End-Expiratory Lung Volume Measurement & Lung Protection

January 2018

Publications Reference List

Learn how measurement of lung volumes may help protect from stress & strain during mechanical ventilation

Learn how lung volume measurement at the bedside could affect ventilation strategy to potentially avoid collapse and over-distension

Learn more about the technology behind our FRC tools (Nitrogen Wash-in/Wash-out method and PEEP INview)

Read more about FRC and bedside lung monitoring from post-doctoral dissertations

Learn how measurement of lung volumes may help protect from stress & strain during mechanical ventilation

Reference	Summary
CHIUMELLO, Davide, et al. Lung stress and strain during mechanical ventilation for acute respiratory distress syndrome. American Journal of Respiratory and Critical Care Medicine, 2008, 178.4: 346-355.	*The aim of the study was to determine whether plateau pressure and tidal volume are adequate surrogates for stress and strain, and to quantify the stress to strain relationship in patients and control subjects. The results demonstrate that plateau pressure and tidal volume are inadequate surrogates for lung stress and strain.*
BRUNNER, Josef X.; WYSOCKI, Marc. Is there an optimal breath pattern to minimize stress and strain during mechanical ventilation? Intensive Care Medicine, 2009, 35.8: 1479-1483.	*A recent hypothesis is that lung injury is caused by excessive stress and strain. This paper elaborates on that hypothesis and proposes a new approach to optimizing the breath pattern. An index to quantify the impact of positive pressure ventilation on the lungs is defined (Stress–Strain Index, SSI) and calculated as a function of the breath pattern (tidal volume Vt and respiratory rate f) for five different levels of EELV. The EELV is the main determinant of the SSI. For a given EELV, the SSI can be minimized by an optimal Vt – f combination.*
PERCHIAZZI, Gaetano, et al. Lung regional stress and strain as a function of posture and ventilatory mode. Journal of Applied Physiology, 2011, 110.5: 1374-1383.	*The aim of this study was to explore the relationship between stress and strain on the regional level using computed tomography in anesthetized healthy pigs in two postures and two patterns of breathing. Strain is inhomogeneously distributed within the healthy lung. Prone positioning attenuates differences between dependent and nondependent regions.*
PROTTI, Alessandro, et al. Lung stress and strain during mechanical ventilation: any safe threshold? American Journal of Respiratory and Critical Care Medicine, 2011, 183.10: 1354-1362.	*The authors sought to identify a strain–stress threshold (if any) above which ventilator-induced lung damage can occur. In healthy pigs, ventilator-induced lung damage develops only when a strain greater than 1.5–2 is reached or overcome. Because of differences in intrinsic lung properties, caution is warranted in translating these findings to humans.*
GATTINONI, Luciano; CARLESSO, Eleonora; CAIRONI, Pietro. Stress and strain within the lung. Current Opinion in Critical Care, 2012, 18.1: 42-47.	*The authors describe the physiological meaning and the clinical application of the lung stress and strain concepts. End-inspiratory stress and strain, as well as the lung inhomogeneity and the stress raisers, must be taken in account when setting mechanical ventilation.*
GONZÁLEZ-LÓPEZ, Adrián, et al. Lung strain and biological response in mechanically ventilated patients. Intensive Care Medicine, 2012, 38.2: 240-247.	*Since strain has been proposed as a marker of such deformation, the authors studied the relationships between strain and matrix remodeling and inflammation markers in mechanically ventilated patients with and without acute lung injury (ALI). Increased strain is associated with a proinflammatory lung response in patients with ALI.*
PROTTI, Alessandro, et al. Lung stress and strain during mechanical ventilation: any difference between statics and dynamics?. Critical Care Medicine, 2013, 41.4: 1046-1055.	*The aim of the study was to clarify whether different combinations of dynamic and static strains, resulting in the same large global strain, constantly produce lung edema. Lung edema forms (possibly as an all-or-none response) depending not only on global strain but also on its components. Large static strains are less harmful than large dynamic strains, but not because the former merely counteracts fluid extravasation.*

Reference	Summary
PROTTI, Alessandro, et al. Role of strain rate in the pathogenesis of ventilator-induced lung edema. Critical Care Medicine, 2016, 44.9: e838-e845.	*Lungs behave as viscoelastic polymers. Harms of mechanical ventilation could then depend on not only amplitude (strain) but also velocity (strain rate) of lung deformation. The authors tested this hypothesis and found that high strain rate is a risk factor for ventilator-induced pulmonary edema, possibly because it amplifies lung viscoelastic behavior.*
BLANKMAN, Paul, et al. Lung stress and strain calculations in mechanically ventilated patients in the intensive care unit. Acta Anaesthesiologica Scandinavica, 2016, 60.1: 69-78.	*Stress and strain are parameters to describe respiratory mechanics during mechanical ventilation. Stress and strain can reliably be calculated at the bedside based on non-invasive EELV measurements during a decremental PEEP trial in patients with different diseases.*
JAIN, Sumeet V., et al. The role of high airway pressure and dynamic strain on ventilator-induced lung injury in a heterogeneous acute lung injury model. Intensive Care Medicine Experimental, 2017, 5.1: 25.	*Improperly adjusted mechanical ventilation can exacerbate ARDS causing a secondary ventilator-induced lung injury (VILI). The authors hypothesized that a peak airway pressure of 40 cm H_2O (static strain) alone would not cause additional injury in either the normal or acutely injured lung tissue unless combined with high tidal volume (dynamic strain). Both normal tissue and ALI tissue are resistant to VILI caused by overdistension alone, but when combined with a high dynamic strain, significant tissue injury develops.*
XIE, Jianfeng, et al. The effects of low tidal ventilation on lung strain correlate with respiratory system compliance. Critical Care, 2017, 21.1: 23.	*The authors aimed to investigate the effects of different tidal volumes on lung strain in ARDS patients who had various levels of respiratory system compliance. Respiratory system compliance affected the relationships between tidal volume and driving pressure and lung strain in ARDS patients. These results showed that increasing tidal volume induced lung injury more easily in patients with low respiratory system compliance.*

Learn how lung volume measurement at the bedside could affect ventilation strategy to potentially avoid collapse and over-distension

Reference	Summary
HEWLETT, A. M., et al. Functional residual capacity during anaesthesia II: spontaneous respiration. BJA: British Journal of Anaesthesia, 1974, 46.7: 486-494.	*Pivotal paper on loss of FRC during anaesthesia in spontaneous respiration. Functional residual capacity has been measured by helium dilution in 26 spontaneously breathing patients before and immediately after anaesthesia, which was induced with thiopentone and maintained with halothane. The mean reduction was 390 ml (16.1% of pre-induction value) and the change was highly significant.*
HEWLETT, A. M., et al. Functional residual capacity during anaesthesia III: artificial ventilation. BJA: British Journal of Anaesthesia, 1974, 46.7: 495-503.	*Pivotal paper on loss of FRC during anaesthesia in mechanical ventilation. The helium dilution technique has been used to measure the FRC of 13 patients before and during anaesthesia with paralysis and artificial ventilation, and also in 5 conscious subjects during spontaneous and artificial ventilation without paralysis. After induction of anaesthesia the mean reduction in FRC was 297 ml or 15.4% of the preoperative value and the change was highly significant.*

Reference	Summary
TERRAGNI, Pier Paolo, et al. Tidal hyperinflation during low tidal volume ventilation in acute respiratory distress syndrome. American Journal of Respiratory and Critical Care Medicine, 2007, 175.2: 160-166.	*Tidal volume and plateau pressure limitation decreases mortality in acute respiratory distress syndrome. Computed tomography demonstrated a small, normally aerated compartment on the top of poorly aerated and nonaerated compartments that may be hyperinflated by tidal inflation. Limiting tidal volume to 6 ml/kg predicted body weight and plateau pressure to 30 cm H_2O may not be sufficient in patients characterized by a larger nonaerated compartment.*
VON UNGERN-STERNBERG, Britta S., et al. The impact of positive end-expiratory pressure on functional residual capacity and ventilation homogeneity impairment in anesthetized children exposed to high levels of inspired oxygen. Anesthesia & Analgesia, 2007, 104.6: 1364-1368.	*During the application of a very low PEEP of 3 cm H_2O, FRC and ventilation distribution decreased significantly at an FiO_2 of 1.0 compared with that at an FiO_2 of 0.3. This decrease could be counterbalanced by the administration of PEEP of 6 cm H_2O, indicating that a low level of PEEP is sufficient to maintain FRC and ventilation distribution regardless of the oxygen concentration.*
BLANKMAN, Paul; GOMMERS, Diederik. Lung monitoring at the bedside in mechanically ventilated patients. Current Opinion in Critical Care, 2012, 18.3: 261-266.	*Nowadays, FRC can be measured without the use of tracer gases and without disconnection from the ventilator. EIT is another noninvasive bedside monitoring tool that provides regional ventilation distribution images and can be used for qualitative and quantitative assessment of regional change in ventilation after a ventilator change. These new noninvasive techniques are discussed and seem promising to help clinicians to improve their ventilator settings in the individual patient at the bedside.*
SATOH, Daizoh, et al. Impact of changes of positive end-expiratory pressure on functional residual capacity at low tidal volume ventilation during general anesthesia. Journal of Anesthesia, 2012, 26.5: 664-669.	*Several reports in the literature have described the effects of positive end-expiratory pressure (PEEP) level upon functional residual capacity (FRC) in ventilated patients during general anesthesia. This study compares FRC in mechanically low tidal volume ventilation with different PEEP levels during upper abdominal surgery.*
CORTES, Gustavo A.; MARINI, John J. Two steps forward in bedside monitoring of lung mechanics: transpulmonary pressure and lung volume. Critical Care, 2013, 17.2: 219.	*In this update, the authors briefly address the management rationale and technical background for monitoring FRC and calculating PTP, placing major emphasis on the potential clinical applicability of these two missing pieces in bedside monitoring.*
GODET, Thomas, et al. How to monitor a recruitment maneuver at the bedside. Current Opinion in Critical Care, 2015, 21.3: 253-258.	*An effective recruitment maneuver is expected to reinflate nonaerated lung units. End-expiratory lung volume, compliance, dead space, volumetric capnography, and bedside imaging techniques such as lung ultrasound and electrical impedance tomography have all different strengths and weaknesses. A multimodal and multiparametric approach could be a valuable option for bedside monitoring of recruitment maneuvers both in the ICU and in the operative room.*
CHEN, Lu; BROCHARD, Laurent. Lung volume assessment in acute respiratory distress syndrome. Current Opinion in Critical Care, 2015, 21.3: 259-264.	*Although lung volume measurements are still limited to research area of ARDS, recent progress in technology provides clinicians more opportunities to evaluate lung volumes noninvasively at the bedside and may facilitate individualization of ventilator settings based on the specific physiological understandings of a given patient.*
CASSERLY, Brian, et al. End-expiratory volume and oxygenation: targeting PEEP in ARDS patients. Lung, 2016, 194.1: 35-41.	*ΔEELV can be measured from a decremental PEEP curve. Since ΔEELV is highly correlated with ΔP_aO_2, measures of $\Delta P_aO_2/\Delta PEEP$ may provide a surrogate for measures of ΔEELV/ΔPEEP. Combining measures of ΔEELV/ΔPEEP with measures of Crs may provide a novel means of determining optimal PEEP in patients with ARDS.*

KAMUF, Jens, et al. Endexpiratory lung volume measurement correlates with the ventilation/perfusion mismatch in lung injured pigs. Respiratory Research, 2017, 18.1: 101.	*The present study examines the association between EELV changes and VA/Q distribution and the possibility to predict VA/Q normalization by means of EELV in a porcine model. EELV measurement depicts PEEP-induced lung recruitment and is strongly associated with normalization of the VA/Q distribution. Determination of EELV could be an intriguing addition in the context of lung protection strategies.*

Learn more about the technology behind our FRC tools (Nitrogen Wash-in/Wash-out method and PEEP INview)

OLEGÅRD, Cecilia, et al. Estimation of functional residual capacity at the bedside using standard monitoring equipment: a modified nitrogen washout/washin technique requiring a small change of the inspired oxygen fraction. Anesthesia & Analgesia, 2005, 101.1: 206-212.	*The authors developed a modified nitrogen washin/washout technique based on standard monitors using inspiratory and end-tidal gas concentration values for functional residual capacity (FRC) measurements in patients with acute respiratory failure (ARF). This study shows good precision of FRC measurements with standard monitors using a change in FiO_2 of only 0.1.*
BIKKER, Ido G., et al. End-expiratory lung volume during mechanical ventilation: a comparison with reference values and the effect of positive end-expiratory pressure in intensive care unit patients with different lung conditions. Critical Care, 2008, 12.6: R145.	*The aim of this study was to measure EELV in mechanically ventilated intensive care unit (ICU) patients with different types of lung pathology at different PEEP levels, and to compare them with predicted sitting FRC values, arterial oxygenation, and compliance values. In combination with compliance, end-expiratory lung volume can provide additional information to optimize the ventilator settings.*
CHIUMELLO, Davide, et al. Nitrogen washout/washin, helium dilution and computed tomography in the assessment of end expiratory lung volume. Critical Care, 2008, 12.6: R150.	*The authors compared the EELV measured by spiral computed tomography (CT) taken as gold standard with the lung volume measured with the modified nitrogen washout/washin and with the helium dilution technique. The EELV measurement with modified nitrogen washout/washin technique (at all lung volumes) correlates well with CT scanning and may be easily used in clinical practice.*
LAMBERMONT, Bernard, et al. Comparison of functional residual capacity and static compliance of the respiratory system during a positive end-expiratory pressure (PEEP) ramp procedure in an experimental model of acute respiratory distress syndrome. Critical Care, 2008, 12.4: R91.	*The authors compared FRC, static thoraco-pulmonary compliance (Crs) and PaO_2 evolution in an experimental model of acute respiratory distress syndrome (ARDS) during a reversed, sequential ramp procedure of PEEP changes. Their results indicate that combined FRC and Crs measurements may help to identify the optimal level of PEEP. Indeed, by considering the value of both parameters, during a sequential ramp change of PEEP from 20 cm H_2O to 0 cm H_2O by steps of 5 cm H_2O, the end of overdistension may be identified by an increase in Crs and the start of derecruitment by an abrupt decrease in FRC.*
BIKKER, Ido G., et al. Lung volume calculated from electrical impedance tomography in ICU patients at different PEEP levels. Intensive Care Medicine, 2009, 35.8: 1362.	*The study compares the relationship between end-expiratory lung volume (EELV) and changes in end-expiratory lung impedance (EELI) measured with electrical impedance tomography (EIT) at the basal part of the lung at different PEEP levels in a mixed ICU population. During a PEEP trial, the assumption of a linear relationship between change in global tidal impedance and tidal volume cannot be used to calculate EELV when impedance is measured at only one thoracic level just above the diaphragm.*

BIKKER, Ido G., et al. Measurement of end-expiratory lung volume in intubated children without interruption of mechanical ventilation. Intensive Care Medicine, 2009, 35.10: 1749-1753.	*The authors evaluated the feasibility and precision of an intensive care unit (ICU) ventilator with an in-built nitrogen washout/washin technique in mechanically ventilated pediatric patients. This ICU ventilator can measure EELV with precision, and can easily be used for mechanically ventilated pediatric patients.*
VEENA, Sheshadri, et al. Functional residual capacity tool: A practical method to assess lung volume changes during pulmonary complications in mechanically ventilated patients. Indian Journal of Critical Care Medicine: Peer-reviewed, Official Publication of Indian Society of Critical Care Medicine, 2010, 14.3:151-153.	*The authors describe a patient in whom they used a functional residual capacity (FRC) tool available on a critical care ventilator to identify the loss of lung volume associated with pulmonary complications and increase in FRC with the application of a recruitment maneuver. The case report underlines the utility of the FRC tool in rapid visualization of the lung volume changes and the effects of application of corrective strategies in patients receiving mechanical ventilation.*
OLEGÅRD, C., et al. Validation and clinical feasibility of nitrogen washin/washout functional residual capacity measurements in children. Acta Anaesthesiologica Scandinavica, 2010, 54.3: 370-376.	*The authors introduced a modified N2 washout method utilizing a change of* FiO_2 *of 0.1 for FRC measurement in adult respiratory monitoring. This study validated the algorithm in a pediatric lung model and investigated the stability and feasibility in a pediatric peri-operative and intensive care setting.*
DELLAMONICA, J., et al. PEEP-induced changes in lung volume in acute respiratory distress syndrome. Two methods to estimate alveolar recruitment. Intensive Care Medicine, 2011, 37.10: 1595.	*Positive end-expiratory pressure (PEEP) contributes to increased end-expiratory lung volume (EELV) and to improved oxygenation, but differentiating recruitment of previously nonaerated lung units from distension of previously open lung units remains difficult. This study evaluated simple methods derived from bedside EELV measurements to assess PEEP-induced lung recruitment while monitoring strain.*
KALENKA, Armin, et al. End-expiratory lung volume in patients with acute respiratory distress syndrome: a time course analysis. Lung, 2016, 194.4: 527-534.	*End-expiratory lung volume (EELV) is FRC plus lung volume increased by the applied positive end-expiratory pressure (PEEP). Measurement using the modified nitrogen multiple breath washout technique may help titrating PEEP during ARDS and allow determining dynamic lung strain (tidal volume over EELV) in patients ventilated with PEEP. In this observational study, the authors found that bedside measurement of EELV may be a novel approach to individualise lung-protective ventilation on the basis of calculation of dynamic strain.*

Read more about FRC and bedside lung monitoring from post-doctoral dissertations

OLEGARD, C. Functional residual capacity. Development of new monitoring techniques for critically ill patients. 2010.	*Functional residual capacity (FRC) and end-expiratory lung volume (EELV) are important parameters for respiratory monitoring in critically ill adult and paediatric patients. Until now we have lacked clinically useful methods to measure these lung volumes. In this thesis two methods for bedside measurements of FRC in mechanically ventilated patients have been developed and evaluated. The first method (FRCflux) is based on quantification of metabolic gas fluxes of* O_2 *and* CO_2 *during a short apnoea. The second method is a modified nitrogen wash-out/wash-in technique (FRCN2) based on standard monitoring equipment.*

BREWER, Lara Marie. Novel bedside techniques for functional residual capacity measurement. The University of Utah, 2011.	*This dissertation describes the development, clinical feasibility testing and clinical accuracy assessment of two novel bedside models for FRC measurement that use tracer gas washin/washout. The first model, called the modified multiple breath nitrogen washout model, makes use of end-tidal gas measurements to measure FRC. The second model, which is called the partial rebreathing carbon dioxide model, allows FRC measurement during fixed inspired oxygen concentration, making FRC measurement possible in the operating room, where circle breathing systems are common.*
DELLAMONICA, J. Variations du volume pulmonaire au cours de la ventilation mécanique : modes ventilatoires et manuvres positionnelles. Médecine humaine et pathologie. Université Paris-Est, 2012. Francais.	*Lung volume measurements remained limited to clinical research until recently when the nitrogen washout/washin technique has been adapted for bedside use and implemented in an intensive care ventilator. The aim of this work was to test the nitrogen washout/washin method in clinical conditions of ARDS treatment with high Positive End Expiratory Pressure (PEEP) and high oxygen fraction (FiO_2). Once this preliminary validation study was realized, the author used the technique to assess the amount of lung recruitment induced by PEEP and positioning.*
BIKKER, Ido. Optimizing mechanical ventilation by bedside lung monitoring systems in critically ill patients. 2015.	*This thesis presents the results of studies aiming at the improvement of bedside PEEP settings to prevent additional lung injury during the challenging task of mechanical ventilation. It is clear that low tidal volume should not only be used in patients with acute respiratory distress syndrome (ARDS) but also in non-ARDS patients on the ICU, and even during mechanical ventilation in the operation room. However, the application of PEEP remains a matter of debate. The aim of this thesis is to guide PEEP settings during mechanical ventilation of patients in the ICU, with the use of EIT and/or specific equipment to measure FRC.*
BLANKMAN, Paul. Bedside lung monitoring in order to optimize ventilator settings in ICU patients. 2016.	*Mechanical ventilation set according to standard protocols or tables is not sufficient for the individual patient. Therefore, we should aim to personalized mechanical ventilation strategies and personalized physiology. The aim of this thesis is to optimize PEEP and the level of ventilatory assist in the individual patient at the bedside, in order to minimize VILI.*

Imagination at work

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