Measurement of Functional Residual Capacity During Mechanical Ventilation for Acute Respiratory Failure*  
A Comparison Between Closed and an Open-circuit Helium Dilution Technique

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Measurement of functional residual capacity (FRC) in mechanically ventilated patients often requires the use of bulky equipment and manipulations near the patient's tracheal cannula. We describe an open-system helium dilution technique to overcome these disadvantages. The FRC was measured in ten patients with acute respiratory failure, in six during different levels of PEEP. The error of the open-circuit method was found to be 10 percent.

All reports about measurement of functional residual capacity (FRC) in patients with acute respiratory failure (ARF) during mechanical ventilation1-2 are based on a closed-circuit helium dilution technique as described by Laws.1 Falke et al3 measured PEEP-induced changes of FRC as the difference between first exhaled tidal volume after abrupt discontinuation of PEEP and last inspired tidal volume with PEEP.

Suter and Schlobohm4 presented a modification of Laws' method, using a bag-in-box driven by the ventilator. This allowed measurement of FRC without disconnection from the ventilator.

The measuring devices, however, are often bulky, and manipulation of the ventilator tubing near the patient is sometimes required. As an alternative, an open-circuit helium dilution technique was developed. This method is a modification of the one originally described by Hickam et al.6 The results are presented and compared with those of a rebreathing method described by Heldt and Peters.7

METHODS AND PATIENTS

Most open-circuit methods for measuring lung volume determine the amount of an indicator gas present in the lungs after previous wash-in. The measurement is made by determining the amount of an indicator gas, expired in a large number of breaths. The quantity M of the indicator gas (in our case helium) expired in n breaths can be given by

\[ M_{He} = \sum_{i=1}^{n} V_i \cdot F_{He (1)} \]  

where \( F_{He (1)} \) is the concentration of helium in the i-th breath and \( V_i \) is the volume expired in that breath. Since the amount of helium present in the lungs equals the inspired concentration of helium \( F_{1,He} \) multiplied by the FRC, the latter is calculated as

\[ FRC = \frac{1}{F_{1,He}} \cdot \sum_{i=1}^{n} V_i \cdot F_{He (1)} \]

In the situation of volume-limited mechanical ventilation, where the expired volume, \( V_T \), is constant and equals the tidal volume, \( V_T \), equation 2 can be reduced to

\[ FRC = \frac{V_T}{F_{1,He}} \cdot \sum_{i=1}^{n} F_{He (1)} \]

Expired volume was measured with a Godart pneumotachograph at the expiration port of the ventilator (Fig 1, tracing 5). We measured the concentration of helium with a katharometer (Godart, response time 0.1 sec), at the expiration port of a Siemens-Elema-900 ventilator. From equations 2 and 3, it follows that absolute calibration of the helium meter is not necessary; only linearity of the meter is important. The linearity of the katharometer has been checked with different concentrations of helium in gas mixtures, comparable to those used in patients. An example of a helium washout curve is shown in tracing 6 of Figure 1.

A mixture of 50 percent helium in oxygen was administered to the patient via the ventilator, by temporarily con-
nnecting the air-inlet of the ventilator's air-oxygen mixer to a gas cylinder containing 50 percent helium in oxygen, thus permitting instantaneous switching between 100 percent oxygen and the helium-oxygen mixture (by simply turning the air-oxygen mixer from 100 percent to "21 percent"). After equilibrium was reached, we switched to 100 percent oxygen for wash-out. Wash-in and wash-out take about two minutes each (Fig 1).

As the mixed expired CO₂ concentration is constant (2 to 3 percent) during wash-in of the indicator gas as well as during wash-out with oxygen, no correction was made for the influence of CO₂ on the katharometer. The concentrations of helium in every expiration, as recorded in the helium washout curve, are summed until no appreciable increase in the sum occurs (15 to 20 breaths). The FRC is then calculated following equation 3.

The following points have to be considered when summing these concentrations:
1. We take as expired helium concentration the flat part of the single expiration curve. The notches on the curve at the beginning and end of each expiration are artifacts due to the opening and closing of the expiration valve.
2. The expiratory helium concentration reaches the presudy baseline only slowly in some cases. Therefore, we construct a baseline by extrapolating from the 20th to the 30th breath in the wash-out curve and by taking all helium concentrations read from the recording paper with respect to this slightly sloping base line.
3. The first expiration is not taken into account, because the first inspiration after switching from wash-in to wash-out contains the helium still present in the ventilator.
4. The volume of the connecting tubes of the expiration circuit (in our case 480 ml) has to be subtracted from the volume measured.

As a reference we used the rebreathing method to determine FRC described by Heldt and Peters. This method uses a small bag-in-box system that can be driven by the ventilator.

The FRC was measured in ten patients with ARF from different causes (Table 1). In seven patients it was measured once, in one patient twice, and in two patients on three occasions during a period of seven days. On each occasion FRC was measured in duplicate with both methods. In six patients measurements were performed at different levels of end-expiratory pressure.

RESULTS AND DISCUSSION

The comparison between the open-circuit method and the rebreathing method is shown in Table 1 and Figure 2. It is clear that the correlation is very good. From 21 determinations, made in duplicate with both methods, we calculated the reproducibility of both methods: the results are 0.05 L or 4 percent for the rebreathing method and 0.12 L or 10 percent for the open-circuit method. We have determined FRC with both methods in six patients before and after changes in PEEP (Fig 3). It is apparent that changes in FRC due to varying PEEP are equally well reflected using both methods.
### Table 1—Clinical Data and Results of FRC Measurements

<table>
<thead>
<tr>
<th>Patient/Age, yr/Sex</th>
<th>Diagnosis, Indication for Mechanical Ventilation</th>
<th>Day of Measurement After Onset of ARF</th>
<th>FRC (L BTPS)</th>
<th>ΔFRC with PEEP (1 BTPS)</th>
<th>PEEP, cm H₂O</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Closed</td>
<td>Open</td>
<td>Closed</td>
</tr>
<tr>
<td>1/38/F</td>
<td>Pneumonia after renal transplant; multiple organ failure</td>
<td>2</td>
<td>0.659</td>
<td>0.375</td>
<td>0.144</td>
</tr>
<tr>
<td>2/55/M</td>
<td>Bilateral pneumonia; pre-existent emphysema, and COLD</td>
<td>2</td>
<td>2.351</td>
<td>2.279</td>
<td>0.266</td>
</tr>
<tr>
<td>3/53/M</td>
<td>Myocardial infarction, with circulatory arrest and cardiogenic shock</td>
<td>3</td>
<td>1.399</td>
<td>1.146</td>
<td>0</td>
</tr>
<tr>
<td>4/57/F</td>
<td>Aspiration and hypoventilation after hypophysectomy</td>
<td>2</td>
<td>1.483</td>
<td>1.324</td>
<td>7</td>
</tr>
<tr>
<td>5/72/M</td>
<td>Pneumonia, COLD</td>
<td>9</td>
<td>1.547</td>
<td>1.812</td>
<td>0</td>
</tr>
<tr>
<td>6/70/F</td>
<td>Sepsis and pneumonia after abdominal surgery, multiple organ failure</td>
<td>7</td>
<td>0.673</td>
<td>0.885</td>
<td>0.233</td>
</tr>
<tr>
<td>7/25/F</td>
<td>Aspiration pneumonia in severe M. Wernicke after hyperemesis in pregnancy</td>
<td>9</td>
<td>0.981</td>
<td>0.851</td>
<td>0.850</td>
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<td>8/57/F</td>
<td>RDS after near-drowning; severe aspiration pneumonia</td>
<td>2</td>
<td>0.622</td>
<td>0.475</td>
<td>0.217</td>
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<tr>
<td></td>
<td></td>
<td>9</td>
<td>0.839</td>
<td>0.693</td>
<td>10</td>
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<td></td>
<td></td>
<td>12</td>
<td>1.007</td>
<td>1.227</td>
<td>10</td>
</tr>
<tr>
<td>9/67/M</td>
<td>Polytrauma (head, neck, scapula, abdomen)</td>
<td>6</td>
<td>1.260</td>
<td>1.298</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8</td>
<td>1.292</td>
<td>1.281</td>
<td>0</td>
</tr>
<tr>
<td>10/36/F</td>
<td>Pneumococcal meningoencephalitis, sepsis, RDS, pneumonia</td>
<td>22</td>
<td>0.738</td>
<td>1.013</td>
<td>0</td>
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<tr>
<td></td>
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<td>27</td>
<td>0.883</td>
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<td>33</td>
<td>0.872</td>
<td>0.931</td>
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<td></td>
<td></td>
<td></td>
<td>1.030</td>
<td>1.298</td>
<td>7</td>
</tr>
</tbody>
</table>

ARF = acute respiratory failure; COLD = chronic obstructive lung disease; and RDS = respiratory distress syndrome.

Two principal sources of error are associated with an open-circuit method: (1) too small a number of expirations are taken into account, and (2) construction of the base line.

The expiratory concentrations were read directly from the recorder. Those breaths were omitted in which the changes of the helium concentration were smaller than 1 percent of the inspired concentration. Assuming that the expiratory concentration during the wash-out will approach zero exponentially, we are left with a truncation error of about 1 percent.

Empirically we found that the error in FRC, resulting from constructing the baseline by extrapolation as described, was about 10 percent, which is reflected in the duplicate measurements. Very slow wash-out of helium from poorly ventilated areas might contribute to the sloping baseline. Those poorly ventilated regions cannot be accurately determined with a gas dilution technique. In addition, some helium might have been taken up in blood and tissue and be released again.8

The breathing of 100 percent O₂ during wash-out might alter FRC. Since the wash-out time is about

![Figure 2. Correlation between results of FRC measurements with open- vs closed-circuit helium dilution method.](image)
two minutes, we do not think that major differences take place. Furthermore, as shown by Cumming and Jones, breathing oxygen has no influence on the inert gas clearance curves.

It is for practical reasons that we used 100 percent oxygen for wash-out; lower concentrations of oxygen-air mixtures can be used alternatively. A concentration of 50 percent helium in oxygen for washing is not necessary and is not superior to mixtures with lower concentration. For us it was the easiest available mixture.

We found some amazingly low values for FRC in patients on mechanical ventilation for ARF from pulmonary causes. After our initial experiences with measurements of FRC—which were with the open-system method—we even discarded the results, because values far less than L did not seem “reasonable” to us. It was not until later, through measuring equally low FRC values with the rebreathing method, that we accepted those results as real ventilated lung volumes, under very pathologic circumstances.

CONCLUSIONS

The open-circuit method, as described here, is able to determine FRC in mechanically ventilated patients. The main advantages of this method are: (1) the measurement is carried out at the ventilator, thus avoiding disconnection and other manipulations directly to the patient’s cannula; (2) the procedure is quick and simple—including duplicate measurement, it takes about 15 minutes; and (3) the method can be applied during PEEP ventilation. In our opinion these advantages compensate for some loss in accuracy. Moreover, the procedure is suitable for automation and permits detection of significant changes in FRC of patients with ARF who are being mechanically ventilated.

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REFERENCES

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