Manuscript type: Review

DOI: 10.5152/TurkThoracJ.2018.177

Title: Basic Concepts for Tidal Volume and Leakage Estimation in Non-Invasive Ventilation

Authors: Manel Luján¹,², Cristina Lalmolda³ Begüm Ergan⁴

Institutions:

¹Pneumology Service, Corporació Parc Taulí, Universitat Autònoma de Barcelona, Sabadell, Spain
²CIBERES Bunyola Spain
³RT, Fundació Parc Taulí, Sabadell, Spain
⁴Department of Pulmonary and Critical Care, Dokuz Eylül University School of Medicine, İzmir, Turkey

Address for correspondence: Begüm Ergan, Department of Pulmonary and Critical Care, Dokuz Eylül University School of Medicine, İzmir, Turkey

E-mail: begumergan@hotmail.com

Received: 04.11.2018

Accepted: 23.11.2018

Cite this article as: Luján M, Lalmolda C, Ergan B. Basic Concepts for Tidal Volume and Leakage Estimation in Non-Invasive Ventilation. Turk Thorac J 2018; DOI: 10.5152/TurkThoracJ.2018.177

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as: Luján M, Lalmolda C, Ergan B. Basic Concepts for Tidal Volume and Leakage Estimation in Non-Invasive Ventilation. Turk Thorac J 2018; DOI: 10.5152/TurkThoracJ.2018.177

©Copyright 2018 by Turkish Thoracic Society - Available online at www.turkthoracj.org
ABSTRACT

The main goals of non-invasive ventilation (NIV) are to maintain sufficient alveolar ventilation, improve pulmonary gas exchange, assist respiratory muscles, and decrease work of breathing. Monitoring variables such as leaks, tidal volume and minute ventilation during therapy is crucial to assess the effectiveness of NIV. However, most of the time, leaks and tidal volume are not measured but estimated by NIV devices. Moreover, there is limited data for the accuracy and reliability of these estimations. Herein, we address some technical considerations for tidal volume and leakage estimation during NIV and its impact in clinical practice.

Keywords: Noninvasive ventilation, tidal volume, leak, estimation, software

INTRODUCTION

Home non-invasive ventilation (NIV) has exponentially grown since its introduction more than 30 years ago. During the last decade, high performance portable devices are becoming at same time ventilators and monitors, offering to the clinician important information about some physiological parameters during the use of the device. Two of the most important parameters are tidal volume (TV) and leakage (that in fact are the two faces of the same coin). Interestingly, the majority of manufacturers do not measure directly these two parameters, but they estimate them through built-in software. Each company offers its own software, and huge differences may be found between them not only in the presentation of variables, but also in the accuracy of estimated parameters (1).

The development of algorithms for TV and leakage estimation should consider all the physical phenomena involved in the delivery to the patient of certain amount of gas by an external ventilator. These phenomena are sometimes a challenge from the mathematical point of view.
and can substantially change when different circuits, anti-rebreathing devices, or interfaces are used.

The goals of the present revision are to reflect the complexity of TV volume and leakage estimation by these commercial algorithms and to summarize the main bench studies addressing this issue. At same time, we emphasize on potential sources of variability between manufacturers and the consequences of this variability in the clinical practice.

**Mathematical basis for tidal volume and leakage estimation.**

In intensive care unit (ICU) ventilators, the TV estimation does not need advanced concepts. In fact, the direct measurement of flow (and volume) by the internal pneumotachograph inside the ventilator needs to be corrected only by the compressible volume, that is the amount of gas (in ml) compressed in the circuit for every cm H₂O of pressure generated by the ventilator during the inspiratory phase. This volume never reaches the patient and usually depends on the compliance and length of the circuit \( C_1 = \Delta V/\Delta P \) and pressure difference. Depending on these factors, the compressible volume can represent up to 20 % of delivered gas, but modern ICU ventilators are usually fitted with algorithms that calculate and compensate for compressible volume (2).

If this limb configuration (double) is used in NIV, the difference between inspired and expired volume (previously corrected by the compressible volume) corresponds to the leakage.

However, double limb configuration, although being clearly the most exact way to estimate leaks and TV is often too bulky for home environment. For this reason, NIV home ventilators are usually equipped with single limb circuit with an expiratory safety system that prevents rebreathing of exhaled gas. This expiratory port can be an intentional and continuous leakage or an expiratory active valve, which opens only during expiratory phase. In both cases, the information about the amount of exhaled gas is not directly measured inside the ventilator, as it happens in the double limb configuration.

In the active valve circuit, a pneumatic device is pressurized above pressure inside the limb, and occludes the valve during inspiration. During expiration, the pressure valve relief makes that all the expired gas escapes through the valve and the expiratory flow signal is missing (Figure 1), and making very difficult the assessment of TV values (especially if leaks occur). In
this setting, the only technical available solution for measuring TV would be to place a pneumotachograph between the valve and the interface.

Nowadays, and due to its simplicity, not only for the patient but also for caregivers, probably the most preferred configuration in home NIV is the single limb with expiratory leak port, either in the whole mask or built as an independent piece between the mask and the tubing. Figure 2 (A/B) schematically represents the flow dynamics during inspiration and expiration when this kind of circuit is used. The expiratory leak port acts as a continuous and intentional leakage (intentional F2 in figure 2A), with a higher resistance (R2) than the imposed by the diameter of the tubing (R1).

Following figure 2A, during inspiration:

Total gas outflow (F1) = F2 + F3 (non intentional leaks, if present) + F4.

Conversely, during expiration (Figure 2B), the expiratory positive airway pressure (EPAP) flow “washes” the circuit and the pneumotachograph only detects a small amount of expired gas. In this case, the expiratory TV would be the sum of this small backward flow (F1) plus intentional / non intentional leaks (if present). Then, in a first step, the influence of this intentional continuous leak should be determined unless the TV and leak estimation could be wrong. From a physic point of view, the intentional leakage is a function of the pressure difference in and out of the tubing, and can be determined following the simplified formula of the Poiseuille’s law:

\[
F2 = P2 - Patm
\]

\[
\frac{R2}{R2}
\]

Intentional leakage can indirectly be explored by means of the so-called “leak test”: in this test, the ventilator automatically increases pressure levels with the distal end of the mask or tubing occluded. Thus, pneumotachograph inside the ventilator captures only the flow escaping through the expiratory port, determining the relationship between pressure and leaks. Finally, the data are plotted in a XY graphic (Figure 3) and a second degree equation can fit with
reasonable accuracy the amount of intentional leak for each level of pressure. Figure 4 shows the fit for a leak test with a linear and second degree equation. These values can be subtracted of the native graphics (F1) to obtain the true gas flow entering to and exiting from the patient (in absence of non-intentional leaks). Unfortunately, few models of ventilators are equipped with this test. Many devices do not use in their estimation any information about what kind of expiratory port is used. In some modern models, the clinician can introduce in the ventilator’s menu the type of interface (nasal, oronasal, etc). If we consider that the flow values of the expiratory ports between masks can present huge differences between the models, it would be easily understandable that there might be an important source of error in tidal volume and leakage estimation.

At same time, it should be taken into account that the conditions when the leak test is done (no TV, distal end occluded) are not the same as when the ventilator is used in the clinical practice (patient flow present). Following the same Poiseuille’s law, there is a loss of pressure across the tubing directly proportional to the ventilator’s outflow. P2 can be estimated though the following equation:

\[ P2 = P1 - F1 \times R1 \]  
(Figure 2A)

For this reason, some commercial ventilators are fitted with a proximal pressure sensor at P2 level. Other manufacturers developed a “pre-use test” to be done before each clinical use. The purpose of such pre use tests (do not confound with leak test) is to calculate the compliance (C1) and resistance (R1) of the circuit, to determine compressible volume and pressure loss respectively. Usually, C1 is measured with the distal end completely closed and resistance is measured with the distal end open (in both cases without intentional leakage). The absence of such algorithms (or absence of direct P2 measurement) may lead to overestimation of P2 (and leaks) and underestimation of TV (3)

The second important problem during the development of algorithms for estimating leaks and tidal volume are the presence of eventual non-intentional leaks around the mask. As displayed in the figure 2, in presence of continuous leaks, the pneumotachograph inside the ventilator “monitors” both TV and leakage. For each instant during the ventilator cycle, the relationship between total outflow, leakage and patient flows (estimated) can be established by an equation as follows (intentional leakage was discarded here to simplify the concepts):
F1 (known) = F4 (TV) + F3 (if present).

In which F1 is total flow monitored inside the ventilator and F4 / F3 are patient flow and leakage flow. Considering that F1 is continuously monitored throughout the entire cycle, the problem is how to solve a system of a single equation with two unknowns. There are only two points in the cycle in which F4 (TV) value is known, for instance the transition points between inspiration and expiration. In these points, patient flow (F4) is 0 l/min, and the entire amount of flow monitored by the pneumotachograph inside the ventilator necessarily belongs to non-intentional leak (fig 5). Manufacturers usually follow this principle and estimate the leak value in the transition between expiration and inspiration, because the slope between inspiration and expiration is clearly steeper and choosing a wrong measure point may lead to leakage over / underestimation.

In fact, when applying this concept, they are determining a resistance value (R3 = EPAP / E-F3) and this value is usually applied throughout the entire cycle to estimate the amount of leaks for every instant in the flow-time curve.

This approach has two main drawbacks. First of all, the P2 value during expiration (EPAP) cannot reflect P1 during the entire expiratory phase, in other words it is not necessarily constant. In fact, during expiration there are changes in flow leading to small changes in P2 value.

The second problem arises when this resistance value (R3) is not constant or is different during inspiration than during expiration. In clinical practice it is not uncommon the finding of a non-intentional leak only during inspiration, or even at the end of inspiration (asymmetric leakage).

In this case, R3 values may show huge differences during a single cycle. This phenomenon can be simulated in a bench environment with the help of a unidirectional valve that generated leaks only during inspiration or expiration (4). The results were that with inspiratory leaks, the commercial software overestimated TV, and vice versa with expiratory leaks. The results obtained in this study (overestimation of tidal volume in a model of inspiratory leaks and underestimation in expiratory leaks) reinforced the hypothesis that the approach of considering unintentional leaks as a linear parameter can lead to significant misestimation of TV. In the same study, an algorithm based on the assumption of lack of proportionality...
between inspiratory and expiratory phases showed minimal deviations in the estimation of tidal volume and unintentional leaks.

The identification of the wrong estimation of TV and leaks when inspiratory non-intentional leaks occur is also possible though the examination of flow time waveform: If the area under inspiratory phase seems much greater than in the expiratory phase it suggests inspiratory leaks. Even more visual interpretation can be the assessment through volume-time waveform (unfortunately, few built-in software display it), which in fact is the integral of flow waveform over time. If the inspiratory (positive) area is greater than expiratory area (for example, in presence of inspiratory leaks) the software must re-start the volume time waveform at the zero level. This re-start is usually seen when flow – time waveform crosses the zero level, from negative to positive flow and it is commonly seen as an abrupt “drop” in volume-time graph (Figure 6). From a clinical point of view, when the mentioned drop appears, the tidal volume values in these cycles are unreliable.

Finally, a third source of variability is the presentation of leak information in the screen and in the built-in software. Whereas some manufacturers provide the information concerning leaks only as non-intentional values, others display global leaks, including values related to the expiratory port. This lack of standardization can be confusing for the clinician.

The drawbacks of this misestimation can go beyond wrong information to the clinician. It should be highlighted that in some new modes of NIV (the dual control or volume-targeted pressure support modes) the ventilator takes their own decisions based on target TV estimation. If asymmetric leaks appear, as demonstrated in a recent study (5) the ventilator can modify its pressure support level in a different way than expected. In this setting, it seems reasonable to recommend setting in the ventilator a safety lower level of pressure support.

**TV and LEAK ESTIMATION IN BENCH STUDIES**

There is growing evidence that bench testing is an important and relevant component for the assessment of the performance of NIV devices although they have some limitations such as the models usually lack reflecting complex variations that occur during real life, such as inspiratory effort, respiratory drive, ventilatory pattern and variability of unintentional leaks. However, few studies addressed the accuracy of the information provided by device software.

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as: Luján M, Lalmolda C, Ergan B. Basic Concepts for Tidal Volume and Leakage Estimation in Non-Invasive Ventilation. Turk Thorac J 2018; DOI: 10.5152/TurkThoracJ.2018.177

©Copyright 2018 by Turkish Thoracic Society - Available online at www.turkthoracj.org
Contal et al (1) analyzed seven home NIV devices for leak quantification and estimation of TV with and without unintentional leaks. Each ventilator was tested for variable degrees of leak (0-10-24-40 and 60L/min) at 15 and 25cmH₂O of inspiratory pressure and 5cmH₂O expiratory airway pressure. Recordings were performed with normal respiratory mechanics model. When compared, it was observed that the estimation of leaks by different software varied significantly between ventilators. The assessment of leaks was highly reliable and correlated well for the three ventilators and bias was very close to zero. In contrast to that finding, the other four ventilators underestimated the magnitude of leaks by 6 to 26L/min. One device estimated leaks only during the expiratory phase. Bias for the estimation of leaks increased with the magnitude of unintentional leaks. Increasing leaks also generated auto triggering in two ventilators. TV was underestimated by all NIV devices, ranging between 66 to 236mL. The difference increased with higher IPAP level (25cmH₂O) and between 89 to 328mL without unintentional leaks and 97 to 404mL with an unintentional leak of 60L/min. In our opinion, these differences simply suggest that manufacturers are using different algorithms to estimate TV and leaks.

A possible explanation for underestimation of TV could be lack of compensation for pressure loss within the tubing system. Lujan et al evaluated the TV estimation of five NIV devices by comparing TV values calculated by built-in-software with TV measured by a calibrated pneumotachograph under increasing levels of the controlled leak (3). The main aim of the study was to determine whether an incorporation of a mathematical algorithm that computes leak related pressure losses between the proximal and distal side of the single tubing might improve the reliability of TV estimation of built-in software of the devices. The ventilators tested for calibrated leak flows (35, 45, 55, 65L/min) on 20cmH₂O of continuous positive airway pressure (CPAP) which corresponds to estimated leak flows for the interfaces that are often used in clinical practice. In addition, each leak level was tested for three different respiratory conditions (normal, obstructive and restrictive) with 3 different levels of inspiratory pressure (5, 10, 15 cmH₂O). The first important finding of this study was all ventilators showed significant differences between displayed and externally measured TV in absolute values and all of them underestimated TV, ranging between 22±9mL and 84±25mL. In the presence of the lowest leak (35L/min on CPAP of 20cmH₂O), which corresponds to values for a nasal mask, ventilators displayed TV in totally different values. The second important finding was a linear relationship between the leak and the difference between displayed and externally measured TV.

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as: Luján M, Lalmolda C, Ergan B. Basic Concepts for Tidal Volume and Leakage Estimation in Non-Invasive Ventilation. Turk Thorac J 2018; DOI: 10.5152/TurkThoracJ.2018.177

©Copyright 2018 by Turkish Thoracic Society - Available online at www.turkthoracj.org
relationship between the magnitude of leak and volume underestimation was observed nearly in all ventilators. The underestimation reached values near 20% of the externally measured TV in the presence of high leaks in some ventilators. In three ventilators underestimation of TV was more pronounced when the breathing pattern was obstructive. The authors reported that incorporating a mathematical algorithm to the software for pressure loss through the tubing improved the accuracy of TV measurements.

One characteristic of unintentional leaks is they are dynamic which means they can change during the inspiratory or expiratory phase of the respiratory cycle. Theoretically, the presence of dynamic (asymmetric) leaks is a challenge for NIV software systems to compensate unintentional leaks. Two bench studies assessed the estimation of TV and unintentional leaks during the asymmetric leak model. In the first study (4), the reliability of TV estimation was tested in a single tube bench model with random dynamic leaks (high and low level) during two levels of pressure support (10 cmH₂O and 15 cmH₂O). In the basal condition with only intentional leaks, which corresponds to standard nasal mask leak, all four ventilators except for one underestimated TV. In the model of inspiratory unintentional leaks, TV was overestimated ranging between 137 mL to 264 mL. Two ventilator software underestimated leaks ranging between -11.5 to -6 L/min. In the model of expiratory leaks, high level of unintentional leaks caused auto triggering in all ventilators. For that reason, the performance of ventilators only assessed during the low expiratory leak. In that case, three ventilators underestimated TV (ranging between -48 to -29 mL) and one ventilator overestimated it. All ventilators overestimated unintentional leaks ranging from 2.2 to 3.1 L/min. These results show that the estimation of TV in the presence of asymmetric leaks is erroneous, either under- or overestimated depending on the phase of the respiratory cycle.

In the second study, the same investigator group (5) studied the effect of these asymmetric leaks occurring either inspiration or expiration in volume guaranteed ventilation with single limb circuit. To simulate asymmetric unintentional leaks, a T-piece was inserted after a commercial leak port that corresponds to the continuous intentional leak used in clinical practice. In the inspiratory leak model, a 7.5 cmH₂O PEEP threshold valve was attached. Two levels of unintentional leaks (low and high) were introduced into the system with calibrated holes. The study showed the addition of inspiratory leak resulted to a progressive decrease
both in pressure support and the delivered TV, falling below targeted value. Clinically it was shown that the mean delivered TV could drop by 40% in the presence of excessive inspiratory leaks. The delivered TV was significantly different between low and high inspiratory leak levels in all ventilators, except one. During expiratory leak model, an active valve was used and attached to the T-piece. It was observed that the presence of expiratory leaks caused an increase in both pressure support and delivered TV. The increase in TV differed between studied ventilators ranging between 16-33%.

Carlucci et al addressed the importance of configuration of tubing in leak and TV estimations during volume-guaranteed ventilation and showed that the ability of ventilators to compensate for unintentional leaks directly depends on the configuration of the circuit used (6). In the bench, they have assessed three home devices with single limb circuits either with an intentional leak or with an expiratory valve. The model consisted of three levels of leak (15, 25 and 37mL/min) during normal, obstructive, and restrictive respiratory pattern. In the absence of leaks all ventilators, irrespective of selected configuration were able to maintain TV in all respiratory conditions. In the presence of intentional leaks, all ventilators achieved to guarantee TV by increasing inspiratory pressure. However, all ventilators failed to maintain minimal TV by dropping the inspiratory pressure during unintentional leaks when a single circuit used with an expiratory valve.

Similar to that, Khirani et al (7) studied seven home ventilators with different circuit configurations. It was observed that among 5 ventilators that can be used with single limb and intentional leak only two maintained TV at its target in the presence of unintentional leaks. In two ventilators used with a single limb circuit and an expiratory valve, TV fell below the preset value. In three ventilators that can be used with a double limb circuit, only one of the ventilators overcompensated TV during unintentional leaks and TV was decreased in the other two ventilators. The authors concluded that volume guarantee mode is only effective when a single limb circuit with an intentional leak (leak port circuit) was used. Ventilators using a circuit configuration of double limb circuit or a single limb circuit and an expiratory valve may misinterpret unintentional leaks as an increase in TV and paradoxically decrease inspiratory pressure and therefore TV.

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as: Luján M, Lalmolda C, Ergan B. Basic Concepts for Tidal Volume and Leakage Estimation in Non-Invasive Ventilation. Turk Thorac J 2018; DOI: 10.5152/TurkThoracJ.2018.177

©Copyright 2018 by Turkish Thoracic Society - Available online at www.turkthoracj.org
The automatic increase in inspiratory pressure during volume guarantee mode in the presence of unintentional leaks is associated with large variations in TV (8). Six NIV devices were evaluated for the delivery of a minimal TV in three conditions associated with alveolar hypoventilation: increase in airway resistance, decrease in lung compliance and unintentional leaks. The authors defined "volume guarantee failure" as the inability to maintain TV more than 500mL and "overshooting" as a TV>650mL. In the model of increased airway resistance, five ventilators were able to maintain a minimal TV of 500mL. Of them, one ventilator overshot TV. In the model of decrease in lung compliance, five ventilators were able to maintain a minimal TV and no overshooting was observed. However, the maintenance of a minimal TV during unintentional leak was not that sufficient. Only one ventilator was able to guarantee minimal TV with overshooting, and patient-ventilator asynchrony was observed with all other devices.

**IMPLICATIONS IN CLINICAL PRACTICE**

The main goals of NIV therapy are to maintain sufficient alveolar ventilation, improve pulmonary gas exchange, assist respiratory muscles, and decrease work of breathing. The ability of a NIV device to maintain a stable TV is related to not only its pressurization capacity but also its accurate assessment of leaks and TV. Ideally a ventilator should be able to respond rapidly to changes for effective TV with and without leaks and in addition changes in respiratory system impedance. Insufficient support due to inaccurate measurement of leaks and therefore TV inevitably would cause ineffective assisted ventilation and therefore, persistent hypercapnia.

Recently, built-in software have been available for clinicians for monitoring and downloading data in NIV devices. The NIV settings are usually adjusted according to the parameters shown by the ventilator software. Clinicians should keep in mind that each NIV device is different and the reliability and the accuracy of leak and TV estimation are highly variable from one device to another. Underestimation or overestimation of leaks and TV by the software would be cause wrong adjustments. Moreover, because of underestimation of TV, clinicians usually tend to increase inspiratory pressures to maintain adequate ventilation. This would eventually lead to increase the possibility of unintentional leaks and/or hyperinflation. If there is marked increase in the inspiratory flow during compensation, several other side effects occur such as increased...
leakage, impaired mask seal, eye irritation and increased aerophagia and gastric distention. The consequences of these problems result to patient discomfort and noncompliance to NIV. This might be particularly more problematic in volume-targeted modes as these modes change IPAP depending on estimated TV. The presence of unintentional asymmetric leaks could lead to clinically significant hypoventilation because of a decrease in inspiratory pressure. An overshooting of TV during volume-targeted ventilation may cause hyperventilation, patient ventilator asynchrony, decrease in patient’s respiratory effort, and arterial carbon dioxide levels lower than apnea threshold (8,9).

Bench studies showed that the underestimation of TV is directly related to the magnitude of leaks (3). The degree of intentional leak is dependent on not only the pressure but also the interface used. The level of intentional leak is determined by the mask but estimation of this leak and therefore variations in inspiratory time and TV is determined by the ventilator (10). Many manufacturers validate the performance of their NIV device only with their own mask. For that reason each built-in software would erroneously estimate leaks and TV in the presence of a different mask/interface. Even in the condition of perfect fitting, the magnitude of intentional leaks can change up to 20 to 25% between different masks. Borel et al showed the capacity of ventilators to achieve and maintain preset IPAP is directly related to mask intentional leaks which were highly variable ranging between 30 to 45L/min (11). Increasing intentional leaks (>40L/min) due to a mask significantly impaired the capacity of all ventilators to attain and maintain a preset IPAP and reduce TV. Moreover, the amount of leaks from mask may produce patient ventilator synchrony. It was also shown that mask with larger air leaks was shown to be associated with auto-triggering and/or decreased inspiratory-trigger sensitivity (10). Underestimation of leak flow would delay expiratory trigger time and therefore increase inspiratory time and TV; whereas overestimation of leak would shorten it and decrease both parameters. Another important technical point to consider is the circuit configuration. So far, studies showed that the best option for NIV configuration for compensation of unintentional leaks and accurate estimation of TV is single limb circuit with an intentional leak (6,7). In the presence of a true expiratory valve, most NIV devices fail to perform efficiently.
Today, many centers use telemonitoring for the management of NIV support. With new developments in technology, remote adjustment of ventilatory settings by the clinician according to electronically transferred data from the patient's device can be an option (12-14). Although electronically transferred data from built-in software may provide important information in a very feasible way, clinicians should be very cautious for the heterogeneity and inaccuracy of parameters from online downloaded data provided by the different software systems of NIV devices. The lack of validation of these software and monitored parameters by independent authorities is one of the main limiting factors of its wider use.

CONCLUSION

NIV is accepted as an effective therapy both for acute and chronic respiratory failure. The success of NIV is directly related to monitoring therapy optimally. Today’s technology gives us the opportunity to monitor, even remotely, many parameters by built-in software systems of NIV devices. However, the results from bench studies showed that the accuracy and reliability of the information provided by the software systems are still questionable and external validation of these systems is an urgent need. For now, we should keep in mind that data from NIV software are helpful but should only be used in conjunction to other monitoring parameters such as the clinical status of the patient, pulse oximetry, arterial blood gas analysis, and polysomnography when needed. Finally, medical societies should ask the manufacturers for homogeneity in their algorithms estimating physiological parameters in the ventilated patient.

REFERENCES


12. Janssens JP, Borel JC, Pepin JL, et al. Nocturnal monitoring of hme non-invasive ventilation: the contribution of simple tools such as pulse oximetry, capnography,


Figure 1. Difficulties in monitoring tidal volume with active valve. P1 reflects pressure inside the tubing. P2 corresponds to the pressure inside the pneumatic valve. P1 – P2 corresponds to the difference (note than during inspiration, P2 is greater than P1, occluding the valve, and conversely during expiration, P1 is greater than P2, leading to valve opening). Finally, flow corresponds to the pneumotachograph signal placed between the ventilator and the valve (note that there is not expiratory flow signal). If non intentional leakage occurs, it is very difficult to estimate true tidal volume.
Figure 2. A. Simplified model of flow / pressure dynamics during inspiratory phase in non invasive ventilation with single circuit and intentional leakage (see text for more details). B. Simplified model of flow / pressure dynamics during expiratory phase in non invasive ventilation with single circuit and intentional leakage (see text for more details).
This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as: Luján M, Lalmolda C, Ergan B. Basic Concepts for Tidal Volume and Leakage Estimation in Non-Invasive Ventilation. Turk Thorac J 2018; DOI: 10.5152/TurkThoracJ.2018.177

©Copyright 2018 by Turkish Thoracic Society - Available online at www.turkthoracj.org
**Figure 3.** Leak test performed in the laboratory with an external pneumotachograph. In the upper panel, there is a progressive increase in pressure, with the corresponding increase in flow with the distal end of the tubing occluded and an expiratory port included in the circuit. In the lower panel, a pressure-leak plot is constructed.
Figure 4. Plot in a Microsoft Excel sheet of the same data contained in Fig 4. Observe how the correlation degree is clearly better if a second degree polynomial model (lower plot) is used instead of a first degree (linear) model (upper plot).
**Figure 5.** Flow measurements in single circuit with intentional leak. P=pressure. Flow A=Flow directly measured on the ventilator’s exit (before intentional leakage) Flow B= flow at the entry of the patient (tidal volume). Note that in the Flow A signal, the baseline level (dashed line) is displaced upwards. E-F1 corresponds to the flow reaching the ventilator during expiration. E- F2 corresponds to baseline flow leakage during expiration.
**Figure 6.** Differences in flow-time and volume-time waveform when monitoring before (upper part) and after the leaks (lower). Observe the drop in volume-time corresponding to restart of the waveform (see text for details).