Lung mechanics at the bedside: make it simple

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Purpose of review

The aim of this review is to describe ventilator–patient interaction, employing the equation of motion and the curves obtained by the ventilator. Practitioners confronted with mechanically ventilated patients every day in intensive care units should be able to sort out from all data available from modern ventilators those relevant for choosing a correct ventilatory strategy for each patient.

Recent findings

Early determination of patient–ventilator asynchrony, air-leaks and variation in respiratory parameters is important during mechanical ventilation. A correct evaluation of data, for patient safety and tailored ventilatory strategy becomes mandatory when non-invasive ventilation by helmet or mask is applied.

Summary

The equation of motion is described and dynamic and static respiratory mechanics are analysed to highlight all those data that can influence decision-making in setting mechanical or assisted ventilation in invasively and non-invasively ventilated patients.

Keywords

flow and pressure trigger, patient-ventilator asynchrony, respiratory monitoring

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Abbreviations

LSF	least square fitting
PCV	pressure controlled ventilation
PEEP	positive end expiratory pressure
PEEPi	intrinsic positive end expiratory pressure
PSV	pressure support ventilation

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Introduction

A lot of data can be obtained from patients mechanically ventilated: measurements of respiratory mechanics can be performed in intensive care in dynamic (no flow interruption) or static (occlusion techniques) conditions. Compliance and resistance can be recorded, while pressure, flow and volume are continuously monitored at the bed side (we will focus on these readily available data instead of more aggressive forms of monitoring such as esophageal pressure). Correct interpretation of data and selection of the right parameter to monitor is crucial for a safe clinical approach to the patient who requires mechanical ventilation. Some clinical examples will be shown, to help the reader to apply in clinical practice the concepts explained.

Equation of motion

Modern ventilators employed in intensive care units display in real time and breath by breath flow ($\dot{V}$), volume (V) and pressure at the mouth (Pa_o) curves, both as a function of time and as a loop. Data obtained from curve analysis help understanding the interaction between patient and ventilator.

Assisted ventilation can be total, partial or absent, depending on respiratory muscles' ability to generate the pressure applied to the respiratory system (P_{rs}).

P_{rs} of a ventilated patient is the sum of the pressure generated by the ventilator Pa_o and the pressure developed by the respiratory muscles (P_{mus}). The latter is negative, as inspiratory muscles act by producing a decrease in pressure below the airways, as described by the equation of motion [1,2].

$$P_{rs} = Pa_o + (-P_{mus}) = \dot{V} \times R + \frac{V}{C} + k$$

where V is the volume, $\dot{V}$ the flow over time, and k is a constant representing the alveolar end expiratory pressure.

The term $\dot{V} \times R$ corresponds to the pressure dissipated across the airway and the endotracheal tube, to overcome the frictional forces generated with gas flow (P_{res}). The rate of P_{res} and $\dot{V}$ defines the resistance of the respiratory system (R_{rs}).

The term V/C, on the other hand, corresponds to the pressure that must be applied to overcome elastic forces (P_{el}), and depends on both the volume insufflated in excess on resting volume (V_r), and on the respiratory system compliance (C_{rs}).

The constant k takes into account the application of positive end expiratory pressure (PEEP) or intrinsic PEEP (PEEPi), if present.

When the patient's breathing activity is entirely passive, P_{mus} is negligible, and the driving pressure necessary to move air in and out of the thorax can be described by the simplified equation of motion:

$$P_{rs} = Pa_o = \dot{V} \times R + \frac{V}{C} + k$$

In summary, a single breath is the expression of three known variables (pressure, flow and volume) and three related factors (R, C and k), as described by the equation of motion.

Actually R, C, PEEP or PEEPi as dynamic properties of the respiratory system (no flow interruption) can be estimated by mathematical resolution of the equation of motion by application of the least square fitting (LSF) method or by occlusion techniques in a static condition.

Dynamic mechanics

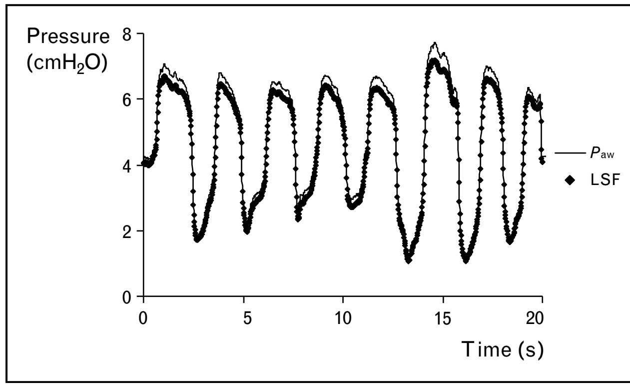
Dynamic mechanics may be derived during spontaneous breathing and in intubated patients in partially or totally supported ventilation [3,4]. The LSF method does not require flow interruption or a peculiar inspiratory flow pattern, it can be applied during the whole breathing cycle or only in the inspiratory or expiratory phase. In patients with flow limitation LSF analysis has to be restricted to the inspiratory phase to avoid unrealistic results [5,6]. An immediate advantage of LSF is the capability to check the ''goodness of fit'' of the pressure curve obtained from the equation of motion superimposed on the Pa_o pressure in real time (Fig. 1).

In patients ventilated with partial support the real time analysis of displayed curves can give much information.

Pressure support ventilation is the most used form of assisted ventilation designed to provide inspiratory support to spontaneously breathing patients. Patient–ventilator synchrony is achieved using a flow or pressure trigger system.

In a pressure trigger mode the ventilatory support detects the drop in airway pressure that occurs during inspiratory efforts that has to overcome the set threshold value. Usually values of 0.5–1 cmH_2O are employed during assisted ventilation, but it is possible to set higher threshold values, up to -20 cmH_2O. Inappropriate trigger sensitivity may lead to increased work of breathing, delaying weaning, or to patient–ventilator dyssynchrony, and subsequent need for sedation [7]. In patients with dynamic hyperinflation the respiratory effort value to trigger the pressure support is the sum of the set pressure and the PEEPi [8–10,11•].

Figure 1 The pressure curve provided by the equation of motion (rhomboidal dots) is compared to measured airway pressure displayed on the ventilator



LSF, least square fitting.

In Fig. 2 pressure, flow and volume waves during pressure support ventilation are shown. Data were obtained during a weaning trial in a pig.

At first the triggering threshold is set at -0.5 cmH_2O, and it is gradually increased up to -20 cmH_2O. As triggering sensitivity is reduced the number of inefficient respiratory efforts increases (no volume is delivered after the inspiratory effort).

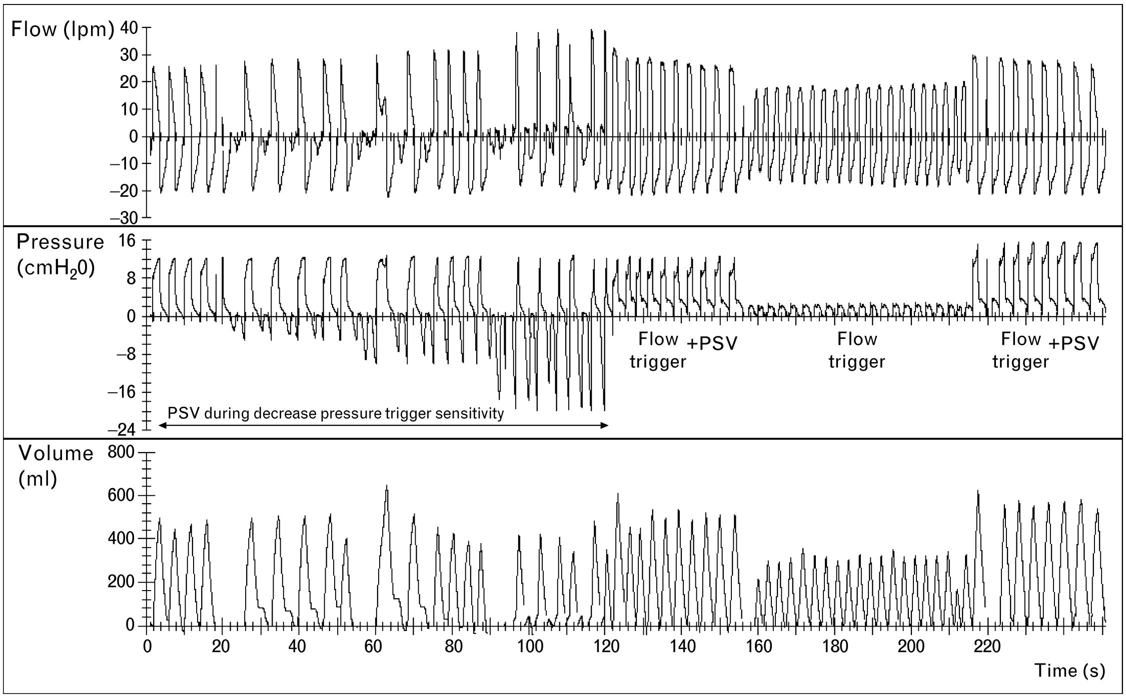
Swithcing the trigger from pressure to flow produces immediate disappearance of negative pressure deflexion and allows the patient to synchronize with the ventilator.

In the end (last part of Fig. 2) pressure support is reset to zero and the animal is spontaneously breathing, uptaking bias flow from the respiratory circuit.

When the patient is spontaneously ventilating in a flow trigger mode, the inspiratory phase shows pressure values close to zero because the ventilator is making up for the volume inspired by the patient; when the patient exhales air into the circuit, positive air pressure is recorded because the expired volume is summed to the bias flow (for a more detailed figure see Fig. 4).

During flow trigger a continuous flow of gas is accessible by the patient and is vented *in toto* through the expiratory tubing unless the patient makes an inspiratory effort. In flow triggering, a continuous flow of gas is sent through the ventilator circuit. The ventilator senses the patient's inspiratory efforts by detecting a change in bias flow irrespective of any significant negative pressure [12–15].

Figure 2 Trend of curves shown by the ventilator display during pressure support ventilation and decreased pressure trigger sensitivity (arrows)



Inspiratory effort is evidenced by negative pressure deflexion measured at the mouth. When flow trigger is employed no inspiratory effort is detectable (flow trigger + pressure support ventilation (PSV)). After some respiratory acts pressure support is withheld (flow trigger) and then restored.

The advantages of flow triggering are less inspiratory workload and more sensitivity, but sometimes it leads to triggering the ventilatory support when patients are not spontaneously breathing (autotriggering) [16,17].

Autotriggering may result from numerous factors, the more frequent being the following: leaks in the circuit; expiratory fluctuations caused by water in the circuit [18]; cardiogenic oscillations [19].

Figure 3 shows curves and loops obtained from two respiratory acts with the same pressure support but with different threshold values of pressure trigger. The airways pressure curve shows a negative deflection preceding inspiration. During this gap of time airflow is absent; when inspiration is triggered flow reaches a higher peak, because of the wider pressure gradient. The delay in inspiration triggering causes displacement in the inspiratory and expiratory cycle. Thereby, besides increasing respiratory work, an excessive threshold for pressure triggering leads to lower tidal volume, as can be seen in flow/volume and pressure/volume loops.

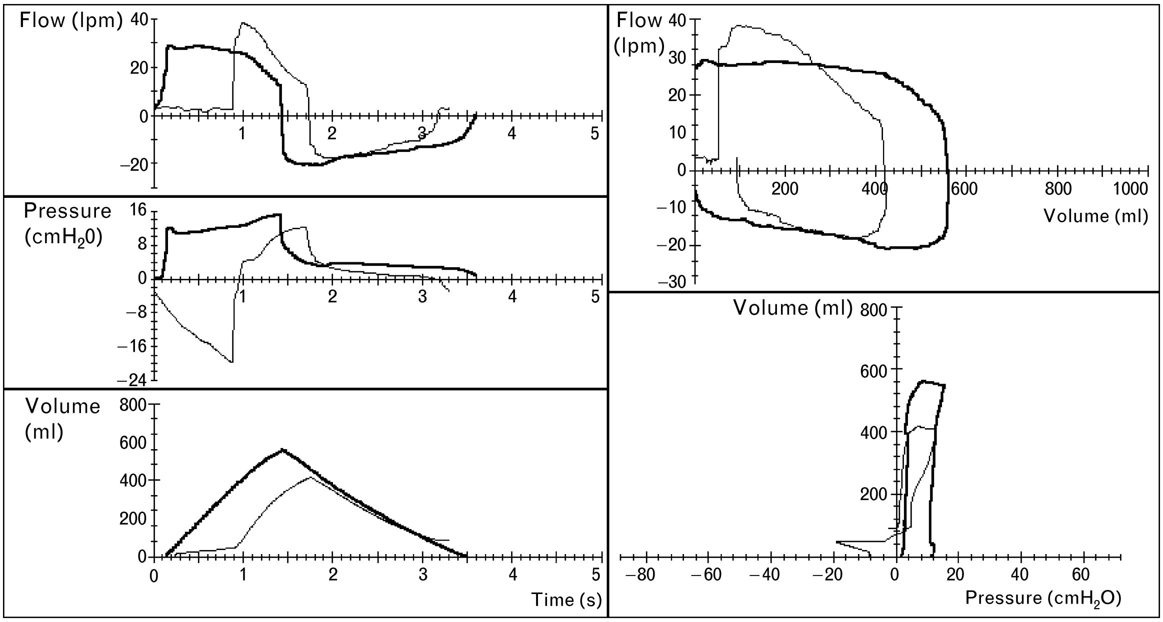
Employment of flow trigger avoids all problems described above, but some potential hazards may go overlooked, such as absence of pressure support ventilation (PSV) setting. In Fig. 4 curves and loops recorded from two flow triggered respiratory acts are compared. The PSV supported act is in bold, while the plain act is not supported. There is no delay in flow delivery, but the inspiratory volume is higher thanks to PSV contribution. Flow and volume curves have the same shape, so, to detect pressure support, the pressure at the mouth curve must be observed.

A correct understanding of flow trigger ventilation is important when managing patients non-invasively ventilated. Employment of masks or helmets during non-invasive ventilation causes frequent air leaks and patient ventilator asynchronies during inspiratory phase [20]. This problem can be overcome setting the bias flow as compensating system, since its capacity reaches 20 l/min; thus, PEEP can be applied without causing autotriggering [21•,22•,23••,24••].

Time course of P_{aw} during constant flow inflation (volume controlled ventilation)

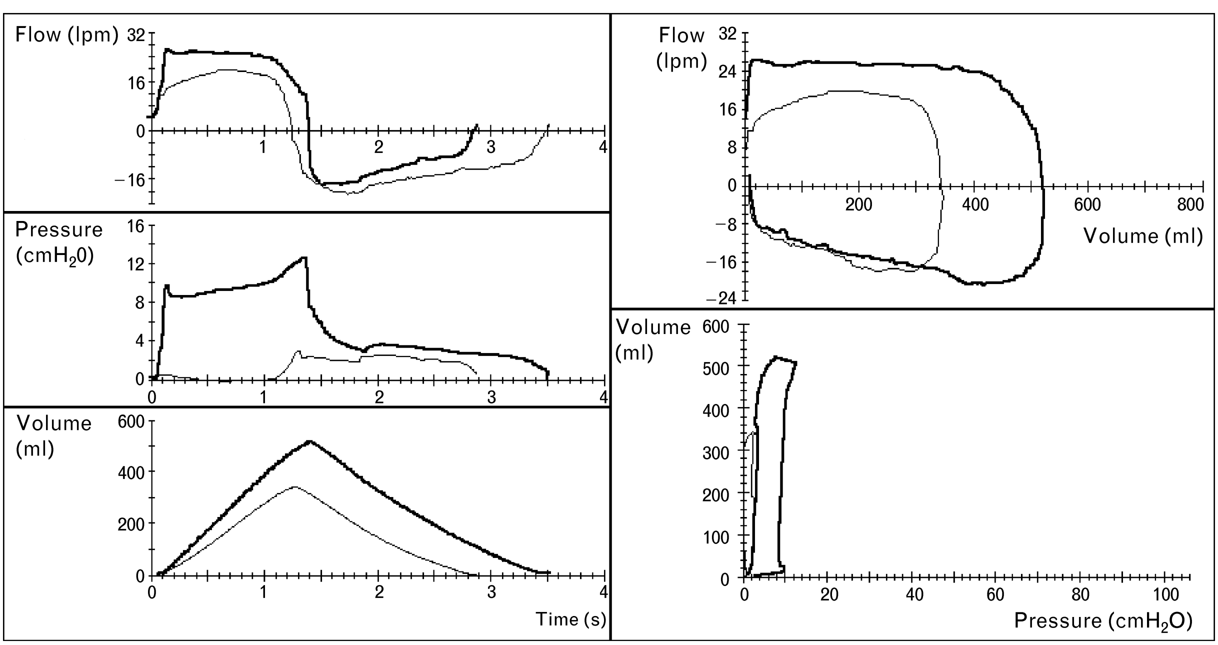
In completely relaxed patients the time course of P_{aw} during constant flow inflation depends linearly on the total respiratory system compliance. The pressure curve over time has a characteristic feature during isovolumetric and constant flow inflation. With the

Figure 3 Trend of flow, pressure and volume curves and respective loops of a respiratory act with adequate triggering (bold) and an excessive triggering threshold ($-20\,cmH_2O$)



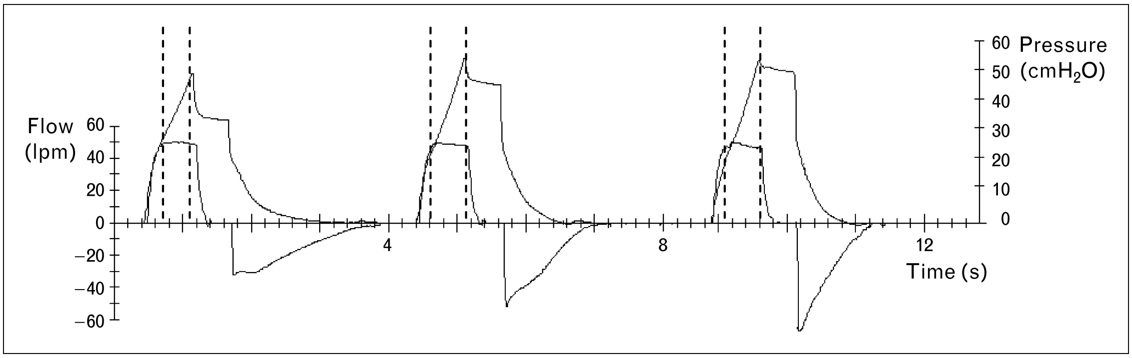
Delivery of flow is delayed by about 1 s, during which time there is neither flow nor volume. Inspiratory effort is shown by negative deflexion in pressure–volume loop.

Figure 4 Trend of flow, pressure and volume curves and respective loops with (bold) and without pressure support ventilation in two respiratory acts flow triggered



Volume increase with pressure support is shown. Notice the characteristic pattern of pressure at the mouth when there is no pressure support.

Figure 5 Time course of airway pressure and flow during volume controlled ventilation



From left to right respiratory system compliance decreases and the morphology of the pressure curve changes turning from concave to linear to convex. Dotted line describes constant flow inflation.

beginning of flow supply, an almost-vertical pressure gap occurs (P_{res}), which is necessary to overcome the resistance provided by the airways and by the endotracheal tube. The curve shape then changes, turning to a linear growth and following a given slope to its maximum value (P_{max}), which occurs at end inspiration. This course, which is normally linear, depends on respiratory system compliance alone.

Real time analysis of P_{aw} curve shape is another bedside monitoring that does not need flow interruption. This method allows an immediate visualization of hyperinflation or lung recruitment by changing the morphology of the curve turning from concave to convex respectively (Fig. 5) [25,26].

From the mathematical analysis of the shape of the dynamic pressure time profile during constant flow ventilation, Ranieri *et al.* [27] derived in an animal model the so-called stress index, which minimizes the risk of ventilatory induced lung injury and detects recruitment and hyperinflation phenomena [28].

Time course of flow and flow–volume loop during dynamic hyperinflation

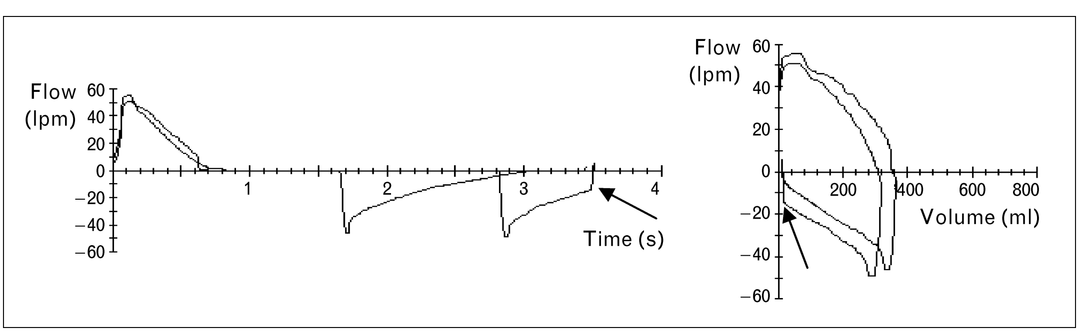
The expiratory flow–time waveform aids the clinician in detecting the presence of dynamic hyperinflation or intrinsic PEEP. Expiratory flow shows air trapping when it fails to return to zero. When the expiratory time is not long enough to allow exhalation of all tidal volume auto-PEEP is generated. In a flow–volume loop, air trapping is characterized by a truncated expiratory phase that does not return to baseline (Fig. 6) [11•,23••].

Time course of flow during pressure controlled ventilation

Analysis of the pressure curve has a scarce clinical utility during pressure controlled ventilation (PCV). Since flow is the variable dependent, it changes as the features of the respiratory system change: the ventilator will constantly adjust flow so that the inspiratory pressure is maintained during the entire inspiratory time [29,30].

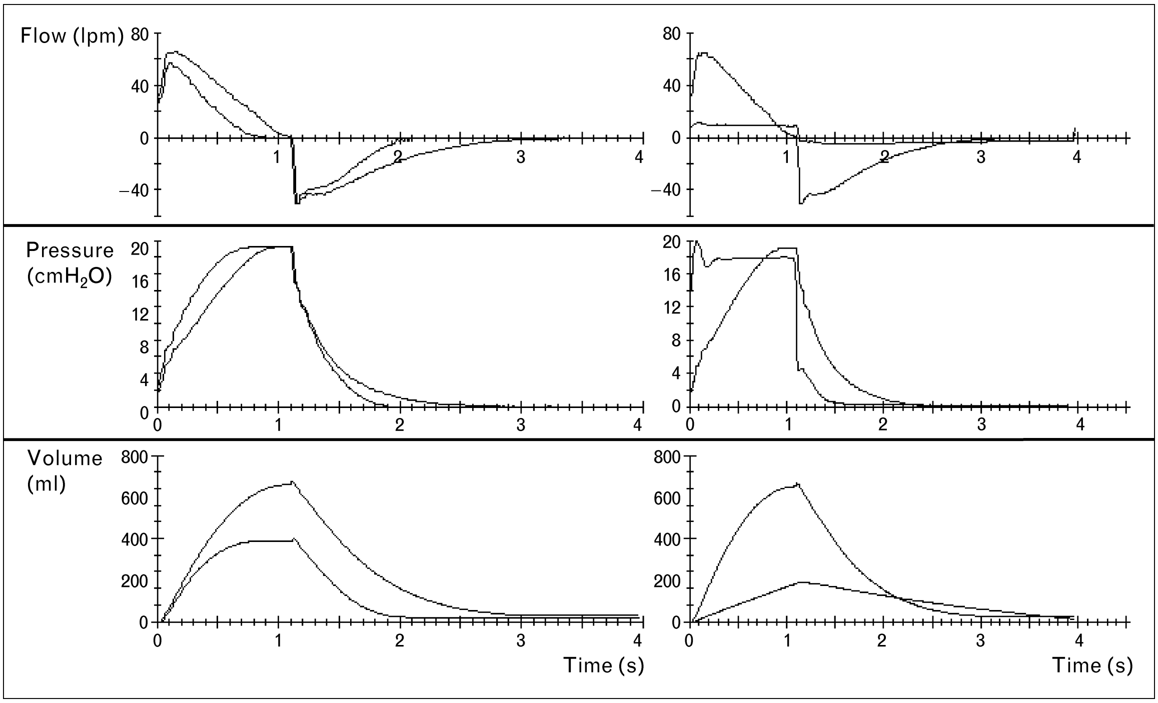
On the other hand flow wave varies as resistance or compliance change, with the hazard of uncontrolled tidal volume delivery (Fig. 7).

Figure 6 Flow curve and flow–volume loop during pressure controlled ventilation at different I : E ratio and constant respiratory rate



The abnormal prolongation of inspiratory time shortens expiratory phase with consequent air trapping (arrows).

Figure 7 Flow pressure and volume waveforms during pressure controlled ventilation and decreased compliance (on the left) and increased resistance of the respiratory system (on the right)



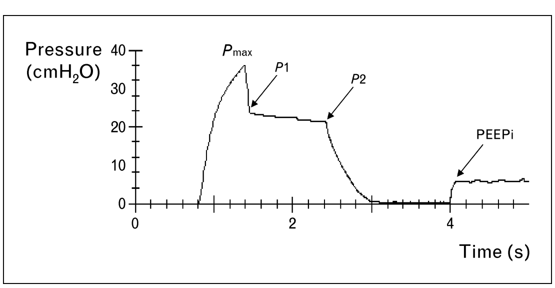
Note that flow time profile changes completely during resistance increment, while compliance reduction does not alter the shape of the curve, which diminishes its amplitude. In both cases volume delivery is affected as the level of pressure is maintained constant.

Static mechanics

During mechanical ventilation the rapid airway occlusion method is the most commonly employed technique for measuring respiratory mechanics.

The P_{aw} wave has a characteristic trend with the highest peak at end inspiration (P_{max}), followed by a rapid drop after the occlusion ($P1$), and a slow decay until a plateau is reached ($P2$) (Fig. 8). $P2$ is the static pressure of the respiratory system ($P_{st,\ rs}$) that, in the absence of flow, equals the alveolar pressure (P_{alv}), reflecting the elastic retraction of the entire respiratory system. The pressure drop from P_{max} to $P1$, represents the pressure required to move the inspiratory flow along the airways, thus representing the pressure dissipated by the flow-dependent resistances.

Figure 8 Airway pressure during volume controlled ventilation with constant flow inflation



Post-inspiratory and expiratory occlusion is performed. P_{max} is the maximum (peak) airway pressure. $P1$ points to the end of the rapid post-occlusion pressure drop. $P2$ points to the end of the slope pressure decay plateau. PEEPi, intrinsic positive end expiratory pressure.

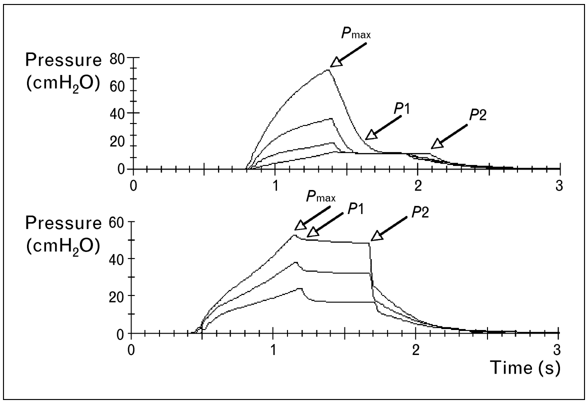
The slow decay after the occlusion from $P1$ to $P2$ depends on the visco-elastic properties of the system and on the pendulum-like movement of the air (*pendelluft*) [31–36].

P_{max} represents the sum of the pressures attempted by the ventilator to overcome the elastic and resistive forces (airways and endotracheal tube) of the respiratory system.

In clinical practice, it is important to remember that the P_{max}-$P1$ pressure gradient is flow and airway resistance dependent (the presence of bronchial secretion, of bronchospasm, and the diameter of the endotracheal tube significantly affect the P_{max} value). $P2$ is only affected by variations in volume or compliance (Fig. 9).

Furthermore, the occlusion manoeuvre at end inspiration allows identification of the presence of a leak in the respiratory circuit, since the plateau pressure cannot be reached.

Figure 9 Volume controlled ventilation with constant flow and isovolumetric condition



Variations in $P_{max}-P1$ pressure gradient at four different airway resistances and constant compliance is not followed by changes in $P2$ (top). Changes in compliance with constant airway resistance produce a variation in $P2$ without affecting Pmax$-P1$ gradient (bottom).

At the end of a normal expiration, in a normal subject, the alveolar pressure is next to zero. Expiratory flow limitation, or an inadequate respiratory pattern (high tidal volume or high respiratory rate) causes PEEPi due to volume trapping. PEEPi is detectable during the post-expiratory occlusion manoeuvre (Fig. 8) [37,38].

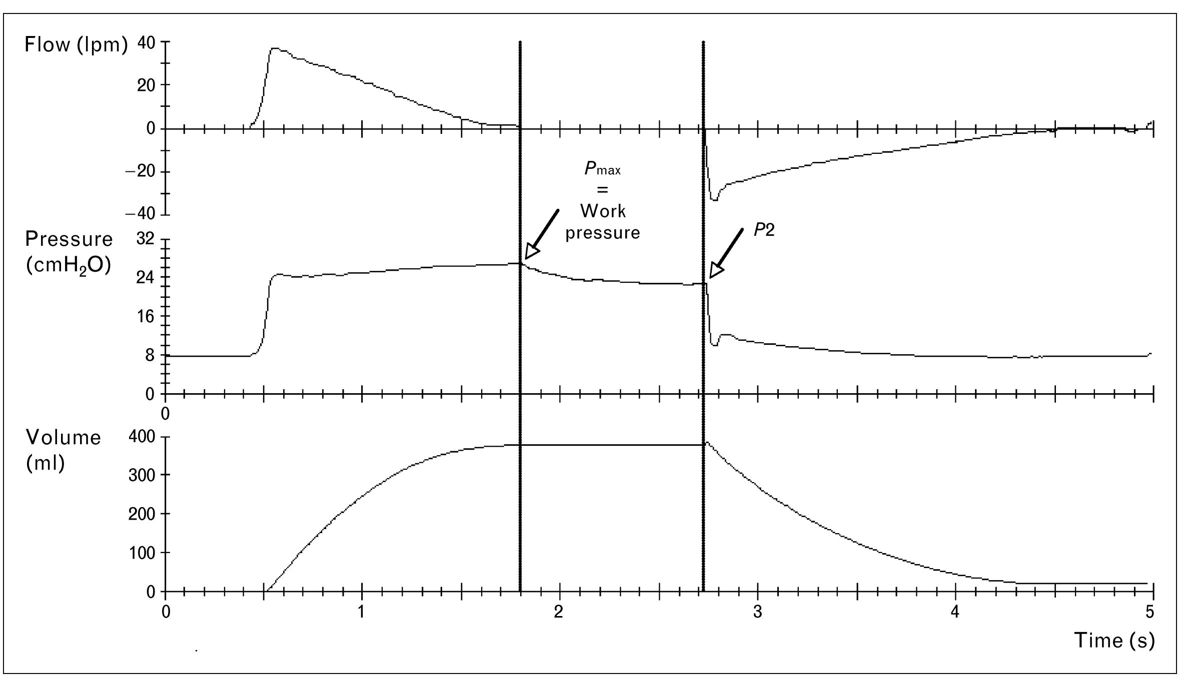
The rapid airway occlusion technique is easy and quick to perform and provides immediate clinical data, when monitoring a paralyzed patient, even with a non-constant flow wave, as during PCV. Plateau pressure ($P2$) can be measured applying a pause at end inspiration during PCV [39].

$P2$ value approximates working pressure during a normal respiratory act in PCV when the characteristic decelerating flow curve reaches zero: when flow is absent, P_{res} is nil and the working pressure set on the ventilator (P_{max}) is close to the alveolar pressure ($P2$) value. If, in addition, an end inspiration pause is applied, a slow decay in working pressure follows, due to dissipation of viscoelastic pressure and *pendelluft* phenomena (Fig. 10).

Conclusion

The knowledge acquired from this review should allow the reader to make a choice of relevant data and curves provided by modern ventilators to plan a ventilator strategy adequate for each patient. Ventilator settings in an intensive care unit are often set by trial and error, so ventilator strategy is influenced by experience and intuition of the intensive care staff. In recent years bedside monitoring developed from an alarm-based methodology to one that describes variations in real time of the thoracopulmonary system. A thorough understanding of ventilator–patient interaction yields immediate

Figure 10 Flow, pressure and volume curves during pressure controlled ventilation



At end inspiration (arrow) flow is zero and set working pressure equals alveolar pressure. By extending the absence of flow by end inspiratory pause the actual value of $P2$ is reached.

recognition of a successful bronchodilatatory therapy [40,41] or efficacy of recruitment manoeuvres [42,43].

Measurements of more complex parameters as work of breathing and esophageal pressure should be reserved for unusually difficult clinical questions [44].

Recent new technologies, simulating respiratory mechanics in pathological condition, will improve understanding pulmonary mechanics and will allow a rapid training and teaching, no more on intuitive bases but with sound physiopathologic basis [45,46•].

References and recommended reading

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- •• of outstanding interest

Additional references related to this topic can also be found in the Current World Literature section in this issue (p. 100).

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