Bench Assessment of Expiratory Valve Resistance of Current ICU Ventilators in Dynamic Conditions

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and Claude Guérin

BACKGROUND: We hypothesized that the lack of benefit of setting a low versus a high PEEP in patients with ARDS may be due in part to differences in the dynamic behavior of the expiratory valve in ventilators. We tested this hypothesis by conducting a bench comparison of the dynamic behavior of expiratory valves on ICU ventilators currently in use. METHODS: We attached 7 ICU ventilators (C5, C6, Carescape, PB980, ServoU, V500, and V680) to the ASL 5000 lung model (passive condition with compliance 20 mL/cm H_2O and resistance 5 cm H_2O/L/s) and set in volume controlled mode (tidal volume 0.8 L, breathing frequency 10 breaths/min). Flow and pressure were measured just before the exhalation valve. At PEEP of 5, 10, and 15 cm H_2O, the median instantaneous expiratory resistance, the time to valve opening, and the pressure time products above or below the values of PEEP (expressed in cm H_2O × s) were determined. RESULTS: Median instantaneous expiratory resistance values differed between the ventilators and PEEP settings with a significant interaction: at PEEP 5 cm H_2O, the median (interquartile range) expiratory resistance values were 3.9 (3.5–4.7), 3.0 (3.0–3.1), 20.9 (15.8–24.9), 27.4 (26.5–43.2), 13.8 (13.6–13.9), 4.4 (4.0–4.6), and 34.3 (33.7–33.8) cm H_2O/L/s, for the C5, C6, Carescape, PB980, ServoU, V500, and V680, respectively. For all the PEEP settings, the corresponding times to valve opening were 0.080 (0.077–0.082), 0.082 (0.080–0.085), 0.110 (0.105–0.110), 0.100 (0.085–1.05), 0.072 (0.062–0.072), 0.145 (0.115–0.150), and 0.075 (0.070–0.080) s, respectively, and pressure-time products were 2.8 (2.1–7.4), 6.8 (6.7–7.3), 2.4 (2.1–2.4), 3.5 (2.7–3.6), 1.8 (1.8–2.1), 2.8 (2.7–2.9), and 5.7 (5.4–5.9) cm H_2O × s, respectively. CONCLUSIONS: The resistance of active expiratory valves differed significantly between the 7 ICU ventilators tested. *Key words: expiratory valve; flow resistance; ICU ventilator; PEEP; ARDS; mechanical ventilation; PEEP device.* [Respir Care 2021;66(4):610–618. © 2021 Daedalus Enterprises]

Introduction

Setting the correct PEEP value is key for patients with ARDS because it improves oxygenation, promotes lung recruitment, and minimizes atelectrauma. However, after 3 large trials failed to demonstrate improved patient outcomes with higher versus lower PEEP in subjects with ARDS,[1-3] the selection of PEEP remains an issue. One possible reason for these negative trials is the variability in PEEP delivery for a given nominal PEEP between ICU ventilators. In the landmark ARMA trial,[4] lower tidal volumes were compared to traditional tidal volumes using the same ventilator across participating centers; in addition, this ventilator was reported in a bench study to be the most accurate in delivering the set tidal volume.[5] Modern ICU

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ventilators adjust PEEP with electromagnetic or electronic valves that act on a diaphragm in proportion to the flow under the control of a microprocessor and software. Typically, a rod is driven by the proportional valve and presses a membrane, which in turn reduces the diameter of the aperture through which the air is breathed out by the patient. The ideal expiratory valve should be able to maintain the airway pressure (P_{aw}) at the PEEP value independently on expiratory flow.[6,7] In actuality, however, expiratory valves have flow-dependent components and are more or less flow-resistors, with the P_{aw} being equal to the resistance of the valve times flow: $P_{aw} = R_{valve} \times \dot{V}_E$, where R is resistance and $\dot{V}_E$ is expiratory minute volume.

If the resistance is constant, then the P_{aw} is proportional to flow (ie, it increases as the flow through the valve increases).[7] Expiratory valves in modern ICU ventilators are active valves, meaning that their resistance varies during expiration depending on an algorithm developed by the manufacturers. This time course variability in P_{aw} may affect the time course of lung volume exhaled during expiration, even though at the very end of expiration the PEEP is reached. This time point is the criterion that is commonly used to assess the accuracy of PEEP delivered by ICU ventilators.[8] It turns out that investigating the dynamic behavior of the expiratory valve is as important as testing the accuracy of the level of PEEP. Previous studies performed more than 30 years ago measured the flow-resistance of expiratory devices of different ventilators in so-called static conditions by injecting a range of flow and measuring the resulting pressure drop across the valve.[9,10] Kayaleh et al[11] reported that the measurement of the expiratory valve in static conditions underestimates the real dynamic resistance. However, no study has reassessed the performance of PEEP devices of ICU ventilators since then. Therefore, we undertook this bench study of current ICU ventilators to measure the flow resistance of expiratory valves in dynamic conditions, with the hypothesis that it varies from one ICU ventilator to another.

QUICK LOOK

Current knowledge

Optimal PEEP settings remain an open question after 3 large randomized controlled trials comparing low and high PEEP failed to demonstrate a benefit to subjects with ARDS. We explored whether the dynamic behavior of the active expiratory valve of the PEEP device might be a reason for the lack of significant clinical impact of PEEP in patients.

What this paper contributes to our knowledge

The dynamic resistance of the PEEP device as well as the opening valve time and the time spent above or below the PEEP differed significantly between 7 ICU ventilators tested in a bench study. The clinical implications of these findings should be explored.

Methods

Setup

The study was performed in the medical ICU at Hospital Edouard Herriot in Lyon, France. The experimental setup consisted of the following components. An ASL 5000 test lung (Ingmar Medical, Pittsburgh, Pennsylvania) was set in passive condition with a compliance of 20 mL/cm H_2O to generate high peak expiratory flow and a linear resistance of 5 cm H_2O/L/s during both inspiration and expiration. Flow and pressure (P_{ev}) were measured proximal to the expiratory valve (Fig. 1). Air flow was measured with a pneumotachograph (3700 series, Hans Rudolph, Shawnee, Kansas). P_{ev} was assessed with a pressure transducer (Gabarith PMSET 1DT-XX, Becton Dickinson, Singapore). Analog signals of flow and P_{ev} were sent to a data logger (MP150, Biopac, Goleta, California) (Fig. 1). A wireless dual limb ventilator circuit (22 mm inner diameter, 1.6 m long; Intersurgical, Berkshire, United Kingdom) was used. Seven ICU ventilators provided by the French representatives of the manufacturers were tested: PB980 (Medtronic, Dublin, Ireland); C5 and C6 (Nihon Kohden Europe, Roshbach, Germany); Carescape860 (GE Health Care, Chicago, Illinois); Evita V500 (Dräger, Lübeck, Germany); Servo U ventilator (Maquet-Getinge, Getinge, Sweden); and Respironics V680 (Philips, Amsterdam, The Netherlands).

Protocol

Each ventilator was fully checked before the experiment according to the procedure described in the user manual. The P_{ev} transducer was calibrated using a manometer (717 1G, Fluke Biomedical, Everett, Washington), and pneumotachograph was calibrated with a 1 L ± 12 mL calibration pump (Viasys, Hochberg, Germany) at room temperature. The ventilators were set in volume controlled mode with a squared inflation flow, tidal volume of 0.8 L, inspiratory flow of 60 L /min, inspiratory time of 1 s, breathing frequency of 10 breaths/min, and F_{IO_2} of 0.21. The heat-and-moisture exchanger filter was omitted. For each ventilator, PEEP was set at 5, 10, and 15 cm H_2O. At each PEEP setting, P_{ev} and flow signals were recorded at 200 Hz for a 1-min stabilization period, and the next 3 cycles were used for offline analysis.

Data Analysis

Data analysis was performed with an Excel macro specifically developed for the present study. On each breath,

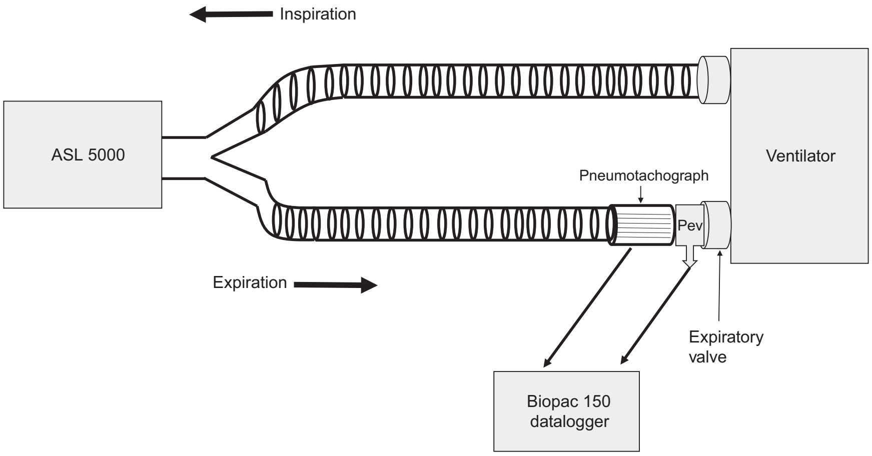

Fig. 1. Experimental setup.

the instantaneous expiratory resistance was determined as the ratio of the pressure drop between P_{ev} and the atmosphere to the corresponding expiratory flow (Fig. 2). For this computation, we discarded flow > 0.01 L/s to avoid extreme values due to the closing time of the valve. Therefore, the instantaneous expiratory resistance was determined in 800–900 instances for each breath. These measurements were done at each PEEP setting for each ventilator. We used the median and the minimal values of the instantaneous resistance in each condition. We also measured the PEEP value delivered by the ventilator. In the P_{ev}-time curve, we calculated the pressure-time product above PEEP (PTP_{above}), the pressure-time product below PEEP (PTP_{below}), and the sum their absolute values ($|PTP_{above}| + |PTP_{below}|$). These computations were done to define a simple index to characterize how the ventilator behaves to maintain the pressure at the PEEP value during the expiratory phase.

We then divided the expiration from onset of expiration (ie, the first zero flow after insufflation) to peak flow (ie, maximum expiratory flow) and from peak flow to the next zero flow. On the P_{ev}-flow plots during each of the 2 parts of expiration, we searched for breakpoints that defined 2 or more linear segments (Fig. 3). The segments with the steepest slope before the breakpoint in the first part of expiration and after the breakpoint in the second part of expiration were taken as estimates of the opening and closing times of the valve, respectively. In the second part of expiration, the linear segment in which P_{ev} decreased as a response to a flow decrease or increased as a response to a flow increase was assumed to represent the expiratory valve in a fixed position. The slope of this segment was taken as the fixed resistance of the expiratory valve. This process was done automatically using the statistical software.

The primary end point was the median instantaneous resistance of the expiratory valve (R_{median}). The secondary end points were minimum instantaneous resistance of the expiratory valve (R_{min}), PTP_{above}, PTP_{below}, $|PTP_{above}| + |PTP_{below}|$, opening and closing times of the valve, and fixed expiratory resistance expressed as its value and as the fraction of expiration length within which it occurred.

The values are presented as median (interquartile range [IQR]) and compared with 2-factor analysis of variance, with PEEP and ventilator being the factors tested. Post hoc comparisons between ventilators (21 occurrences) were performed with the Tukey honestly significant difference test if there was an overall significant ventilator effect. We also evaluated the potential correlation between resistance and PTP_{below} or PTP_{above}. Correlation between variables was performed with the rho Spearman coefficient and its 95% CI. The critical *P* value was adjusted for multiple comparisons by taking into account the number of statistical tests (10 criteria × 7 ventilators × 3 PEEP levels × 21 pairwise comparisons between ventilators) and applying a Bonferroni correction. Therefore the *P* value taken as the level for statistical significance was $< .0007$. The statistical analysis was performed with R 3.5.2 (The R Foundation for Statistical Computing software).

Results

Instantaneous Resistance of the Expiratory Valve

The median instantaneous expiratory resistance was significantly different between ventilators and PEEP with a significant interaction between them (Fig. 4). Therefore, ventilators were compared at each PEEP. Between C5, C6, Carescape, PB980, ServoU, V500, and V680, the median (IQR) expiratory resistance values were 3.9 (3.5–4.7), 3.0 (3.0–3.1), 20.9 (15.8–24.9), 27.4 (26.5–43.2), 13.8 (13.6–13.9), 4.4 (4.0–4.6), and 34.3 (33.7–33.8) cm H_2O/L/s, respectively, at PEEP 5 cm H_2O (Fig. 4). At PEEP 10 cm H_2O, the corresponding values were 3.8 (3.7–11.8), 3.8

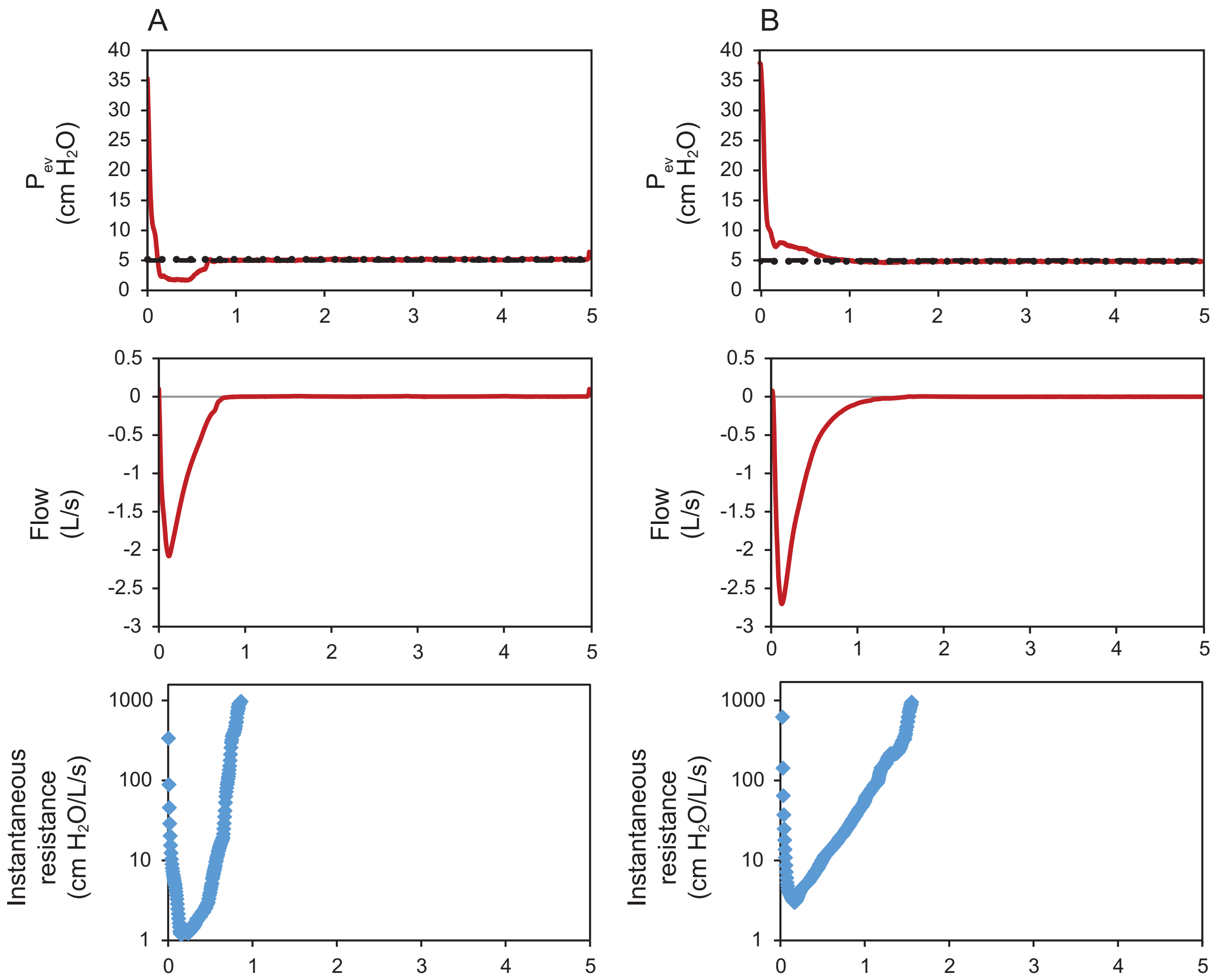

Fig. 2. Signals of airway pressure (P_{ev}), flow, and instantaneous resistance over expiratory time in A: the C5 ventilator and B: the PB980 ventilator at a PEEP of 5 cm H_2O. The resistance was computed as the ratio of P_{ev}-atmospheric pressure to flow for flow $>$ 0.01 L/s.

(3.8–3.9), 35.0 (34.0–36.5), 60.1 (60.4–99.0), 26.0 (25.8–36.4), 12.5 (12.3–12.7), and 76.4 (75.2–76.9) cm H_2O/L/s, respectively (Fig. 4). At PEEP 15 cm H_2O, the values were 12.5 (12.2–53.3), 10.2 (10.1–10.2), 45.9 (45.0–46.5), 104.3 (101.0–105.2), 39.5 (38.2–40.8), 16.1 (16.0–17.1), and 127.4 (127.0–131.1) cm H_2O/L/s, respectively (Fig. 4). Briefly the main result is the emergence of 2 groups of ventilators: a group with low resistance values (C5, C6, V500), and a group with higher resistance (Carescape, PB980, ServoU, V680). The value of the median instantaneous resistance means that $>$ 50% of the measurements (ie, almost 400) were greater than this value and that each measurement was performed over 5 ms.

The minimum instantaneous resistance of the expiratory valve was significantly different across the ventilators and PEEP, with a significant interaction between them (Fig. 5). Every pairwise comparison of the minimum instantaneous resistance between ventilators was significant at PEEP 5 cm H_2O. The same was true at PEEP 10 cm H_2O except between C5 and C6, PB980 and Carescape, and V500 and ServoU ventilators (Fig. 5). At PEEP 15 cm H_2O, the minimum instantaneous resistance was significantly different between C5 and C6 and every other ventilator (Fig. 5).

Pressure-Time Product

PTP_{below} differed significantly between PEEP settings and ventilators with a significant interaction between them (Fig. 6). Overall, our results outline 3 groups of ventilators: a group with low values of PTP_{below} (PB980, ServoU, V680), a group with higher values of PTP_{below} (C5, C6), and an intermediate group (Carescape, V500).

PTP_{above} did not differ significantly between PEEP settings. Our results delineate a group with a relative high value of PTP_{above} (C6 with 6.8 [6.7–7.3] cm H_2O × s; V680 with 5.7 [5.4–5.9] cm H_2O × s), and another group

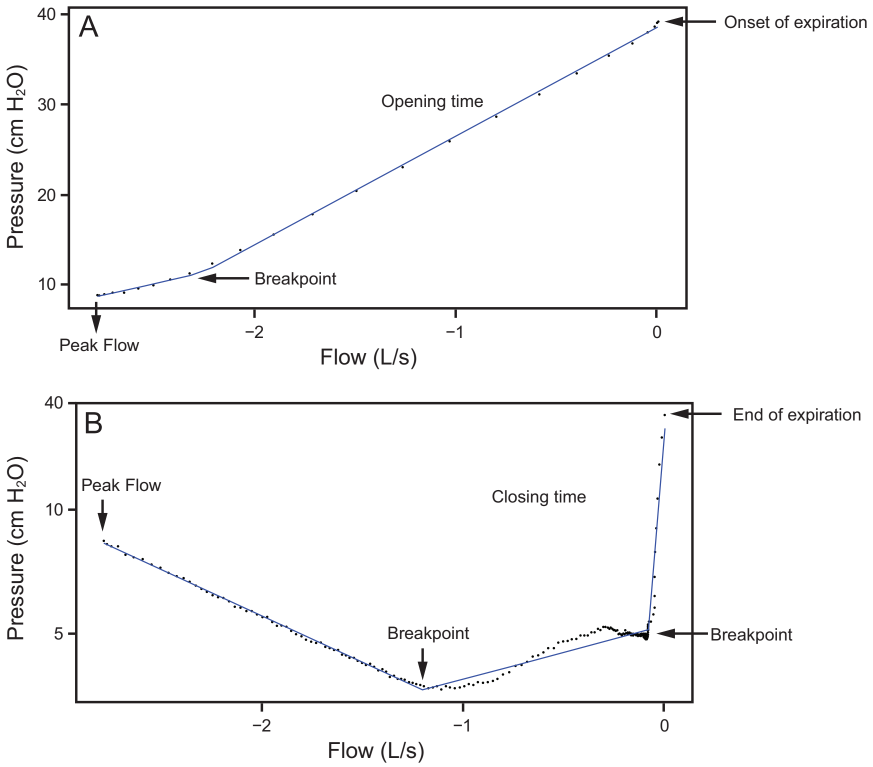

Fig. 3. Plots of pressure to flow from A: onset of inspiration to peak flow and B: from peak flow to end of expiration, illustrating the method to measure the opening and closing times of the valve and the linear resistance at the time the valve is assumed to be in a fixed open position. The automatically determined breakpoint is shown with a vertical arrow. Opening and closing times are defined as the time spent between the two corresponding horizontal broken lines.

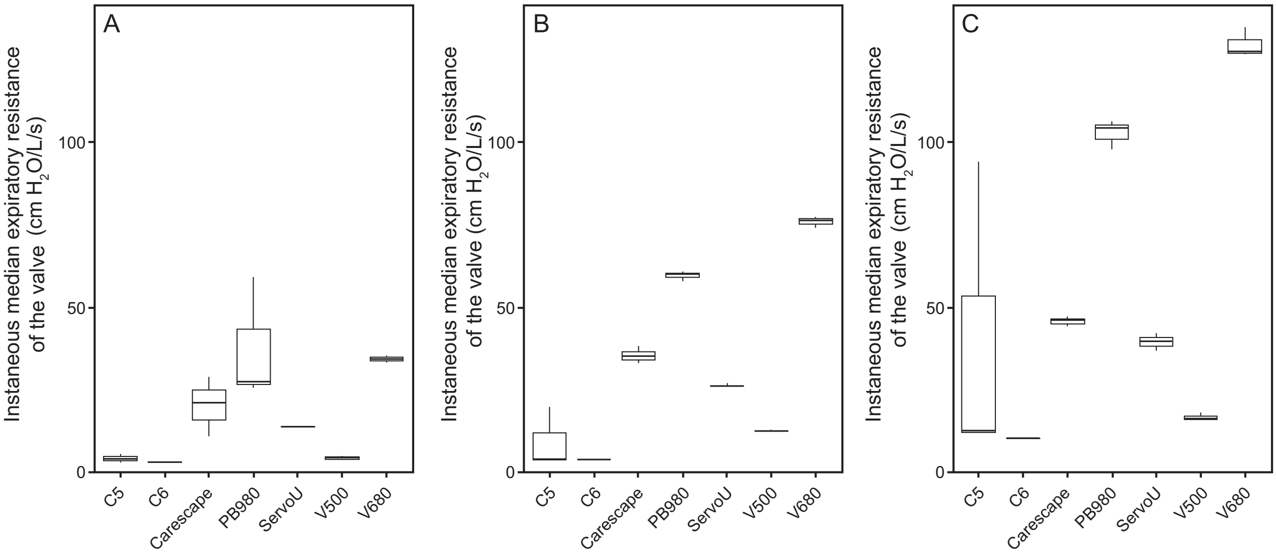

Fig. 4. Box-and-whisker plots of the median instantaneous resistance of the expiratory valve across the 7 ventilators and PEEP settings. A: PEEP 5 cm H_2O, B: PEEP 10 cm H_2O, and C: PEEP 15 cm H_2O. Whiskers denote median$\pm$1.58 × IQR × $\sqrt{3}$. IQR = interquartile range.

with smaller values (ServoU with 1.8 [1.8–2.1] cm $H_2O \times$ s; Carescape with 2.4 [2.1–2.4]; V500 with 2.8 [2.7–2.9]; C5 with 2.8 [2.1–7.4]; PB980 with 3.5 [2.7–3.6]).

The median (IQR) values for $|PTP_{above}| + |PTP_{below}|$, which yields the total gap between the ideal valve (P_{aw} = PEEP) and the measured pressure, did not differ with PEEP

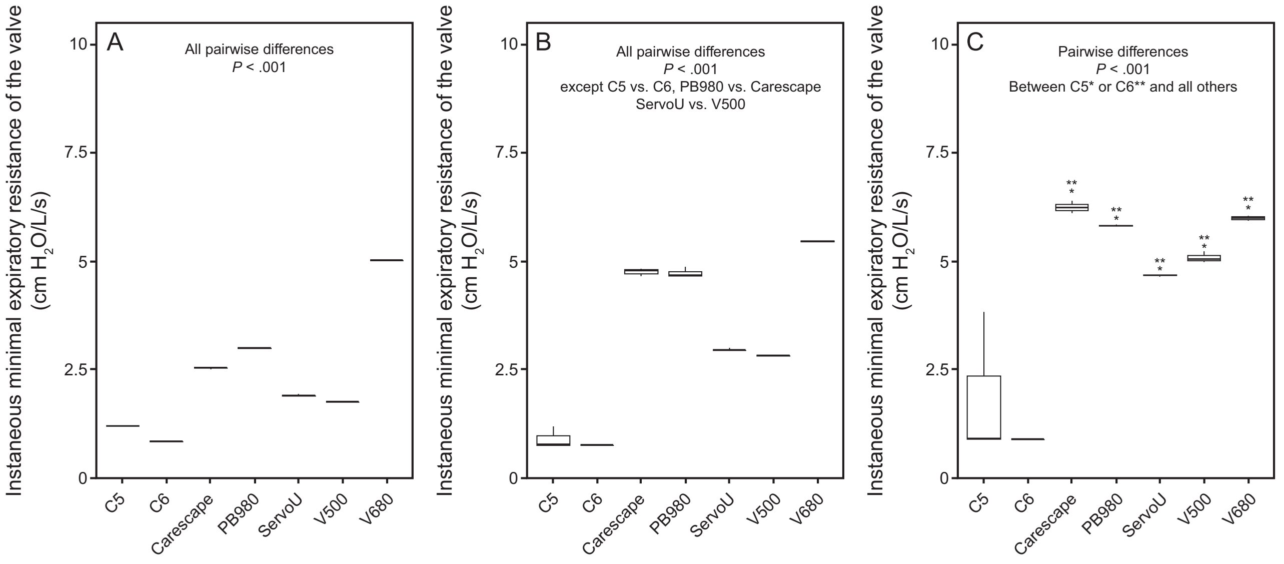

Fig. 5. Box-and-whisker plots of the minimal instantaneous resistance of the expiratory valve across the 7 ventilators and PEEP settings. A: PEEP 5 cm H_2O, B: PEEP 10 cm H_2O, and C: PEEP 15 cm H_2O. Whiskers denote median ± 1.58 × IQR × $\sqrt{3}$. IQR = interquartile range.

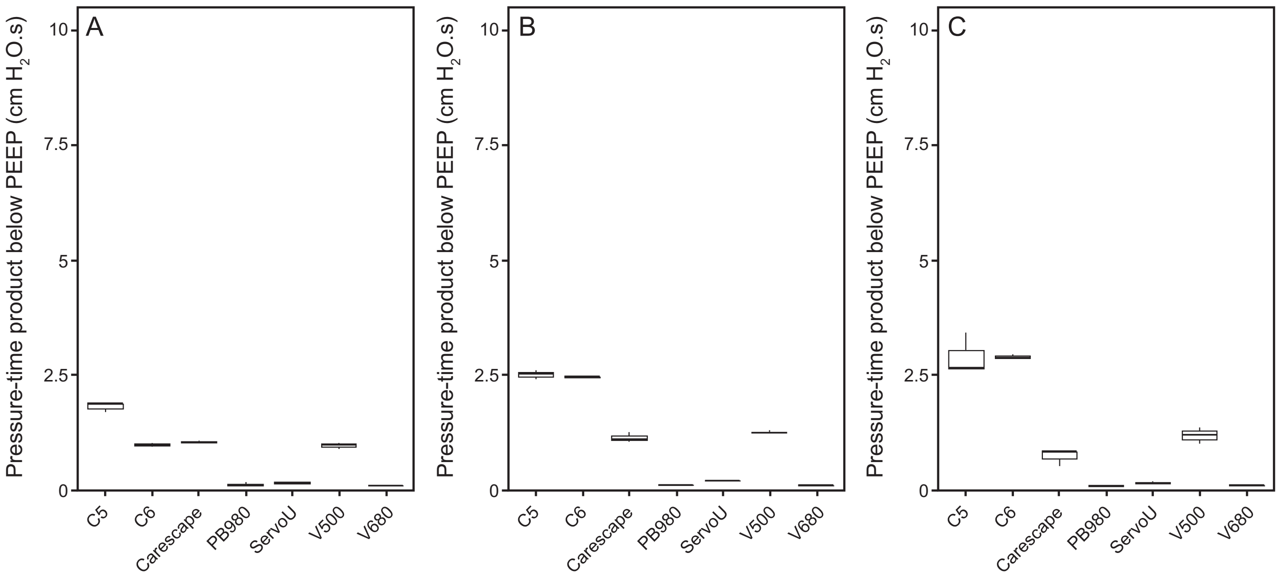

Fig. 6. Box-and-whisker plots of the pressure-time product (PTP) below PEEP for the expiratory valve across the 7 ventilators and PEEP settings tested. A: PEEP 5 cm H_2O, B: PEEP 10 cm H_2O, and C: PEEP 15 cm H_2O. Whiskers denote median ± 1.58 × IQR × $\sqrt{3}$. IQR = interquartile range.

settings. It was the lowest with ServoU (1.9 [1.9–2.2] cm H_2O × s), and it was highest with C5 (5.8 [3.8 – 9.8] cm H_2O × s), C6 (4.8 [4.5–5.3] cm H_2O × s), and V680 (5.8 [5.5–5.9] cm H_2O × s). Carescape (3.4 [2.8–3.5] cm H_2O × s), PB 980 (3.6 [2.7–3.7] cm H_2O × s), and V500 (3.9 [3.8–4.1] cm H_2O × s) exhibited intermediate values.

Opening and Closing Times

The median (IQR) opening times of the valve did not differ between PEEP settings. It was the shortest for ServoU (0.072 [0.062–0.072] s), which differed from the longest found in Carescape (0.110 [0.105–0.110] s), PB980 (0.100 [0.085–1.05] s), and V500 [0.145 (0.115–0.150] s), whereas the opening times of V680 (0.075 [0.070–0.080] s), C5 (0.080 [0.077–0.082] s), and C6 (0.082 [0.080–0.085] s) were in between. The valve closing times also were not different between PEEP settings. It was the shortest with C6 (0.020 [0.020–0.040] s), which was significantly lower than the longest values with V500 (0.085 [0.080–0.095] s), V680 (0.080 [0.065–0.095] s), and ServoU (0.070 [0.070–0.080] s). Valve closing times

Table 1. Fixed Linear Resistance of the Expiratory Valve per Ventilator at Different PEEP Settings

PEEP, cm H_2O	Fixed Linear Resistance, cm H_2O/L/s						
	C5	C6	Carescape	PB980	ServoU	V500	V680
5	6.0 (5.4–6.1)†	3.1 (2.9–3.3)*†	3.7 (3.7– 3.8)†	1.0 (0.9–1.2)*†‡	1.4 (1.3– 1.4)*†‡	2.9 (2.9– 3.0)*†	9.3 (9.1–9.3)*
10	8.5 (6.2–9.0)	8.9 (7.7–9.4)§	3.9 (3.7–4.0)	3.3 (3.3–3.6)	1.6 (1.6–1.6)†	3.4 (3.2–3.8)	8.8 (8.8–8.9)§
15	12.3 (10.5–13.4)§	8.7 (8.7–9.9)§‖	3.7 (3.5–3.8)*	2.8 (2.6–2.9)*	1.5 (1.5–1.6)	4.1 (3.9–4.2)*	7.7 (7.7–7.8)§

Data are presented as median (interquartile range).

* $P < .001$ vs C5.

† $P < .001$ vs V680.

‡ $P < .001$ vs Carescape.

§ $P < .001$ vs ServoU.

‖ $P < .001$ vs PB980.

for C5 (0.040 [0.040–0.070] s) and PB980 (0.040 [0.040–0.055] s) were in between.

Linear Fixed Resistance of the Expiratory Valve

The linear fixed resistance was significantly different between PEEP and ventilators with a significant interaction between them. Between ventilators at each PEEP, it was consistently < 5 cm H_2O/L/s with Carescape, PB980, ServoU, and V500, and with C6 at 5 cm PEEP and it was > 5 cm H_2O/L/s with the others (Table 1). The time spent with a defined linear fixed resistance as the percentage of expiratory length was $< 5\%$ for C5, C6, Carescape, and V500, and it was $> 15\%$ for ServoU, PB980, and V680, with no significant effect of PEEP.

Measured PEEP

PEEP measured just before the closure of the expiratory valve was in the 10% range of the set value in every ventilator and tended to be lower than set with the V500 ventilator and higher than set in the others (not shown). To investigate the correlation between PTP and instantaneous resistance, we normalized this latter for that of C6, which was the lowest at each PEEP. We found a significant negative correlation between PTP_{below} and normalized R_{median} (rho $=$ -0.81 [–0.92 to –0.59], $P < .01$) and between PTP_{below} and normalized R_{min} (rho $=$ –0.70 [–0.87 to –0.39], $P = .04$). No other significant correlation was found.

Discussion

The main finding of the present study is that the resistance of the expiratory valve of current ICU ventilators was markedly different between the devices tested.

Methodological Considerations

During passive spontaneous expiration to the atmosphere in an intubated and sedated patient, flow is generated by the elastic recoil of the respiratory system, which overcomes the resistance of the airways and the equipment (eg, endotracheal tube, ventilator circuit, and expiratory valve). The ventilator does not control the flow, and this explains the shape of the expiratory flow with a peak followed by a progressive reduction to the next insufflation. The PEEP setting operates through the interaction of a pneumatic component (eg, a diaphragm or membrane) and an electronic control managed by software. In this study, we analyzed in detail the resistance of the expiratory valves of current ICU ventilators. The valve does not behave like a pure threshold resistor. With such functioning, once the inspiratory valve closes, the expiratory valve should immediately open, reach the PEEP, and adjust its resistance to maintain P_{aw} at the PEEP value up to the next inspiration. First, there is a time lag for the expiratory valve to open due to the time between the passive gas decompression of the ventilator circuit and the elimination of the gas that compresses the membrane. The valves that are used in the ICU ventilators tested are all electromagnetic (ie, solenoid) valves.[12] A magnetic field is generated by an electric current in a coil that in turn moves a needle along a distance proportional to the current intensity. The needle compresses the membrane with a magnitude that depends on the PEEP setting and is driven by a microprocessor. We measured the opening time of the valve as the time between the first zero flow after insufflation (ie, when both inspiratory and expiratory valves are closed) to a time point at which flow becomes stable while pressure continues to decrease. Four of the ventilators had opening times < 0.1 s, and 3 had opening times equal to or greater than this value. The differences we found in this opening time may be due to the method we used: for the ventilators with shortest opening delay, this time point of apparent stabilization of the valve occurred at the time the first breakpoint was automatically determined; in the others, it took additional milliseconds to reach the time point of apparent stabilization. Another reason for the difference in opening times may also come from the type of motor controlled by the microprocessor that governs the opening of the valve (eg, piston, stepper motor, or rotating ball). In addition, electromagnetic valves are proportional to flow and operate by constantly adjusting the instantaneous expiratory flow resistance to control P_{aw}. This results in variable resistance of the expiratory valve. Our computation of instantaneous expiratory resistance attempted to capture this phenomenon. Our use of the median value of the instantaneous resistance of expiratory valve then makes sense. We noted differences between the ventilators and an effect of PEEP, but there was an interaction between them. This suggests that the effect of a ventilator on expiratory resistance was different at different PEEP setting. Interestingly, the 2 ventilators of the same brand (C5 and C6) had similar values of expiratory valve resistance. It is worth emphasizing the meaning of instantaneous expiratory resistance. The values were much higher than expected. However, these values reflect the process of adjustment that the microprocessor undertakes to try to maintain P_{aw} at the PEEP value during expiration. The microprocessor constantly adjusts the degree of closing and opening and is rarely in a stable state. The partial success of this procedure explains why P_{aw} is below or above the set PEEP at various parts of the expiration and for various lengths of time. We attempted to describe this by computing PTP_{below} and PTP_{above}. PTP_{above} corresponds to the effect of over-resistance of the valve, which slows down expiration. PTP_{below} corresponds to the effect of under-resistance of the valve, which does not permit the ventilator to maintain P_{aw} at the PEEP level. As expected, we found a relationship between PTP_{below} and R_{median} or R_{min} normalized for the lowest value across the 7 ventilators. This relationship, combined with the fact that PTP_{above} and PTP_{below} seem to be very little affected by the PEEP for each ventilator, suggests that the sum of PTP_{above} and PTP_{below} constitutes an index that characterizes the ability of the ventilators to continuously adjust the valve resistance to minimize the swing of P_{aw} around PEEP throughout expiration. Therefore, ServoU, Carescape, and V500 seem to be the ventilators that best control the valve resistance during expiration.

We attempted to identify a phase during expiration within which the magnitude of the valve aperture was stable. We did that by using an unbiased method and by defining this time frame as having a concurrent decrease in flow and in pressure. Differences were found between the ventilators regarding not only the value of the expiratory resistance but also the fraction of time spent with the valve in a stable position during expiration.

The active nature of the expiratory valve facilitates expiration in case of assisted breathing. Jiao and Newhart[13] conducted a bench assessment in 4 ICU ventilators to test this, reporting differences between ventilators in terms of pressure overshoot during the expiratory effort. They measured expiratory resistance with the EvitaXL and the Servo-i ventilators and noted values of 6.6 and 3.0 cm H_2O/L/s, respectively. These values were higher than in our study for ventilators of the same brands (ie, V500 and ServoU respectively), probably because Jiao and Newhart[13] used the pressure overshoot. Nevertheless, we found the same type of the difference between the 2 devices in our study.

Clinical Implications

The fact that P_{aw} (ie, P_{ev}) is not constant during expiration and spends some time below the PEEP suggests that some de-recruitment may occur during these periods. This, coupled with periods of P_{aw} above the PEEP, results in a swinging pattern of P_{aw}. While these periods are short, they are repeated, and the succession of opening and closing of the lung may promote shear stress and atelectrauma. There are no data to support this hypothesis, and whether this finding can explain negative trials comparing lower and higher PEEP is purely speculative; however, our results indicate that the ventilators distribute the P_{aw} differently during expiration regardless of its final value (ie, PEEP). A new option in passive mechanical ventilation was recently introduced in a prototype that controlled flow during expiration to make it square-shaped, similar to what is seen during constant flow insufflation in the volume controlled mode.[14] The aim was to slow expiration and avoid abrupt drops in pressure. Preclinical studies reported physiological benefits in terms of oxygenation and de-recruitment prevention in subjects with acute lung injury.[15] These results suggest that the ventilators with a minimal PTP_{below} are more suitable for this kind of patient.

Another clinical implication of our findings relates to the determination of expiratory flow limitation during mechanical ventilation. Expiratory flow limitation defines a situation in which expiratory flow does not increase after an increase in expiratory driving pressure. This is a cardinal feature in patients with COPD but also in those with ARDS.[16-18] Expiratory flow limitation assessment in patients with ARDS has value because it is frequent, can be used to set PEEP,[19] and may be associated with patient outcome.[20] There are basically 2 methods to assess expiratory flow limitation during mechanical ventilation: the atmospheric method, and a small change in PEEP. The former may increase the risk of de-recruitment. Our results suggest that the second method may be limited by the resistance of the expiratory valve, which varies during expiration at a given PEEP, between PEEP levels, and across ventilators.

Of course, depending on the type of patient, a specific expiratory valve may be more or less appropriate. If there is a risk of de-recruitment or a risk of expiratory flow limitation, a system with a PTP_{below} as low as possible seems to be something to look for independently of the value of PTP_{above}. By contrast, a highly resistive patient without de-recruitment risk but with the need of some help at expiration could benefit from a system with a PTP_{above} as low as possible associated with a non-negligible PTP_{below}. The opening and closing time of the valve may also be a key patient-dependent point. Indeed, to maintain P_{aw} at the PEEP, the valve adjustment should be made as quickly as the expiratory flow variations. In other words, the time constant of the patient should not be too small in relation to the typical opening and closing time of the valve.

The current COVID-19 pandemic has stretched the resources of health care systems as never before, and has led to a shortage of ICU ventilators.[21] To meet the increased demand for ventilators and to equip low- and middle-income countries, there is a rush to deploy a large volume of inexpensive ventilators that are mostly dedicated to non-invasive ventilation with a single-limb ventilator circuit.[22] Because an expiratory valve is an essential component of an ICU ventilator, it is important to assess the expiratory valve function in these ventilators, especially considering the further waves of the pandemic and future pandemics due to other microorganisms are expected.

Limitations

Our study has limitations inherent to all bench assessments. While it is not possible to design a clinical study evaluating all of the ventilators with the same subject to determine the clinical relevance of our findings, this could be done in an animal model. Furthermore, electrical impedance tomography to monitor lung volume during expiration could be used to compare subjects randomly allocated to the 2 ventilators with the most contrasting results in our study in terms of expiratory resistance.

Conclusions

This results of our bench assessment indicate that the resistance of the active expiratory valve differed significantly between ICU ventilators used in current practice.

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