

Measurement of the Respiratory Functional Residual Capacity on an Artificial Lung System

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Abstract

Decreases in functional residual capacity (FRC), the residual respiratory volume following an expiration, are associated with the application of anesthesia and supine body positioning, both common in the ICU. We are developing two non-invasive methods of measuring the FRC on patients under mechanical ventilation. FRC increases are typically accomplished by increasing the Positive End Expiratory Pressure (PEEP) until the arterial O₂ content is saturated; however, increased PEEP may also cause a decrease in cardiac output due to the increased thoracic cavity pressure, resulting in a net decreased O₂ delivery. Measurement of the FRC will be useful in optimizing the application of PEEP to maximize O₂ delivery. FRC determination as a function of PEEP was made on a test lung using a partial CO₂ rebreathing method and an N₂ washout method in order to compare their accuracy. The CO₂ rebreathing method uses Fick's principle along with a perturbation of gas concentrations initiated by partial rebreathing. The N₂ washout method also utilizes Fick's principle, but creates the perturbation through an increase in inspired O₂ concentration. Preliminary FRC measurements were made using the NICO₂ system which includes a pneumotachograph for volumetric measurements and a CAPNOSTAT™ sensor for CO₂ concentration measurement. Although both methods correlated to measured FRC volumes in the test lung, the N₂ washout method resulted in greater precision and less variability, most likely due to the greater magnitude of perturbation that is made and the use of data from multiple breaths. Both methods will require further bench testing to verify their accuracy within typical ranges of mechanical ventilation variables, followed by *in vivo* studies in order to characterize any inherent physiologic implications and to determine repeatability.

Introduction

The measurement of the functional residual capacity (FRC) can be used to optimize the titration of Positive End Expiratory Pressure (PEEP) during mechanical ventilation. The objective of this study is to develop a simple tool that can be used at the bedside to monitor FRC while minimizing interference with the patient. This measurement would be incorporated into an existing tool that monitors cardiac output, PEEP, and arterial oxygen saturation. FRC monitoring would be useful in numerous applications, including the determination of the minimum PEEP level at which FRC increases plateau, determination of the need for a recruitment maneuver, as well as the necessary PEEP required to maintain FRC following a recruitment maneuver, identification of chronic FRC decline or improvement, and any other applications that require the optimization of PEEP.

FRC monitoring was performed on a test lung using two methods (the CO₂ partial rebreathing method and the N₂ washout method) in order to determine the accuracy, as well as any potential benefits or drawbacks of each method. Both methods rely on Fick's principle, as well as a perturbation of gas concentrations, in order to make the measurement non-invasively. The perturbation for the CO₂

rebreathing method consists of periodic rebreathing of expired volume to temporarily increase the end tidal CO₂ concentration (etCO₂) and decrease the CO₂ elimination rate (VCO₂). The perturbation of the N₂ washout method consists of an increase in inspired O₂ concentration. The advantages of the CO₂ rebreathing method include a smaller effect on the patient, the direct use of the fast CO₂ sensor, and the ability to simultaneously obtain cardiac output measurements. The advantages of the N₂ washout method include a larger signal to noise ratio due to a larger perturbation of gas concentration, the insolubility of N₂ in blood and tissue, and the ability to average measurements from multiple breaths.

Methodology

Instrumentation

The methods were tested on the bench using a mechanical lung simulator (TTL, Michigan Instruments, Grand Rapids, MI). A fan was placed in the lung to ensure adequate gas mixing. During testing of the methods the test lung was ventilated using a Siemens 900C ventilator and 250 ml/min of CO₂ were infused into the lung to approximate the CO₂ emanating from the body. Various levels of PEEP and test lung compliance were used to alter the simulated FRC. An anesthetic gas monitor (Datex

Ultima, Helsinki, Finland) was used to measure the ratio of the $\Delta_{\min\text{-max}} \text{O}_2$ to $\Delta_{\min\text{-max}} \text{CO}_2$ concentrations. The monitor drew a sidestream flow of 210 ml/min from the breathing circuit. The ratio was used in the N_2 washout method, but the concentrations were not directly used to determine the inspired and expired CO_2 volume due to the time delay created by the side stream configuration of the monitor. The inspired and expired volumes and CO_2 concentrations were measured using a Respirationics-Novamatrix Non-Invasive Cardiac Output Monitor (NICO₂) that included the Series 3 flow and concentration sensors as detailed below.

Pneumotachograph Flow Measurement

In order to determine expired and inspired volumes, the integral of the expired and inspired flow rates was determined. Flow rate measurement was made using a pneumotachograph placed in the breathing circuit as detailed in Figure 1. The NICO₂ pneumotachograph is a fixed orifice differential pressure flow meter. This type of flow meter consists of a flow obstruction that reduces the annular area of the breathing tube and two pressure sensors (upstream and downstream of the obstruction). The pressure drop across the obstruction is measured by the pressure sensors and is proportional to the square of the flow rate [1]. This pressure differential is converted to a corresponding flow rate using a calibration factor. The flow rate was then used in

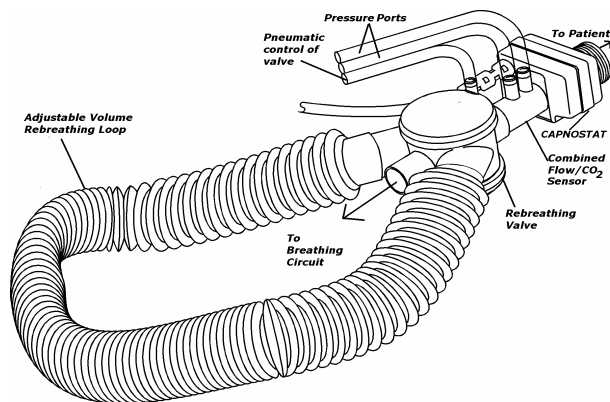


Figure 1 – NICO₂ sensor including the switchable rebreathing deadspace loop used by the NICO₂ monitor

conjunction with the concentration data to provide the volumetric flow rate of CO_2 and to estimate the flow rate of O_2 .

CO_2 Concentration Measurement

The CO_2 concentration was measured with an infrared (IR) mainstream CAPNOSTAT™ III CO_2 sensor. CO_2 has a strong absorption band in the near

IR region. IR absorption due to CO_2 can be distinguished from absorption bands of other elements that may be present in the breathing circuit (H_2O , N_2O) through careful characterization and the use of narrow band pass optical filters [1]. The sensor utilizes this absorption property to measure the CO_2 concentration in the gas. It consists of an IR radiation source that passes a beam through a port on the mainstream ventilation tube (Figure 1). A photodetector on the other side of the port, consisting of a “solid-state sensor with broad-spectral sensitivity and an optical filter that transmits radiation in the appropriate region,” absorbs the remaining light [1]. An electronic signal corresponding to the amount of remaining light is compared to the energy of the radiation source and a calibration curve in order to quantify the CO_2 concentration in the mainstream ventilation tube. The calibration settings are stored in the NICO₂ monitor and a reference channel is used to account for any optical changes in the sensor, eliminating the need for recalibrations [2].

Combination of Flow and CO_2 Measurements

The CO_2 concentration and the flow rate vary continually during respiration. In order to provide accurate volumetric flow rate measurements, the flow and concentration measurements are taken 100 times per second and each portion of data is summed to give the integral volumetric measurements. In order for this calculation to be accurate, the pneumotachograph and concentration sensor signals must be properly matched in frequency. This is achieved by locating the sensors as close together as possible (Figure 1) and matching the frequency response of the two sensors [1].

Test Lung Calibration Verification

The test lung volume increments, as indicated on the lung, were verified by injecting various volumes of CO_2 into the lung chamber with the chamber propped open throughout its testing range. The final CO_2 concentration after injection was then measured and used to calculate the FRC volume.

N_2 Washout Method

In this system, the oxygen uptake (V_{O_2}) was calculated using V_{CO_2} as measured by the NICO₂ and the ratio of the $\Delta_{\min\text{-max}} \text{O}_2$ to $\Delta_{\min\text{-max}} \text{CO}_2$ concentrations as measured by the anesthetic gas monitor. The ratio was used to transform the V_{CO_2} per breath to the V_{O_2} per breath. The O_2 and CO_2 waveforms are essentially mirror images [3]. This enabled the use of the fast CO_2 sensor to estimate the O_2 concentration. The V_{O_2} and V_{CO_2} measurements were then used to calculate the change in volume of nitrogen (V_{N_2}) expired due to a step change in

inspired O₂ concentration (FiO₂). The FiO₂ was adjusted using an air/O₂ blender. In the N₂ washout method, the change in V_{N₂} with a change in FiO₂ was measured to determine the FRC using equation 1. N₂ concentration was calculated as 1-F_{O₂}-F_{CO₂}. The excreted V_{N₂} was calculated as the integral of the change in V_{O₂} above baseline, since the change in FiO₂ has a negligible effect on F_{CO₂} and V_{CO₂}. Similar methodology to perform the N₂ washout method is described by Fretschner [4].

$$\text{FRC} = (\text{sum } V_{O_2}[n] - V_{O_2} \text{ baseline}) / (\text{Fet}_{O_2} - \text{Fet}_{O_2} \text{ baseline}) \quad (\text{Equation 1})$$

CO₂ Rebreathing Method

In this method, the CO₂ elimination rate (V_{CO₂}) was measured by the NICO₂ monitor directly using the fast CO₂ sensor. The NICO₂ monitor also controlled a rebreathing valve set to initiate 35 seconds of rebreathing every 3 minutes. The change in V_{CO₂} with the change in rebreathing was measured to determine the FRC using equation 2. Because CO₂ is a very blood and tissue soluble gas, measurements from only a single breath were used in the calculations in order to minimize dynamic errors.

$$\text{FRC} = (V_{CO_2}[n-1] - V_{CO_2}[n]) / (\text{Fet}_{CO_2}[n] - \text{Fet}_{CO_2}[n-1]) \quad (\text{Equation 2})$$

Results

As displayed in Figure 2, measurement of the test lung FRC resulted in verification of the calibration markings on the lung, as well as verification that the test lung FRC as marked at zero volume was 901cc. An additional 130cc were added to the measured test lung volumes to account for the dead space volume in the tubing between the test lung and the NICO₂ sensors approximating the trachea volume.

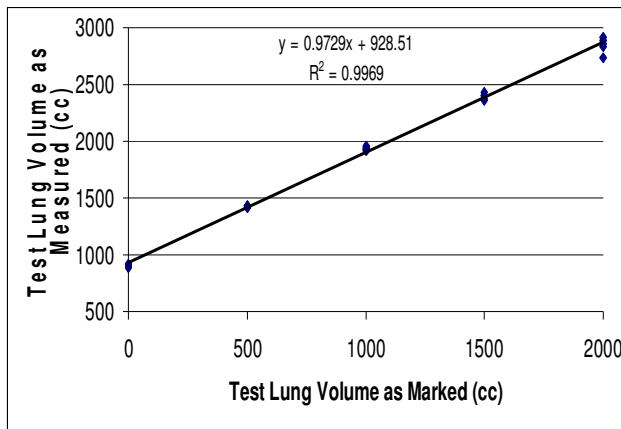


Figure 2 – Verification of Test Lung Calibration

Figure 3 displays the FRC measurements that were made using the N₂ washout method. The correlation between the calculated and measured FRC was linear and tight with an R² of 0.9977.

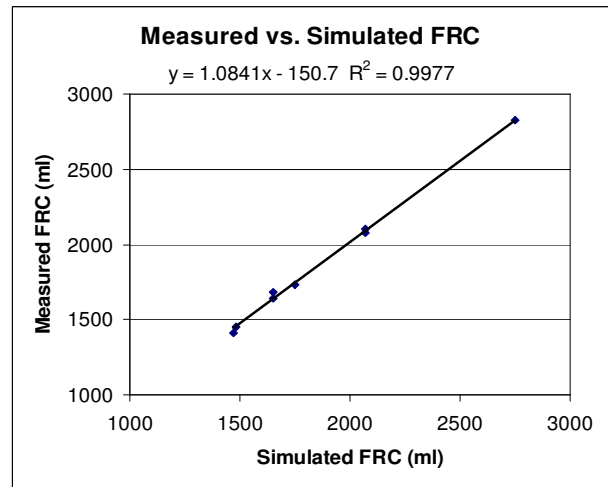


Figure 3 – Preliminary FRC measurements with the N₂ Washout Method

The measurements of the FRC using the CO₂ rebreathing method are found in Figure 4. The measured FRC using this method also correlated well with the actual FRC; however, the fit was looser than the N₂ washout method with an R² of only 0.961.

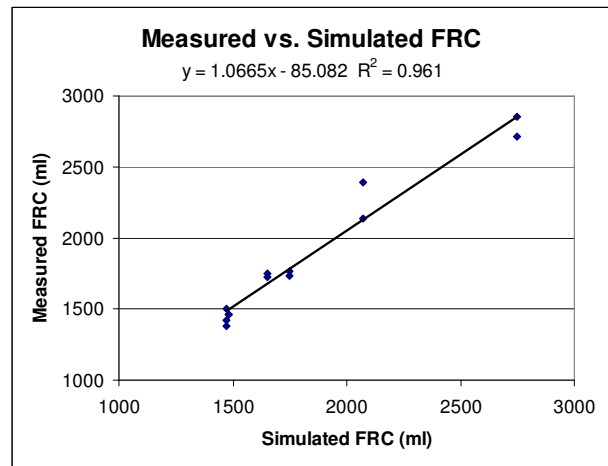


Figure 4 – Preliminary FRC measurements with the CO₂ Rebreathing Method

Discussion and Conclusions

The bench study of these methods was effective in establishing both as potentially effective methods of measuring and monitoring FRC. The N₂ washout

method returned data that more closely correlated with the actual FRC over the measured range than the CO₂ rebreathing method. The CO₂ rebreathing method also resulted in outliers that could be significant if used as single points in a clinical setting. The most significant outlier was 250mL higher than the actual FRC volume. Although the N₂ washout method appeared to be more accurate and consistent than the CO₂ rebreathing method, both may be sufficiently accurate for clinical use. The CO₂ rebreathing method may be preferable with some patients due to the smaller perturbation that is made to the patient's respiratory concentrations. Additional bench data is needed to determine the accuracy of the methods throughout the range of normal mechanical ventilation operation and to establish the statistical significance of the conclusions. Both methods will also require testing en vivo in order to establish the repeatability of the methods as well as to characterize the impact of any physiologic interactions between the lung tissue and CO₂ concentrations.

References

- [1] Gravenstein JS, Jaffe MB, Paulus DA. Capnography: Clinical Aspects. Cambridge University Press 2004. Cambridge, UK. pp. 399-425.
- [2] CO₂SMO Plus User's Manual. Novamatrix Medical Systems Inc. 1999 August. pp. 9-10
- [3] Weingarten M, "Respiratory Monitoring of Carbon Dioxide and Oxygen: A Ten-Year Perspective." Journal of Clinical Monitoring. 1990 July. 6(3) pp. 217-225
- [4] Fretschner R, Deusch H, Weitnauer A, Brunner JX, "A simple method to estimate functional residual capacity in mechanically ventilated patients." Intensive Care Medicine 1993. vol. 19, pp. 372-376.