	5.7	9.8	4.7	6.1	6.6 ± 1.8	Servo-i: < .001 e500: < .001 840: < .001
Servo-i	0.9	2.2	3.0	4.5	3.7	3.6	3.0 ± 1.3	Evita XL: < .001 e500: .93 840: .78
e500	1.8	2.1	2.4	3.9	2.8	2.8	2.6 ± 0.8	Evita XL: < .001 Servo-i: .93 840: .42
840	2.3	2.9	3.9	4.5	3.2	4.1	3.5 ± 0.8	Evita XL: < .001 Servo-i: .78 e500: .42

* Comparison of the mean exhalation resistance of each ventilator to the other ventilators.
P_{target} = target pressure
P_{mus} = respiratory muscle pressure, which represents the expiratory effort

Table 3. Pressure Under-Shoot

	Pressure Under-Shoot (cm H_2O)							
	P_{target} 15 cm H_2O P_{mus} 5 cm H_2O	P_{target} 15 cm H_2O P_{mus} 10 cm H_2O	P_{target} 15 cm H_2O P_{mus} 15 cm H_2O	P_{target} 25 cm H_2O P_{mus} 5 cm H_2O	P_{target} 25 cm H_2O P_{mus} 10 cm H_2O	P_{target} 25 cm H_2O P_{mus} 15 cm H_2O	Mean ± SD	*P**
Evita XL	0.6	1.8	2.1	1.1	2.0	3.4	1.8 ± 0.9	Servo-i: < .001 e500: .924 840: .001
Servo-i	3.1	5.0	6.3	4.0	5.4	6.3	5.0 ± 1.3	Evita XL: < .001 e500: < .001 840: < .001
e500	1.1	1.6	2.2	1.1	2.1	2.0	1.7 ± 0.5	Evita XL: .924 Servo-i: < .001 840: < .001
840	1.6	3.0	3.3	2.2	3.4	4.4	3.0 ± 1.0	Evita XL: < .001 Servo-i: < .001 e500: < .001

* Comparison of the mean pressure under-shoot of each ventilator to the other ventilators.
P_{target} = target pressure
P_{mus} = respiratory muscle pressure, which represents the expiratory effort

among these 4 ventilators. Pressure over-shoot was significantly higher in the ventilator without active exhalation valve than in the ventilators with active exhalation valves. The exhalation resistance was very different between the ventilators with and without active exhalation valves, because the ventilators with active exhalation valves all allow a certain degree of gas-release if expiratory effort occurs during the inspiratory phase, whereas the ventilator without active exhalation valve does not.

Ventilators without active exhalation valves use a high exhalation-valve driving pressure to keep the exhalation valve closed during the inspiratory phase. This prohibits gas-release from the exhalation valve during the inspiratory phase. If the patient coughs or makes an expiratory effort prior to the end of the set inspiratory time (eg, if the set inspiratory time is longer than the patient's neural inspiratory time), the expiratory effort elevates the airway pressure. Therefore, with a ventilator that does not have an active exhalation valve, the high-pressure alarm should be set at a conservative level to avoid excessive pressure in the patient's lungs in case the patient makes an expiratory effort during the inspiratory phase.

In contrast to older ventilators that did not have active exhalation valves, newer-generation ventilators with active exhalation valves allow the exhalation valve to "float" at the set target pressure. An ideal active-exhalation-valve system would have no delay between the input and output and therefore no pressure over-shoot or under-shoot. In reality, the control systems in available ventilators all have some delay[6] (the exhalation valve cannot open instantaneously), so the exhalation valve causes some resistance as the patient initiates an expiratory effort, which results in a certain degree of pressure over-shoot. As the patient's expiratory effort decays, the exhalation valve closes in proportion to the expiratory-flow decrease, but there is also mechanical delay at this point, so there is also a certain degree of pressure under-shoot. All the ventilators with active exhalation valves had both over-shoot and under-shoot. The over-shoot was as high as 5.5 cm H_2O.

Many studies have shown that, to protect the lungs from barotrauma during mechanical ventilation, airway pressure should be limited to 30–35 cm H_2O in patients with acute lung injury.[7-9] If our results can be extrapolated to humans, clinicians should keep in mind the risk of pressure over-shoot when setting the target pressure, even with a ventilator that has an active exhalation valve. The existence of pressure over-shoot as high as 5.5 cm H_2O indicates that ventilator manufacturers should make more efforts to optimize active-exhalation-valve systems to minimize pressure over-shoot.

Under our test conditions the biggest pressure under-shoot magnitude was 6.3 cm H_2O, with the Servo-i. Unlike the harm of pressure over-shoot, which has been extensively studied and quantified,[1] the potential harm from pressure under-shoot has not been quantified. Therefore, whether this degree of pressure under-shoot could cause alveolar collapse and/or compromise gas exchange remains to be explored.

Limitations

Our study was conducted with a bench setup, to eliminate independent variables, for consistency and reliability purposes. However, a bench study has certain limitations and its results have to be validated in a study with patients. We chose a sine respiratory-muscle-pressure waveform. Patients might have a different respiratory-muscle-pressure waveform, which could result in different findings.

Our statistical power was limited because we created only 6 combinations of test conditions for each ventilator.

Our data may not reflect all situations found in clinical care.

In computing exhalation resistance, we chose the first-order model for the resistance calculation, assuming that pressure over-shoot has a linear relationship with the released flow. A more complicated model for the resistance calculation might be warranted, because physiologically the relationship between pressure and flow is often nonlinear,[10,11] but we discovered through close scrutiny of our data that the relationship between the pressure over-shoot and the release flow was closer to a linear relationship, probably because of the manipulation of the software control of the exhalation valve in these ventilators.

Conclusions

Among the ventilators with active exhalation valves, there was a significant difference in exhalation resistance during the inspiratory phase between the Evita XL and the others. All of these ventilators had pressure over-shoot and pressure under-shoot. However, the ventilator without an active exhalation valve allowed no gas-release from the exhalation valve during inspiratory phase, and this resulted in significantly higher pressure over-shoot than the ventilators with active exhalation valves. If our results can be extrapolated to humans, clinicians should keep in mind the risk of pressure over-shoot, regardless of whether the ventilator has an active exhalation valve.

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