Hospital respiratory care

The V680 dynamic respiratory mechanics algorithm

Philips Respironics V680 ventilator system

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The resistance (R) and compliance (C) calculations on the Respironics V680 ventilator system leverage advanced data acquisition and signal processing capabilities to allow pause-free, dynamic, breath-to-breath estimates of these parameters. Not only does the system estimate inspiratory and expiratory R and C, but it also estimates plateau pressure in both invasive and non-invasive applications. The dynamic respiratory mechanics measurements on the V680 ventilator approach the accuracy of measurements obtained with static methods requiring an inspiratory pause maneuver, while also avoiding the limitations of Least Squares curve-fitting methods.

Introduction

Estimates of the viscoelastic parameters of the respiratory system (i.e., respiratory mechanics) in mechanically ventilated patients can quantify changes in a patient's respiratory condition so that the ventilator and associated therapies can be appropriately modified. The waveforms of flow, pressure, and volume measured at the patient's airway reflect those changes (**Figure 1**), and these waveforms are used to estimate the viscoelastic parameters. The methods used clinically to compute these estimates on mechanically ventilated patients include both static methods and dynamic methods.

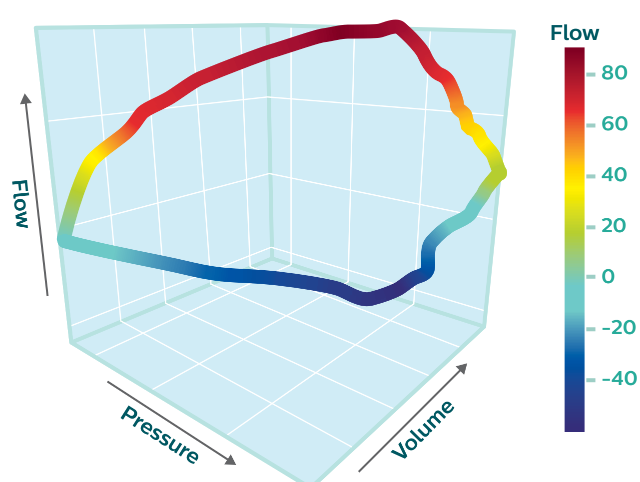

Figure 1 The relationships between flow, pressure and volume (with a mechanical breath from a test lung)

Static methods have been considered the gold standard for many years, most likely due to the adaptation of methods from constant volume plethysmography (Dubois, 1956) to ventilated patients. Static methods are conceptually simpler from a physiological and computational viewpoint but require that the flow be interrupted. This interruption is most commonly done with an inspiratory breath hold that allows sufficient time for equilibrium to be reached once flow is stopped. However, given that the patient is at times paralyzed or heavily sedated in order to acquire a sufficiently stable or "static" pressure state, the calculated static values may not reflect active ventilation well. One author even noted,

> " **The static conditions are so different from those of actual ventilation that it is hard to imagine how and why the former should apply to the latter."**
> *(Lichtwarck-Aschoff, 2000)*

These differences are most likely due to differences in the calculations of pressure and volume as measured by static versus dynamic methods (Lichtwarck-Aschoff, 2000). Dynamic methods, which can be computationally and physiologically more complex than static methods, are becoming the preferred approach because they don't require alteration or interruption of the respiratory waveforms.

In addition, dynamic methods are relatively simple to apply, provide immediate feedback, and have generally demonstrated sensitivity to alterations in the underlying mechanics.

A new dynamic approach

The V680 ventilator Dynamic Respiratory Mechanics algorithm is a dynamic approach that addresses the need for accurate estimation of lung compliance, resistance, and plateau pressure. The V680 approach to respiratory mechanics makes use of the fact that when lung flow is zero, the pressure drop (i.e., pressure delta) between the lung and the tubing circuit's wye is also zero. Thus the pressure at the wye and the lung are equal. Then, compliance is measured during both the inhalation and the exhalation phases of the breath by using the volume at two different times when flow into or out of the lung is zero (in this case, the beginning of physiological inspiration and beginning of physiological expiration). The estimate of compliance obtained during the inhalation phase is to be used only when the patient is not active during this phase; the estimate obtained during the exhalation phase is to be used if patient activity was detected during the inhalation phase. Resistance is measured during both the inhalation and exhalation breath phases, at the points where the flow magnitudes are maximum (for inhalation) and minimum (for exhalation).

Resistance is measured at points of maximum lung flow (into or out of the lungs) because it is a well-known fact that resistance changes with the level of flow through the space on which it is being measured. That is, the higher the flow through the resistive path, the higher the resistance in the path and vice versa. In this way, the information presented to the user represents the maximum resistance experienced by the patient during the phases of the breath. As with lung compliance, the resistance estimates are made during both phases of the breath, but are accurate only if the patient is inactive for the breath phase for which the estimate is calculated. It is typical, but not always true, for the patient to be inactive during the exhalation phase of the breath, thus the usefulness of the estimates during the exhalation phase.

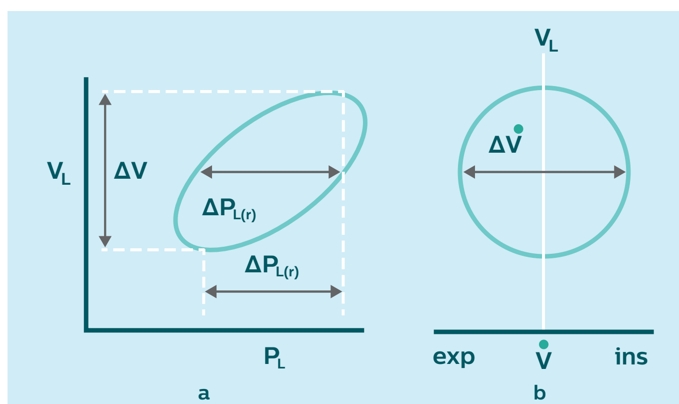

Figure 2 (**a**) Pressure volume and (**b**) flow-volume curves for the lung in a single breath volume excursion (**ΔV**) and elastic pressure change ($\Delta P_{L(e)}$) are used to compute compliance, and the inspiratory-expiratory flow difference ($\Delta \dot{V}$) and resistive pressure difference ($\Delta P_{L(r)}$) are used to compute resistance (adapted from Loring, 1998).

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Dynamic compliance estimation

The V680 algorithm's method of determining dynamic compliance is based on this equation of motion for ventilation.

$$P_{mus} = R * QL + VL/CL - P_{prox}$$

Where:

P_{mus} = **Pressure exerted by the respiratory muscles**

QL = **Lung flow**

VL = **Lung volume**

P_{prox} = **Pressure at the airways opening**

More specifically, when **QL** and P_{mus} are zero (i.e., patient is not active then P_{mus} = 0), the equation of motion transforms into:

P_{prox} = **VL/CL** and from this we get **CL** = **VL**/P_{prox}

Note that the points in time where the Physio_IE signal transitions from zero to 80 and from 80 to zero are points where $Q_{Lung} = 0$.

$$CI_{NH} = (V_{BOPE} - V_{BOPI}) / (P_{PLAT} - PEEP_{INTR})$$

Where:

C_{INH} is the inhalation phase lung compliance estimate

V_{BOPE} is the volume at the start of physiological exhalation

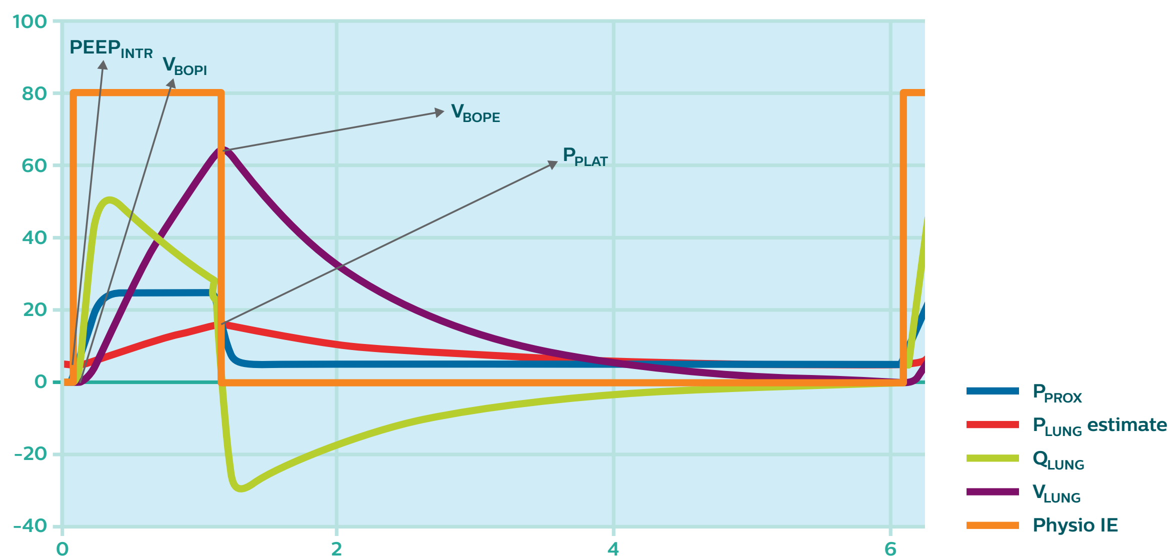
V_{BOPI} is the volume at the start of physiological inhalation

P_{PLAT} is the proximal pressure measured at the start of physiological exhalation (plateau pressure)

$PEEP_{INTR}$ is the proximal pressure measured at the start of physiological inhalation (intrinsic PEEP). This is a point of zero (0) lung flow and therefore the lung pressure equals the proximal pressure.

As with conventional static approaches, the estimate is then carried out by measuring the estimated change in volume over the estimated change in pressure. The measurements at the zero flow points are used to calculate the differences of the corresponding volume and pressure values needed for the calculation of inspiratory and expiratory lung compliance. (See the graph and equations used below.)

Inhalation Phase calculation



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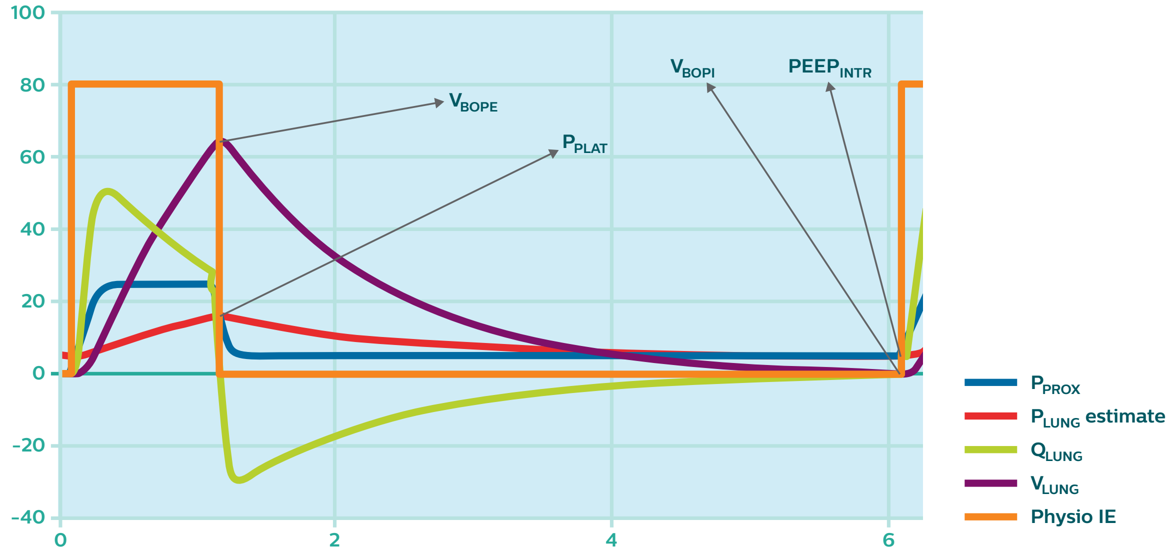
Exhalation Phase calculation



$$C_{EXH} = (V_{BOPI} - V_{BOP}E) / (PEEP_{INTR} - P_{PLAT})$$

Where:

C_{EXH} is the inhalation phase lung compliance estimate

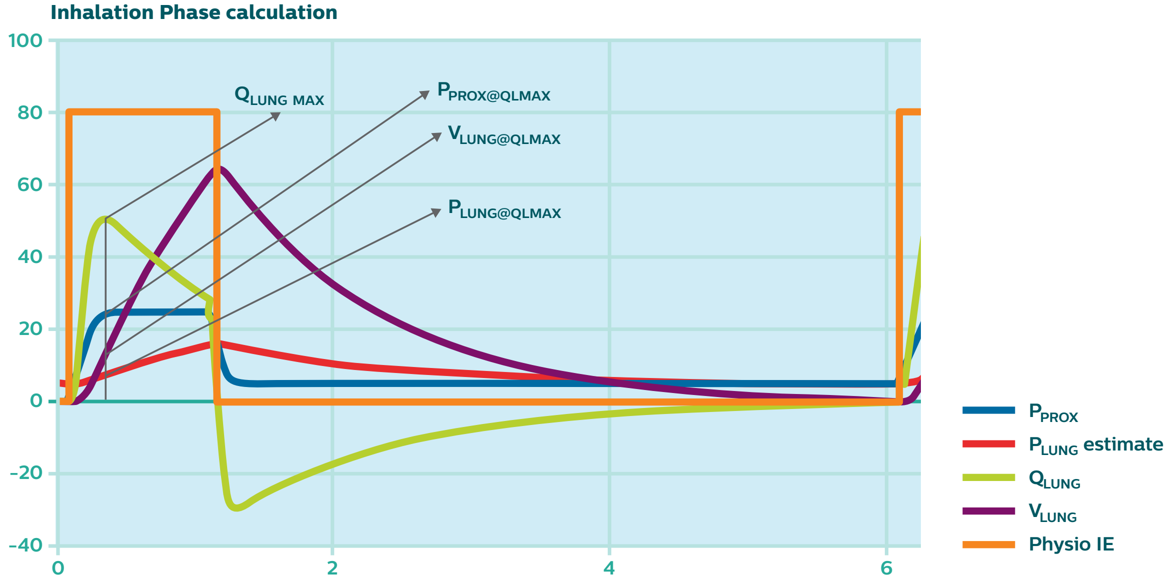
Note that $\mathbf{P_{PLAT}}$ and $\mathbf{PEEP_{INTR}}$ have been introduced. The $\mathbf{P_{PLAT}}$ measurement represents the resting state pressure of the lung at the end of the physiological inhalation (i.e., zero lung flow). Similarly, the $\mathbf{PEEP_{INTR}}$ measurement represents the resting state pressure of the lung at the end of the physiological exhalation (i.e., zero lung flow). These two measurements are also of importance for the caregiver, and while they merely mimic the true resting states, they convey information about the patient that, if trended, may be used to determine how the patient is progressing.

Elastance is calculated as the reciprocal of the compliance value. The units of elastance are $\mathbf{cmH_2O/L}$.

Dynamic resistance estimation

The V680 ventilator uses the inhalation and exhalation lung compliance estimates, found as indicated above, to estimate both inspiratory and expiratory resistance. The V680 algorithm's method of determining dynamic resistance, as with conventional static approaches, uses the ratio of the driving pressure to the flow. The driving pressure, in this case, is the pressure delta created across the airway by the flow in or out of the lung, as the case may be. For inhalation, the point of maximum flow is used as the reference point to select the pressure point, as well as the volume data point to be used in the calculations (see the figure below).

Inhalation Phase calculation



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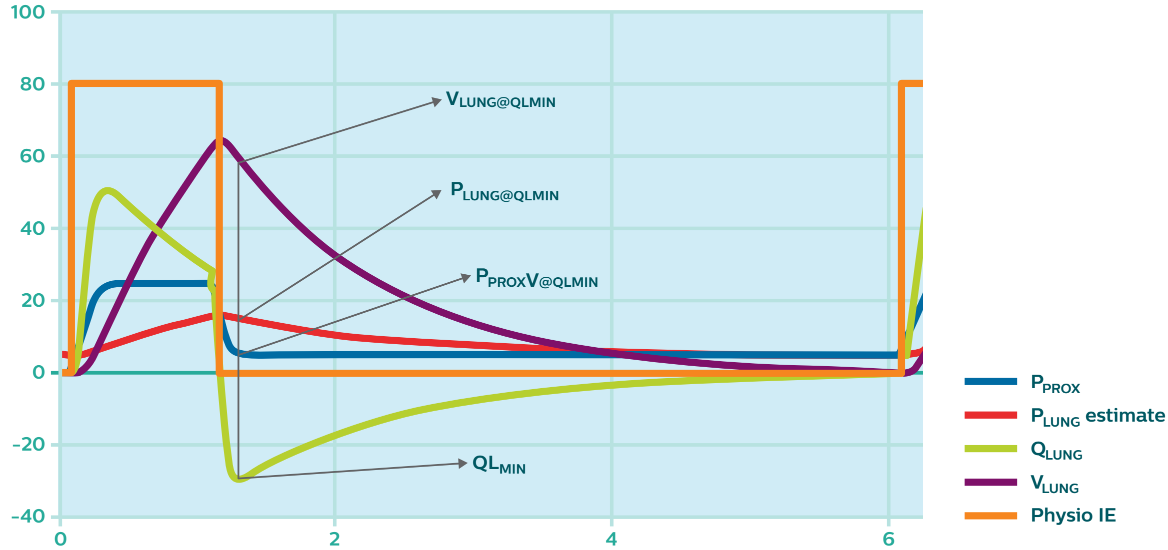
Exhalation Phase calculation



Inhalation Phase calculation

$$R_{LUNG\_INH} = (P_{PROX@QLmax} - P_{LUNG@QLmax}) / Q_{LUNG\_max}$$

Where:

R_{LUNG_ING} is the inhalation phase lung resistance estimate at the point where the lung flow is maximum

$P_{PROX@QLmax}$ is the proximal pressure measured at the inhalation phase flow reference point (i.e., Q_{LUNG_max})

$P_{LUNG@QLmax} = P_{PLAT} - [(V_{BOPE} - V_{LUNG@QLmax}) / C_{INH}]$ is the estimated lung pressure at the inhalation phase flow reference point

Q_{LUNG_max} is the peak estimated patient flow during the inhalation phase

P_{PLAT} is the proximal pressure measured at the start of physiological exhalation (plateau pressure)

V_{BOPE} is the volume at the start of physiological exhalation

$V_{LUNG@QLmax}$ is the volume at the inhalation phase flow reference point

C_{INH} is the inhalation phase compliance calculated on the current breath

Exhalation Phase calculation

$$R_{LUNG\_EXH} = (P_{PROX@QLmin} - P_{LUNG@QLmin}) / Q_{Lmin}$$

Where:

R_{LUNG_EXH} is the exhalation phase lung resistance estimate at the point where the lung flow is minimum

$P_{PROX@QLmin}$ is the proximal pressure measured at the maximum negative flow during exhalation

P_{PLAT} is the proximal pressure measured at the start of physiological exhalation (plateau pressure)

$P_{LUNG@QLmin} = P_{PLAT} - [(V_{BOPE} - V_{LUNGg@QLmin}) / C_{EXH}]$ is the estimated lung pressure at the point of maximum negative flow during exhalation

V_{BOPE} is the volume at the start of physiological exhalation

$V_{LUNG@QLmin}$ is the volume at the point of maximum negative flow during exhalation

C_{EXH} is the exhalation phase compliance calculated on the current breath

Q_{Lmin} is the maximum negative flow during exhalation

Since in volume control mode, with square wave flow waveform, the maximum flow is the same at the end of the inhalation as in the earlier part of the inhalation, a value of Peak Flow near the end of the inspiratory phase is used to compute the resistance (in a similar fashion as that carried out for the static method).

The units of resistance are **$cmH_2O/L/s$**.

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Because the V680 ventilator samples the pressure and lung flow signals continuously for enhanced performance, the V680 algorithm employs:

- Interpolation methods on the flow, volume and pressure signals for increased accuracy in the assessment of their values at the time of the zero-crossings (e.g., start of inhalation and exhalation)
- A higher data sampling rate (1 KHz) than typically used with conventional algorithms, which may use a sampling rate of 100 Hz or less

The V680 advantage

The V680 algorithm differs from other methods in important ways.

- It is capable of calculating both static and dynamic values.
- For all but the most critical cases, it doesn't require performing an inspiratory hold maneuver, as traditional static methods do. This means the mode of ventilation does not have to be changed when ventilation is carried out in modes other than VCV, and there's no need to make sure that the patient is inactive while the static maneuver takes place, saving valuable clinician time.
- As with any respiratory mechanics measurements, the inhalation phase compliance and resistance values are not considered accurate when the patient is actively breathing or even triggering the breath. With the V680, the exhalation phase calculations are used for the estimates on those breaths, since the patient is not typically active during the exhalation phase.
- The V680 uses a very reduced data set to assess the patient respiratory parameters, and the results are independent of the breath phases durations. This is in contrast to statistic-based methods such as the Least Squares Method, which uses all of the data samples in a breath or portion of a breath, and when ventilation is carried out with short inspiratory times, the Least Squares Estimation (LSE) approach may underestimate compliance and over/under estimate resistance for two primary reasons. First, the LSE method requires a minimum data set to converge to the final values for lung compliance and resistance. Second, the estimate/result is the value that best fits the data, and since the lung resistance is flow dependent and the lung compliance is volume dependent, the estimate tends to be an average value.

Additionally, it has been experimentally demonstrated that the values for dynamic and static plateau pressure are closely related, in the absence of patient activity.

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Printed in The Netherlands.
4522 991 07651 * DEC 2014