

# Relationship Between Functional Residual Capacity, Respiratory Compliance, and Oxygenation in Patients Ventilated After Cardiac Surgery

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**BACKGROUND:** Measurement of functional residual capacity (FRC) is now possible at bedside, during mechanical ventilation. **OBJECTIVES:** To determine the relationship of measured absolute and relative predicted FRC values to oxygenation and respiratory-system compliance, and to identify variables that influence FRC in ventilated patients after cardiac surgery. **METHODS:** We retrospectively analyzed data from 99 patients ventilated after cardiac surgery. Each patient underwent an alveolar recruitment maneuver and was then ventilated with a positive end-expiratory pressure of 10 cm H<sub>2</sub>O and a tidal volume of 6–8 mL/kg predicted body weight. We measured quasi-static 2-point compliance of the respiratory system, FRC (with the oxygen-wash-out method), P<sub>aO<sub>2</sub></sub>, and fraction of inspired oxygen (F<sub>IO<sub>2</sub></sub>). We indexed the FRC values to predicted FRC reference values from sitting and supine healthy volunteers. **RESULTS:** Correlation analyses revealed no meaningful association between FRC and P<sub>aO<sub>2</sub></sub>/F<sub>IO<sub>2</sub></sub> ( $r^2$  0.20,  $P < .001$ ). There was a moderate association between absolute FRC and respiratory-system compliance ( $r^2$  0.50,  $P < .001$ ). Indexing the absolute measured FRC values to the predicted FRC values did not improve the correlation. We conducted multiple linear regression analyses of height, weight, age, sex, presence of mild chronic obstructive pulmonary disease, minute volume, and peak inspiratory pressure during ventilation, and revealed weight, minute volume, and peak inspiratory pressure ( $r^2 = 0.65$ ) as independent covariates of FRC. **CONCLUSIONS:** Indexing the measured FRC values to the predicted supine and sitting FRC values does not improve the association between P<sub>aO<sub>2</sub></sub>/F<sub>IO<sub>2</sub></sub> and respiratory-system compliance. In mechanically ventilated patients after cardiac surgery, FRC is influenced more by the ventilator settings than by physiologic variables (as in spontaneously breathing persons). *Key words:* functional residual capacity; FRC; mechanical ventilation; oxygenation; respiratory compliance; postoperative; cardiac surgery; alveolar recruitment maneuver. [Respir Care 2010;55(5):589–594. © 2010 Daedalus Enterprises]

## Introduction

Despite knowing the influence of many variables on arterial oxygenation, including atelectasis, shunt, amount

of lung edema, global and pulmonary hemodynamics, oxygen consumption, and levels of hemoglobin, many clinicians look only at oxygenation variables to describe lung function in ventilated patients. For example, the ratio of P<sub>aO<sub>2</sub></sub> to fraction of inspired oxygen (F<sub>IO<sub>2</sub></sub>) is used to quantify the amount of alveolar collapse or recruitment in post-operatively ventilated patients<sup>1,2</sup> and in patients with acute respiratory distress syndrome/acute lung injury (ALI).<sup>3-5</sup>

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In the clinical setting,  $P_{aO_2}/F_{IO_2}$  seems to be the preferred method of assessing lung function.<sup>6</sup>

As the lung volume at end-expiration (ie, the functional residual capacity [FRC]) is the variable directly affected by many therapeutic interventions, including positive end-expiratory pressure (PEEP), alveolar recruitment maneuvers, and endotracheal suctioning, monitoring of FRC has been recommended<sup>7</sup>; however, mainly for technical reasons, FRC is not routinely measured at the bedside.

Recently, bedside FRC-measurement techniques with clinically acceptable accuracy and repeatability have been presented,<sup>8,9</sup> but how FRC measurements can be used to guide respiratory therapy is under debate. As no normal FRC values for mechanically ventilated patients have been described, absolute FRC values have been compared to reference values obtained in spontaneously breathing sitting persons.<sup>10</sup> But mechanical ventilation, PEEP, and supine patient position may lead to a composite of closed, open, expanded, and hyperinflated alveoli. FRC obtained in spontaneously breathing persons is influenced by sex, weight, height, and age. During mechanical ventilation, variables such as airway pressure may have a more profound influence on FRC than do sex, weight, height, and age, so the comparison with those reference values seems questionable.

To study the role of FRC measurements in ventilated patients we conducted this retrospective data analysis to compare absolute and relative FRC values with commonly measured lung-function variables. Our primary goal was to determine the relationship of absolute and relative FRC to oxygenation and respiratory-system compliance ( $C_{RS}$ ). Our secondary goal was to study the influence of demographic and ventilator-setting variables on FRC in mechanically ventilated patients.

## Methods

We retrospectively analyzed the data of 99 patients from 3 previous studies.<sup>11-13</sup> The data reported here were collected before the patients underwent the protocol procedures (suctioning and recruitment, described elsewhere<sup>11-13</sup>). Patients were transferred to the intensive care unit after uncomplicated elective cardiac surgery. The exclusion criteria were: age < 18 y; hemodynamic instability (intra-aortic balloon pump, adrenaline > 0.05  $\mu\text{g}/\text{kg}/\text{min}$ , dobutamine > 5  $\mu\text{g}/\text{kg}/\text{min}$ , or milrinone > 0.3  $\mu\text{g}/\text{kg}/\text{min}$ ); severe pre-existing chronic obstructive pulmonary disease (COPD, forced expired volume in the first second or vital capacity below predicted value minus 2 standard deviations); or absence or withdrawal of informed consent.

All patients were mechanically ventilated with pressure-controlled biphasic intermittent positive airway pressure ventilation (BIPAP) (Evita XL, Dräger Medical, Lübeck,

Germany). PEEP was set to 10 cm  $\text{H}_2\text{O}$ . Peak inspiratory pressure (PIP) was adjusted to deliver a tidal volume ( $V_T$ ) of 6–8 mL/kg predicted body weight.  $F_{IO_2}$  was set to 0.4, with a few exceptions; a maximum of  $F_{IO_2}$  of 0.6 was used at the attending physician's discretion. Respiratory rate was adjusted to achieve normocapnia. Patients were sedated with continuous infusion of propofol and intermittent boluses of piritramid. No neuromuscular blockade was administered. Spontaneous breathing was allowed.

## Study Protocol

We used an alveolar recruitment maneuver in which PEEP and PIP were gradually increased until PEEP was 15 cm  $\text{H}_2\text{O}$  and PIP was 40 cm  $\text{H}_2\text{O}$ , or  $V_T$  was 18 mL/kg (at PEEP of 15 cm  $\text{H}_2\text{O}$ ). That PEEP and PIP (or  $V_T$ ) were maintained for 10 breaths, then PEEP and PIP were gradually decreased to their previous settings (BIPAP mode with PEEP of 10 cm  $\text{H}_2\text{O}$  and PIP set to deliver a  $V_T$  of 6–8 mL/kg predicted body weight).<sup>14</sup> Two minutes after the alveolar recruitment maneuver the FRC measurement was started. At the end of the FRC measurement (about 15 min after the alveolar recruitment maneuver) we measured the mean quasi-static  $C_{RS}$ , without an end-inspiratory pause, during 10 ventilator breaths. We calculated  $C_{RS}$  as  $V_T$  divided by the pressure difference between the end-inspiratory pressure and PEEP ( $n = 67$ ). We did not measure  $C_{RS}$  if the patient was making spontaneous breathing efforts, which was the case in 32 patients. We also sampled arterial blood and measured (ABL 505, Radiometer, Copenhagen, Denmark) pH,  $P_{aO_2}$ ,  $P_{aCO_2}$ , base excess, hemoglobin, and lactate, and calculated  $P_{aO_2}/F_{IO_2}$ . At the same time we recorded heart rate, mean arterial pressure, and central venous pressure.

## Measurement of Functional Residual Capacity

The LUFU system (Dräger Medical, Lübeck, Germany) estimates FRC by oxygen wash-out, which is a variant of the multiple-breath nitrogen wash-out method.<sup>15</sup> A side-stream oxygen analyzer calculates FRC from the end-inspiratory and end-expiratory oxygen concentrations during a step-change of the inspired oxygen concentration. The measurement is started by increasing the  $F_{IO_2}$  by at least 0.1 (wash-in).<sup>12</sup> FRC measurement is terminated automatically when the accumulated net ventilated volume is greater than 8 times the calculated FRC. After termination of measurement,  $F_{IO_2}$  is lowered back to baseline (wash-out). We calculated the mean FRC following one wash-in and the consecutive wash-out.

## Statistical Analysis

We indexed FRC to the relative predicted sitting FRC with the formulas:

Table 1. Demographic Data

Female/male ( <i>n</i> )	26/73
Age (mean $\pm$ SD y)	68 $\pm$ 9
Height (mean $\pm$ SD cm)	173 $\pm$ 9
Weight (mean $\pm$ SD kg)	84 $\pm$ 14
Body mass index (mean $\pm$ SD kg/m <sup>2</sup> )	28 $\pm$ 4
Left-ventricular ejection fraction (mean $\pm$ SD %)	62 $\pm$ 14
Chronic obstructive pulmonary disease ( <i>n</i> )	19
EuroSCORE (mean $\pm$ SD)	5.1 $\pm$ 2.6
Coronary artery disease ( <i>n</i> )	67
Valve disease ( <i>n</i> )	59
Procedure ( <i>n</i> )	
Coronary artery bypass graft	47
Valve surgery	17
Combination	35

EuroSCORE = score on European system for cardiac operative risk evaluation<sup>18</sup>

Men: [(2.34 height) + (0.009 age)] - 1.09

Women: [(2.24 height) + (0.001 age)] - 1.00

in which height is in meters and age is in years.<sup>16</sup>

We indexed FRC to the relative predicted supine FRC with the formulas:

Men: (5.48 height) - 7.05

Women: (1.39 height) - 0.424

in which height is in meters.<sup>17</sup>

We assessed correlations by calculating Pearson's coefficient (*r*) and the coefficient of determination (*r*<sup>2</sup>). We also performed multivariate linear regression, in which we considered sex (using woman as the reference), presence of mild COPD, height, weight, age, minute volume ( $\dot{V}_E$ ), and PIP. All data are presented as mean  $\pm$  SD unless stated otherwise.

## Results

Table 1 summarizes the demographic data.<sup>18</sup> For the entire study population, the mean FRC was 3.1  $\pm$  0.9 L, the mean *C*<sub>RS</sub> was 60  $\pm$  15 mL/cm H<sub>2</sub>O, the mean *P*<sub>aO<sub>2</sub></sub>/*F*<sub>IO<sub>2</sub></sub> was 360  $\pm$  100 mm Hg, and the mean *F*<sub>IO<sub>2</sub></sub> was 0.4  $\pm$  < 0.1.

Table 2 summarizes the hemodynamic, blood gas, and respiratory variables. The absolute FRC values and *P*<sub>aO<sub>2</sub></sub>/*F*<sub>IO<sub>2</sub></sub> values showed significant but very weak correlations (Fig. 1). Using the FRC values relative to the predicted sitting or supine values did not substantially improve the correlations (see Fig. 1). The absolute FRC and *C*<sub>RS</sub> values correlated well (*r*<sup>2</sup> 0.50, *P* < .001), but this correlation became worse with FRC values relative to predicted sitting or supine values (Fig. 2). *P*<sub>aO<sub>2</sub></sub>/*F*<sub>IO<sub>2</sub></sub> and *C*<sub>RS</sub> showed no meaningful association (*r*<sup>2</sup> 0.08, *P* = .02).

Multiple linear regression of height, weight, age, sex, presence of mild COPD,  $\dot{V}_E$ , and PIP showed the follow-

Table 2. Hemodynamic, Blood Gas, and Respiratory Variables

	Mean $\pm$ SD
Heart rate (beats/min)	89 $\pm$ 12
Mean arterial pressure (mm Hg)	75 $\pm$ 12
Central venous pressure (mm Hg)	14 $\pm$ 3.5
pH	7.36 $\pm$ 0.6
<i>P</i> <sub>aCO<sub>2</sub></sub> (mm Hg)	39.6 $\pm$ 6.1
Base excess (mEq/L)	-3.3 $\pm$ 1.8
Hemoglobin (g/dL)	9.6 $\pm$ 1.2
Lactate (mmol/L)	1.2 $\pm$ 0.7
Peak inspiratory pressure (cm H <sub>2</sub> O)	21 $\pm$ 1.9
Minute ventilation (L/min)	9 $\pm$ 1.4

ing results: the adjusted *r*<sup>2</sup> was 0.65 (*P* < .001); the standardized  $\beta$  was 0.234 for height (*P* = .08), -0.264 for weight (*P* = .008), -0.039 for age (*P* = .61), -0.130 for sex (*P* = .21), -0.145 for the presence of mild COPD (*P* = .052), 0.366 for  $\dot{V}_E$  (*P* = .001), and -0.590 for PIP (*P* < .001).

## Discussion

In patients ventilated after cardiac surgery we found a slight association between FRC and *C*<sub>RS</sub>. Absolute FRC and *P*<sub>aO<sub>2</sub></sub>/*F*<sub>IO<sub>2</sub></sub> showed a significant but very weak correlation, whereas *P*<sub>aO<sub>2</sub></sub>/*F*<sub>IO<sub>2</sub></sub> and *C*<sub>RS</sub> showed no meaningful correlation. Using the relative FRC values compared to predicted sitting or supine FRC values did not improve the correlations.

For many years absolute values of arterial oxygenation have been used to classify acute respiratory failure and guide respiratory therapy, and tolerable limits were incorporated in recent guidelines.<sup>19,20</sup> Safe absolute arterial oxygenation limits are an accepted standard of care. *C*<sub>RS</sub> measurement has been extensively used in research, and *C*<sub>RS</sub> measurement techniques are incorporated in most modern mechanical ventilators. Although a strong association between *C*<sub>RS</sub> and mortality has been verified,<sup>19</sup> many clinicians choose ventilator settings based on blood gas values rather than on lung mechanics measurements.

FRC measurement during mechanical ventilation has been recommended to assess the amount of ventilated alveoli,<sup>7</sup> and new FRC-measurement technology has been incorporated in commercially available ventilators.<sup>21</sup> The idea of assessing the adequacy of pulmonary gas exchange via measurement of lung volume is quite simple. Atelectasis, which is common during general anesthesia<sup>22</sup> and mechanical ventilation of patients with acute respiratory failure,<sup>23</sup> decreases FRC and increases shunt, and thereby decreases oxygenation. Increasing FRC should improve oxygenation and pulmonary gas exchange.

We found no association between FRC and *P*<sub>aO<sub>2</sub></sub>/*F*<sub>IO<sub>2</sub></sub>. Several reasons may be responsible. Ventilated lung vol-

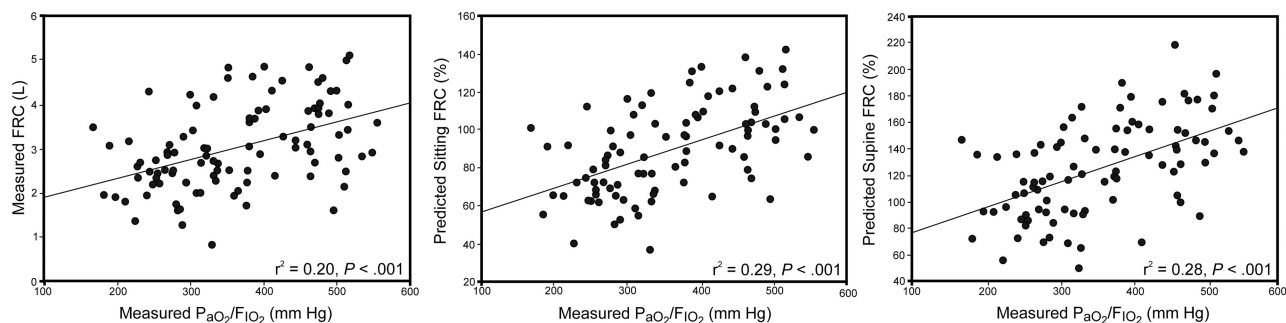


Fig. 1. Correlation of ratio of  $P_{aO_2}$  to fraction of inspired oxygen ( $F_{IO_2}$ ) and measured functional residual capacity (FRC), predicted relative FRC while sitting, and predicted relative FRC while supine.

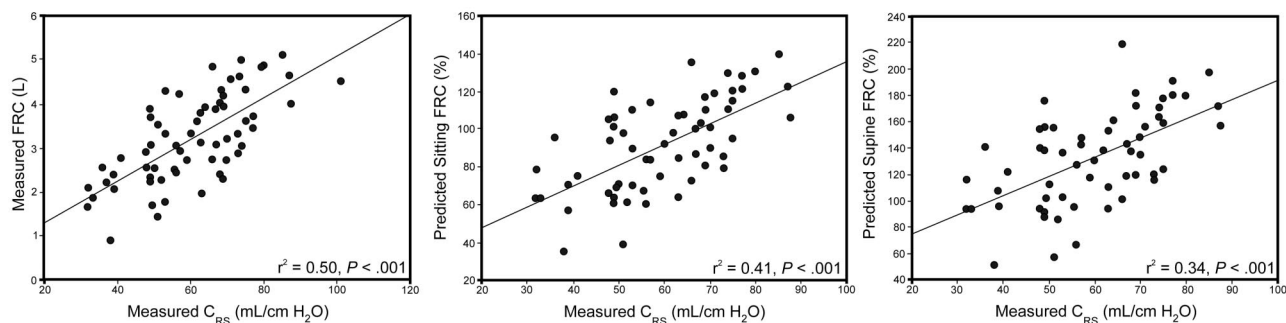


Fig. 2. Correlation of respiratory-system compliance ( $C_{RS}$ ) and measured functional residual capacity (FRC), predicted relative FRC while sitting, and predicted relative FRC while supine.

ume is influenced by a variety of factors, including height, weight, age, sex, body position, chronic or acute disease, type of mechanical ventilation, and ventilator settings.

Also,  $P_{aO_2}/F_{IO_2}$  depends on many important factors that do not influence FRC, such as  $F_{IO_2}$ , distribution of lung perfusion,<sup>24</sup> and hemodynamics.<sup>25,26</sup> We studied patients after cardiac surgery, ventilated with an  $F_{IO_2}$  of 0.4. In these patients a low  $P_{aO_2}/F_{IO_2}$  is caused mainly by collapsed lung tissue with concomitant shunt, and not by other kinds of low ventilation-perfusion mismatch. Thus, a low  $P_{aO_2}/F_{IO_2}$  is more dependent on the amount of collapsed and perfused lung tissue than on the amount of gas in the open alveoli (ie, FRC). Therefore, FRC and  $P_{aO_2}/F_{IO_2}$  seem to give information on different but integrated aspects of lung function.

FRC values in ventilated patients have been compared to reference FRC values obtained in healthy sitting persons, and FRC is markedly lower during ventilation.<sup>10</sup> Any maneuver to increase FRC up to a normal level should improve gas exchange.<sup>7</sup> But FRC measurement cannot differentiate between alveolar recruitment and alveolar overinflation. So an FRC increase relative to the predicted value could be due to alveolar recruitment, leading to improved oxygenation, or to hyperinflation of already open alveoli, leading to no oxygenation change, or even to a decrease. Our data do not support stronger correlations

when FRC is indexed to predicted sitting or supine FRC. This is not surprising, as FRC at PEEP of 10 cm  $H_2O$  may indicate the composite of open, expanded, and hyperinflated alveoli, not the number of open alveoli at zero PEEP. If the measurements had been done at zero PEEP, the association with  $P_{aO_2}/F_{IO_2}$  might have been better. We do not recommend a deliberate increase of FRC in ventilated patients to normal values seen in spontaneously breathing patients with zero PEEP. The rather high FRC values ( $> 3$  L) in our patients may be explained by the ventilation with PEEP of 10 cm  $H_2O$ , which might lead to over-distention of alveoli. But Maisch et al studied anesthetized patients with healthy lungs and found that the optimal PEEP was 10 cm  $H_2O$ , which provided the highest  $C_{RS}$  and the lowest dead-space fraction, and they found FRC values similar to those in our study.<sup>27</sup>

In contrast to  $P_{aO_2}/F_{IO_2}$ ,  $C_{RS}$  and FRC showed a moderate correlation, as was previously found by Gattinoni and Pesenti in patients with acute respiratory distress syndrome.<sup>28</sup> Bikker et al found a correlation between a change in FRC and a change in  $C_{RS}$  when changing PEEP from 15 cm  $H_2O$  to 10 cm  $H_2O$  or 5 cm  $H_2O$  only in septic patients with secondary ALI, but not in patients with primary ALI or no ALI.<sup>10</sup> They argued that patients with a secondary lung disorder benefitted from higher PEEP, which recruits alveoli and thus increases FRC, whereas in



patients with primary lung injury high PEEP over-distends alveoli.<sup>10</sup> We found that the correlations became weaker when using FRC values relative to predicted sitting or supine values, which again calls into question the use of relative to predicted FRC values in ventilated patients.

The multiple linear regression analyses indicate that 65% of the variance of FRC values can be explained by PIP,  $\dot{V}_E$ , and weight. Normal FRC values in spontaneously breathing subjects are influenced mainly by height, weight, age, and the presence of COPD.<sup>16</sup> These variables (with the exception of weight), showed no significant influence on FRC values in our ventilated subjects. This may be due to the mechanical ventilation, where the positive airway pressure plays a more important role than other physiologic variables.

Beside FRC measurement in ventilated patients is now possible, but how FRC measurements can be used to guide respiratory therapy is still under debate. As absolute FRC in a ventilated patient is influenced by several variables, a single FRC value could be misleading. In contrast, FRC changes during therapy or disease reflect different states of alveolar recruitment and derecruitment<sup>29,30</sup> and can eventually be used to guide therapy. Further investigations should study this issue. In addition, FRC measurement to determine alveolar strain, as proposed by Gattinoni and Pesenti, might improve therapy in the near future.<sup>28</sup>

### Limitations

First, we obtained  $C_{RS}$  during ongoing ventilation, without a respiratory pause, which could result in measuring errors.<sup>31</sup> But measurements of classic static respiratory mechanics with a pressure-volume curve and a respiratory pause are very cumbersome and complicated to interpret. In contrast, 2-point quasi-static  $C_{RS}$  during ongoing ventilation is easy to obtain in clinical routine and may give a good estimate.<sup>31,32</sup>

Second, we used a PEEP of 10 cm H<sub>2</sub>O in every patient, which might have been too high for some of these post-operative patients. An individualized approach would have been preferable.

Third, we obtained only single measurements of  $P_{aO_2}/F_{IO_2}$ , FRC, and  $C_{RS}$ , and no therapeutic intervention was included, so we can draw no conclusions on the association of repeated measurements of the studied variables during disease progression or therapies.

### Conclusions

Relating measured FRC values to predicted FRC values (based on reference FRC values from supine or sitting spontaneously breathing persons) does not improve the association between  $P_{aO_2}/F_{IO_2}$  and  $C_{RS}$ . FRC in mechanically ventilated patients after cardiac surgery is influenced

more by the ventilator settings than by physiologic variables (as in spontaneously breathing persons).

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