A Comparison of Proximal and Tracheal Airway Pressures During Pressure Controlled Ventilation

Mark O Zander, Nikola Stankovic, Mirko Meboldt, Thomas O Erb, Jürg Hammer, and Marianne Schmid Daners

BACKGROUND: Airway pressure is usually measured by sensors placed in the ventilator or on the ventilator side of the endotracheal tube (ETT), at the Y-piece. These remote measurements serve as a surrogate for the tracheal or alveolar pressure. Tracheal pressure can only be predicted correctly by using a model that incorporates the pressure at the remote location, the flow through the ETT, and the resistance of the ETT if the latter is a predictable function of Y-piece flow. However, this is not consistently appropriate, and accuracy of prediction is hampered. METHODS: This in vitro study systematically examined the ventilator pressure in dependence of compliance of the respiratory system (C_{RS}), inspiratory time, and expiratory time during pressure-controlled ventilation by using a small intratracheal pressure sensor and a mechanical lung simulator. Pressures were measured simultaneously at the ventilator outlet, at the Y-piece, and in the trachea during pressure-controlled ventilation with a peak inspiratory pressure of 20 cm H_2O and a PEEP of 5 cm H_2O while changing C_{RS} (10, 30, 60, 90, and 100 mL/cm H_2O) and varying inspiratory time and expiratory time. RESULTS: Tracheal pressures were always lower (maximum 8 cm H_2O during inspiration) or higher (maximum 4 cm H_2O during expiration) than the pressures measured proximal to the ETT if zero-flow conditions were not achieved at the end of the breathing cycles. CONCLUSIONS: Dependent on C_{RS} and the breathing cycle, tracheal pressures deviated from those measured proximal to the ETT under non–zero-flow conditions. Intratracheal pressure and pressure curve dynamics can differ greatly from the ventilator pressure, depending on the ventilator setting and the C_{RS}. The small pressure sensor may be used as a measurement method of tracheal pressure via integration onto an ETT. *Key words: invasive ventilation; pressure-controlled ventilation; intratracheal pressure; respiratory system compliance; intratracheal pressure sensor; mechanical lung simulator.* [Respir Care 2023;68(12):1639–1645.

Introduction

Common contemporary ventilator monitoring includes numeric and graphic information of flow, pressure, and volume over time. The underlying sensors are usually placed in the ventilator or at the proximal end of the endotracheal tube (ETT), the Y-piece.[1] Hence, ventilator pressure measurements are only a surrogate for the actual airway pressure in the trachea.[2,3] The difference is mainly dependent on the ETT resistance (eg, inner diameter, bending, tube obstruction). Numerous models were developed to estimate the intratracheal pressure, compliance of the respiratory system (C_{RS}), and resistance during ventilation.[4-6] However, in clinical practice, ETT resistance as well as C_{RS} can vary over time to an unknown extent and the actual tracheal pressure may deviate considerably from the proximal airway pressure shown on the ventilator monitor.[7] This study intends to increase clinicians' awareness of the importance of zero-flow conditions for setting the ventilator during pressure-controlled ventilation.

The shortage of ventilators at the beginning of the COVID-19 pandemic initiated many development projects of pandemic (low-cost) ventilators.[8] Such ventilators would consist of only the most necessary functionalities and may lack advanced safety, control, and monitoring systems.[9] However, clinicians rely on numerical and graphic patient data from the ventilator to set ventilator parameters correctly according to the underlying condition.[10-12] The present study was initiated to investigate a possible integration of intratracheal pressure measurement into the respiratory monitoring of patients who are invasively ventilated. In contrast to previous studies,[1,7,13-18] a small pressure sensor was used and secured to the endotracheal tube (ETT) tip (given the size of available sensors and connection of the transducer via an ultrathin flexible printed circuit board).

The intratracheal pressure measurement may serve to provide more accurate instantaneous information on the delivered airway pressure. Ultimately, this may improve insight in respiratory mechanics and would enable the continuous calculation of driving pressure. The current in vitro study investigated the intratracheal pressure in dependence of target pressure set on the ventilator, the C_{RS}, and of inspiratory time (T_I) and expiratory time (T_E) during pressure-controlled ventilation.

Methods

Experimental Test Setup

The experimental test setup in Figure 1 consists of the mechanical lung simulator TestChest (TestChest V3, Organis, Landquart, Switzerland) connected via an ETT (Parker Flex-Tip PFHV, Parker Medical, Danbury, Connecticut) with an inner diameter of 7.5 mm and a 1.8-m-long inspiratory and expiratory tubing (QTube, Envisen Industry, Shenzhen, China) to a commercial ventilator (GE Engström, General Electric, Boston, Massachusetts) driven in the pressure-controlled ventilation mode. The measurement apparatus consists of one flow sensor (SFM3019, Sensirion, Stäfa, Switzerland) and 3 pressure sensors (BME280, Bosch, Stuttgart, Germany). The pressure sensors with the dimension 2.5 mm × 2.5 mm × 0.93 mm and an accuracy of 0.2 Pa were connected via a flexible printed circuit board to the electronic hardware. The TestChest can mimic different lung mechanics by varying the C_{RS} and airway resistances.[9,19-21] Three pressure sensors were placed at the outlet of the ventilator, at the Y-piece, and inside the trachea to measure the ventilator pressure, Y-piece pressure, and intratracheal pressure. The flow sensor was placed at the Y-piece.

Test Procedure

The experiments were performed under laboratory conditions by using compressed room air (21% oxygen, 21°C). The C_{RS} was set to 5 different values, 10, 30, 60, 90, 100 mL/cm H_2O, and the TestChest airway resistance was set to a constant value of 5 cm H_2O/L/s. The TestChest defines a C_{RS} = 60 mL/cm H_2O and airway resistance = 5 cm H_2O/L/s as healthy physiologic conditions. The peak inspiratory pressure (PIP) and PEEP values were set to 20 cm H_2O and 5 cm H_2O, respectively. The PIP and PEEP are synonymously considered as target pressures during the respective breathing phase in the following. T_I and T_E were varied according to the settings S1-S9 in Table 1. The ventilator pressure rise time was 100 ms. For each test, one setting (either the ventilator settings T_I and T_E or the TestChest C_{RS}) was varied consecutively, which resulted in 45 sets of measurements.

QUICK LOOK

Current knowledge

In non–zero-flow conditions, the intratracheal pressure is different to the pressure measured at the ventilator. Mathematical formulas can approximate the intratracheal pressure. Only a few previous studies have measured intratracheal pressure during invasive ventilation, mostly in vitro.

What this paper contributes to our knowledge

This study represents comprehensive data with a graphic illustration of the impact of a wide range of compliance conditions and inspiration and expiratory time on tracheal pressure. It shows in detail the difference of the pressure at the ventilator and the trachea for non–zero-flow conditions. We demonstrate a measurement method of tracheal pressure for the integration onto an ETT.

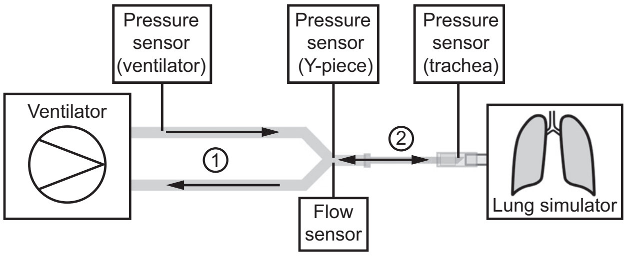

Fig. 1. The experimental components include the ventilator, the mechanical lung simulator TestChest, inspiratory and expiratory tubing (1) and an endotracheal tube (2). Three pressure sensors were placed at the outlet of the ventilator, at the Y-piece, and inside the trachea. A flow sensor was placed at the Y-piece.

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Table 1. Ventilator Settings: Inspiratory Time, Expiratory Time

Setting	Inspiratory Time, s	Expiratory Time, s
S1	3.00	3.00
S2	1.50	1.50
S3	1.00	1.00
S4	2.00	4.00
S5	1.00	2.00
S6	0.67	1.33
S7	1.50	4.50
S8	0.75	2.25
S9	0.50	1.50

Data Recording, Signal Processing, and Data Analysis

The flow and pressure sensors were connected via cables and a multiplexer (Adafruit TCA9548A 1-to-8 I2C, Adafruit Industries, New York, New York) to a printed circuit board (Arduino Mega 2560, Arduino, Ivrea, Italia). The signals were recorded by using MATLAB (MathWorks, Massachusetts) at a sampling rate of 135 Hz for 60 s to guarantee recording of at least 10 breathing cycles per test setting. Data were processed by using MATLAB. A frequency analysis was conducted, and a filter (second-order low-pass Butterworth filter with a cutoff frequency of 1/15 Hz) was applied to both pressure and flow signal. The parameters of interest (Fig. 2) were identified and averaged over 9 breathing cycles for each setting. The PIP was defined as the maximum pressure value of each breathing cycle.[22] The inspiration and expiration phase were derived from the flow signal. The PEEP was defined as the average pressure over the last 50 ms of the expiration.[10,23]

The T_{IRtr} was defined as the ratio between the time when the PIP is reached in the trachea during inspiration (T_{PIPtr}) and the inspiration time (T_I) (Equation 1). The T_{ERtr} was defined as the ratio between the time when the PEEP is reached in the trachea during the expiration phase (T_{PEEPtr}) and the expiratory time T_E (Equation 2). In case the target pressure is not reached during either phase, the T_{IRtr} or the T_{ERtr} is equal to 100%.

$$T_{IRtr} = (T_{PIPtr}/T_I) \times 100 \tag{1}$$

$$T_{ERtr} = (T_{PEEPtr}/T_E) \times 100 \tag{2}$$

Results

The pressure time curves measured at 3 different measurement locations for ventilator setting S5 and for 5 different C_{RS} of 10, 30, 60, 90, and 100 mL/cm H_2O are presented in Figure 3A-E, respectively. Results of the remaining 8 ventilator settings are given in the supplementary material (Supplementary Figures S1–S8, see the supplementary materials at http://www.rcjournal.com). The difference between PIP and PEEP at each measurement location decrease with increasing C_{RS}.

At the ventilator outlet and the Y-piece, the length of the plateaus increases with increasing C_{RS}. The ventilator pressure and Y-piece pressure curves are similar for all C_{RS}. When depending on the C_{RS}, the intratracheal pressure differs markedly from the ventilator pressure and Y-piece pressure curves. The inspiratory intratracheal pressure for ventilator setting S5 does not reach the PIP for $C_{RS} \geq 60$ mL/cm H_2O but increases throughout the entire inspiration and the flow remains positive.

The expiration pressure gradient (slope of the pressure curve) is negative and decreases with increasing C_{RS} at each measurement location. The time when the PEEP is reached (T_{PEEP}) increases with increasing C_{RS}. For $T_E \leq 1.5$ s and $C_{RS} \geq 60$ mL/cm H_2O, the measured intratracheal pressure remains above the target PEEP value, and the difference is

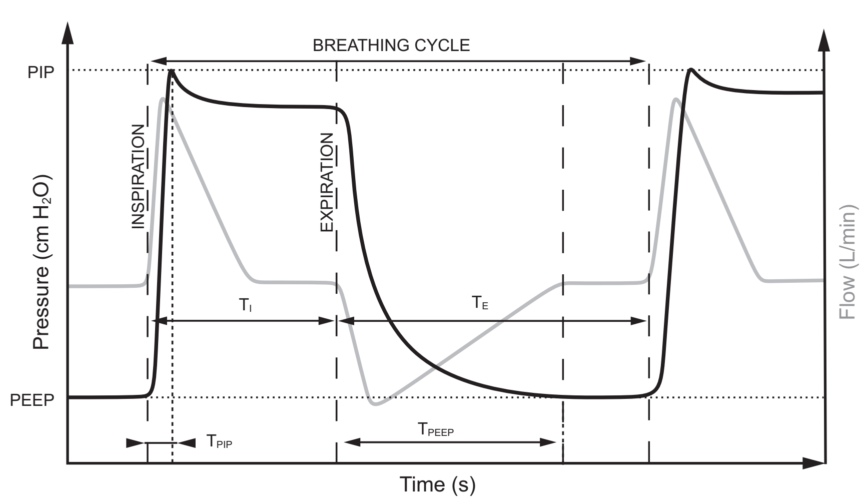

Fig. 2. Schematic pressure and flow curves over time with indicated points of interest: peak inspiratory pressure (PIP), time to reach PIP (T_{PIP}), inspiration time (T_I), PEEP, time to reach PEEP (T_{PEEP}), and expiratory time (T_E).

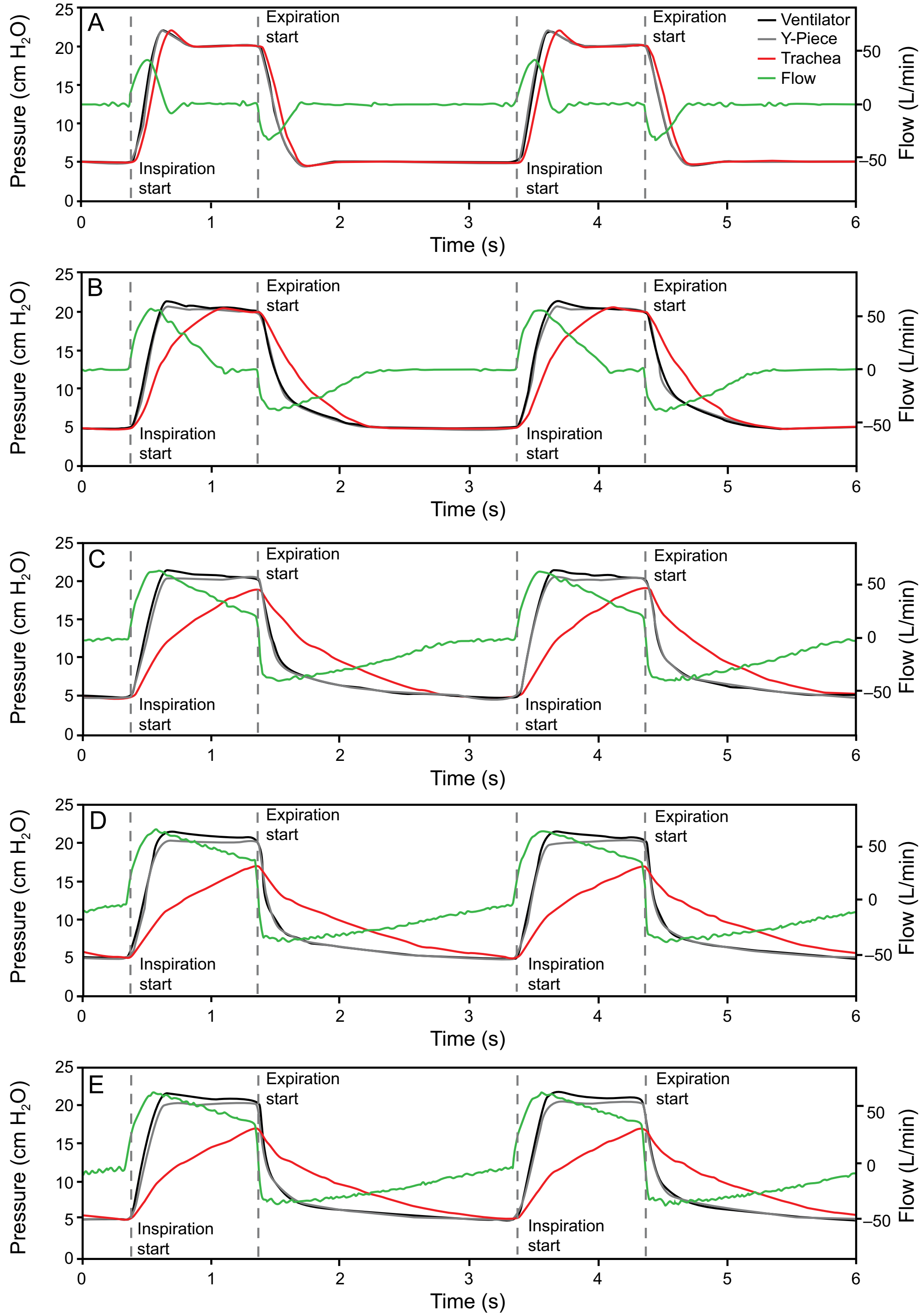

Fig. 3. The pressure curves of 2 breathing cycles (inspiration and expiration) at the 3 measurement locations ventilator, Y-piece, trachea, and the corresponding flow profile. The ventilator settings are unchanged for each plot: peak inspiratory pressure (PIP) = 20 cm H_2O, PEEP = 5 cm H_2O, T_I = 1 s and T_E = 2 s and lung airway resistance of 5.1 cm H_2O/L/s. The respective compliances of the respiratory system (C_{RS}) in panels A, B, C, D and E correspond to 10, 30, 60, 90, 100 mL/cm H_2O, respectively. The start of inspiration and expiration are indicated by vertical dashed lines.

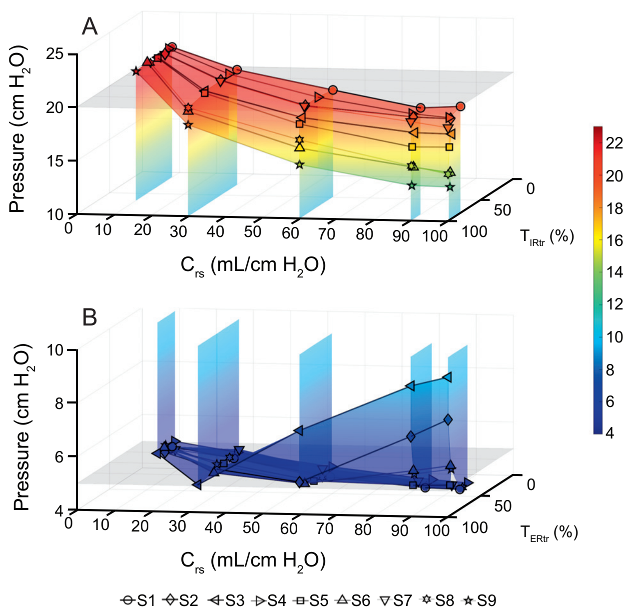

Fig. 4. Three-dimensional (3D) plot of the tracheal peak inspiratory pressure (PIP_{tr}) and time ratio T_{IRtr} (A), and the PEEP ($PEEP_{tr}$) and time ratio T_{ERtr} (B) over the TestChest compliance of the respiratory system (C_{RS}) for the ventilator settings S1–S9. The target pressure values of 20 cm H_2O for inspiration and 5 cm H_2O for expiration are indicated by the gray planes. The PIP_{tr} values decrease and the T_{IRtr} values increase for increasing C_{RS}. The target $PEEP_{tr}$ is reached for most ventilator settings except for settings S2, S3, and S6. However, the T_{ERtr} increases with increasing C_{RS} for each ventilator setting. Additional 3D representations are provided as supplementary material (see the supplementary materials at http://www.rcjournal.com).

increased with shorter T_E, which results in higher end-expiratory flow. The expiratory pressure curve progression of ventilator pressure and Y-piece pressure are similar for all C_{RS} and ventilator settings. The expiratory pressure gradient in the trachea is smaller than at the ventilator and Y-piece.

With increasing C_{RS}, the tracheal PIP (PIP_{tr}) decreases progressively as long as T_I is kept constant and below a value to reach zero flow and T_{IRtr} increases toward a value of 1 (Fig. 4A). The PIP_{tr} decreases with a shorter T_I. At low C_{RS}, the PIP_{tr} is similar for all ventilator settings (~22 cm H_2O) and the T_{IRtr} differs markedly. At high C_{RS}, this is the exact opposite, the T_{IRtr} values are similar (equal or close to 1) and the pressures differ markedly. Additional movies of Figure 4A and B are provided as supplementary material (see the supplementary materials at http://www.rcjournal.com).

The tracheal PEEP ($PEEP_{tr}$) values and the T_{ERtr} values increase for increasing C_{RS} (Fig. 4B) as long as T_E is kept constant and below a value to reach zero flow. T_E increases for each ventilator setting with increasing C_{RS}. With increasing C_{RS}, a shorter T_E results in an increased PEEP and T_{ERtr} close or equal to 100%. Under conditions with low C_{RS}, the $PEEP_{tr}$ values are similar for all ventilator settings at ~5 cm H_2O. Nonetheless, the T_{ERtr} differ markedly. In contrast, under the condition of C_{RS} 100 mL/cm H_2O, the T_{ERtr} values are similar (equal or close to 1) and the pressure varies greatly. The $PEEP_{tr}$ increases with decreasing T_E.

Discussion

This in vitro investigation shows the deviation of pressures measured at different locations of the ventilation system with a large number of exemplary ventilator settings. The influence of C_{RS} and of T_I and T_E was analyzed by using a small pressure sensor. The pressure set at the ventilator and the tracheal pressure only match when zero flow ($T_{IRtr} < 100\%$ or $T_{ERtr} < 100\%$) conditions are achieved. When depending on the C_{RS}, the time required to reach zero-flow conditions in both inspiration and expiration may vary widely.[13] The lower the C_{RS}, the shorter is the time to achieve this. This is illustrated with our experiments. Whereas various factors, such as the diameter or length of the tube,[4] tube connectors, or secretions, have been previously assessed,[13,14] a systematic presentation of their interaction with a wide range of various C_{RS} was never examined.

Zero flow at the end of inspiration or expiration implies a pressure equilibrium across the ETT. Only under this condition, pressure measurements located proximal to the tube reflect the intratracheal pressure accurately. This must be respected when setting T_I and T_E in pressure-controlled ventilation. Nevertheless, in patients with changing respiratory conditions and ETT characteristics, this perfect match of ventilator settings and respiratory system mechanics is hardly permanently achieved. We demonstrate that, under conditions with non-zero flow, the extent of the difference between the pressure measured at the ventilator and the pressure present in the trachea remains obscure. This study shows the pressure difference among the various measurement locations along the breathing circuit in greater detail.

A T_{IRtr} or T_{ERtr} value of 100% indicates a non-zero flow and continuous pressure increase or decrease inside the trachea throughout the entire inspiration or expiration, respectively. The slope of the pressure curves inside the trachea and the ventilator can differ drastically, depending on C_{RS}. Although, in the pressure-controlled mode, the pressure curve at the ventilator is of a rectangular shape, the pressure curve in the trachea shifts from a similarly rectangular curve at low C_{RS} toward a triangular curve at high C_{RS}. For high C_{RS}, intratracheal pressure did not reach the respective target pressure for most T_I values that were set in this experiment. Although this relationship is theoretically well known, the extent to which intratracheal pressure actually differs from the ventilator pressure remains ambiguous. In practice, there is no point in prolonging the T_I beyond the time required to achieve zero-flow conditions to achieve the set inspiratory pressure. This will not increase the tidal volume but may result in prolonged lung loading. Conversely, if zero-flow conditions are not achieved, then prolonging the T_I

will increase the tidal volume. Similarly, if zero-flow conditions are not achieved during expiration, then breath-stacking may occur and cardiovascular function may be compromised.

Changes of C_{RS} translate to alterations of the time constant and thus have implications for both inspiration and expiration. When considering the approximation of the lung as a linear one-compartment model, the accuracy of the time constant fits best in healthy lungs.[24] However, changes in breathing frequency, tidal volume, mean lung volume, viscoelastic properties, inhomogeneities in ventilation, and nonlinearities of plastic behavior lead to changes of resistance and compliance that cannot be described precisely with a single time constant.[10] For the understanding of the mechanical consequences of different respiratory conditions, defining the determinants of the time constant remains fundamental; however, maneuvers such as inspiratory or expiratory hold are not always feasible and provide, at best, a temporary idea.[25] Identifying a correlation between static and dynamic tracheal pressures may obviate the need for an inspiratory or expiratory hold to determine static pressures and lung mechanics.[7] However, this was not examined in the present study and may be part of future research. Continuous measurement of the tracheal pressure may facilitate assessments of respiratory system mechanics and, therefore, may simplify efforts to optimize ventilator settings, especially under changing conditions.[7,25]

Several in vitro and in vivo studies investigated the relationship among intratracheal pressure, ventilator pressure, and Y-piece pressure during mechanical ventilation in healthy and diseased lungs of adults and children.[4,26-30] The effects of various ETT sizes, ETT lengths, and lung characteristics on intratracheal pressure or using intratracheal pressure as a trigger to reduce work of breathing or as a control input have been examined.[4,28,31,32] Based on that, a coefficient-based model was developed that takes into account the flow, gas composition, breathing frequency, and the general ETT shape and diameter. Although the accuracy of such a model is generally good, aspects such as changes in the patency of the ETT (kinking, conformation changes, secretion obstruction) were not considered. Hence, direct measurement of intratracheal pressure in vivo may be more accurate and independent of flow direction than such calculations.

So far, intratracheal pressure was measured by using a sidewall opening in the ETT or a catheter placed through the ETT into the trachea.[4,27,29,30,32] The described catheter method is limited by its diameter, is prone to become occluded by secretions,[28] and impedes regular respiratory care, for example, suctioning. Integrating pressure sensors into clinical practice is hampered by sensor contamination and moisture. These are major barriers to integrating invasive pressure sensors (inside the trachea or the esophagus) into conventional ventilators.[33] Due to its small size, such pressure sensors as used in the present study could potentially be incorporated into the ETT for in vivo use. An accurate and continuous airway pressure measurement at the level of the trachea may simplify reliable monitoring of lung mechanics during the entire respiratory cycle and could enable optimization of ventilator settings (personalized ventilation management). A potential advantage of measuring tracheal pressure during mechanical ventilation is the option to continuously calculate dynamic compliance accurately.[7,15]

Our study confirmed the differences between ventilator pressure or Y-piece pressure versus intratracheal pressure during pressure-controlled ventilation as observed in previous work.[2,7] The availability of sensors of small size connected via flexible printed circuit boards allows the fixation to the ETT tip (eg, mounting by using an additive manufactured part or direct integration in the tube). However, the pressure sensor's robustness when exposed to intratracheal conditions, such as humidity or secretions, must still be evaluated. Previous attempts of continuous measurement of intratracheal pressures by using tubes with embedded pressure-measuring lumen in the tube sidewall or passing a low-compliant air-filled pressure line through the lumen of the tube proved to be cumbersome and prone to failure in the clinical setting.[7,32] Therefore, application to clinical use did not occur, although potential advantages, for example, improved patient-ventilator synchrony, were demonstrated.[28] Robust functioning during long-term application still needs to be confirmed in vivo. The continuous intratracheal pressure measurement may serve as a potential control parameter.

One limitation of our study is that the TestChest is a 2-bellows mechanical lung model that mimics the lung only to a limited extent. The internal lung model had an impact on the observed results and the findings deserve further validation in vivo. Furthermore, we did not examine the effect of the respiratory system resistance and did not include possible clinical scenarios, for example, tube obstruction caused by kinking or secretions.

Conclusions

With this study, we intend to increase awareness of the actual tracheal pressures during pressure-controlled ventilation, especially when ventilation parameters do not allow zero flow at the end of inspiration and expiration. Our intratracheal pressure measurement method may be an option for monitoring purposes and could be used as a control input.

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