Determination of Functional Residual Capacity during Mechanical Ventilation

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The determination of functional residual capacity (FRC) during mechanical ventilation has become important in clinical investigations in anesthesiology and for diagnostic and therapeutic evaluation of patients in acute respiratory failure. Since the introduction of the closed-circuit helium-dilution technique by Meneely,[1] this has been regarded as the simplest and most accurate method. Laws described an application of this technique for patients requiring mechanical ventilation,[2] and this has found wide application in anesthesia and intensive care. His apparatus allows manual ventilation of the patient by means of a self-inflating bag included in the closed circuit.

The purpose of this communication is to present a modification of Laws' method for FRC determination by helium dilution which has several advantages. First, FRC can be determined while the patient continues to be ventilated with the frequency and tidal volume used prior to the study or during mechanical ventilation with positive end-expiratory pressure (PEEP). The patient is not disconnected from the ventilator for the measurement; the connection to the FRC circuit is made by turning two valves. FRC can be determined at any inspired oxygen concentration. In-line analysis of this concentration allows for correction of the catharometer deflection produced by oxygen. Finally, the method does not require physiologic knowledge of ventilation, or technical skills, and can

be learned by inhalation therapists, nurses, and paramedical personnel.

APPARATUS

The circuit (fig. 1) includes a 6-l spirometer (Warren Collins), circulation motor, CO_2 absorber, disposable bacterial filter (Ohio), helium meter (catharometer, Godart), oxygen analyzer (Beckman E2) and a "bag-in-the-box" device. The last consists of a 1.8-l self-inflating rubber resuscitation bag (Air-viva, CIG Australia) with a "box" which is a 5-l glass bottle with two openings: the bag is connected to the FRC circuit by one opening, while the space surrounding the bag is connected to the ventilator by the other. A series of valves assures a unidirectional flow of the gas mixture around the following circuit: the self-inflating bag is filled from the spirometer (during expiration), the gas mixture then enters the patient's lungs, the expired gas passes through the bacterial filter and CO_2 absorber before it is returned to the spirometer. Helium meter and oxygen analyzer are arranged in series parallel to the main circuit. The gas sampled is returned to the circuit after analysis.

The apparatus contains an airspace of 4.2 l, including the self-inflating bag. This volume would be difficult to reduce without sacrificing adequate tubing lengths for safe patient connections, flexibility of tidal volume, and low resistance within the circuit.

For FRC measurements at spontaneous ventilation, the "bag-in-the-box" can easily be removed. The apparatus volume is 2.4 l with this arrangement. PEEP can be maintained with a valve (Puritan Bennett mushroom valve or Emerson PEEP Assembly) included in the expiratory part of the circuit. This arrangement allows measurements at PEEP, whereby only a small segment of the circuit is under continuous positive pressure.

The connections for component parts, most

Fig. 1. Circuit for FRC determination

1-WAY VALVE

2-WAY VALVE

(P) *PEEP VALVE*

MB   *MIXING BYPASS*
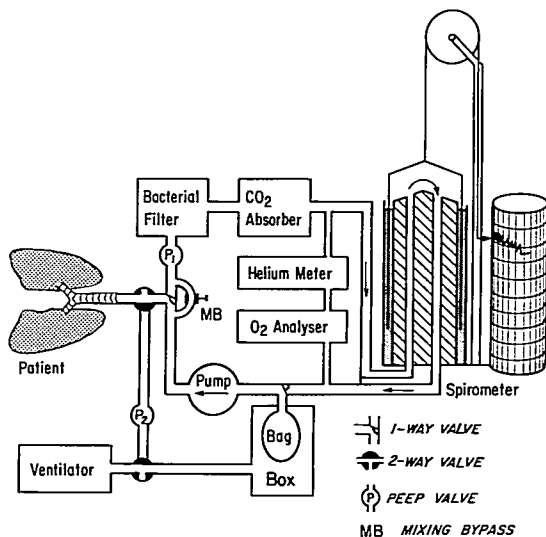
of which must be removable for sterilization, are conducive to leaks. Two tests are used to check for leaks: first, a static, low-pressure test of the entire system is made by placing a one kilogram weight on the spirometer bell. Second, a dynamic, high-pressure test of the inspiratory portion of the circuit can be made during the mixing period, when the ventilator compresses the "bag." With the tests described, the low and high pressure values were 8–10 and 60–80 cm H_2O, respectively. During mixing, the one-way valve near the patient's airway is bypassed via small-diameter, high-resistance tubing. A change in the baseline of the spirometer tracing representing more than 3 ml/min indicates an unacceptable leak.

The helium meter is set to read zero for room air before each study. Nitrogen and oxygen do not have identical thermal conductivities. A change in concentration of these gases during an FRC measurement will result in an error in the reading of the helium concentration. Errors due to water vapor and car-

bon dioxide conductivites are cancelled by appropriate absorption systems. Oxygen–nitrogen correction factors were derived from testing the catharometer with known gas mixtures, and the helium concentrations calculated in this manner were also checked by gas chromatography. The helium correction formula obtained by least-squares analysis of these data was:

$$He_c = He_d + 9.1 - 46.0 \times F_{O_2} + 13.4 \times (F_{O_2})^2$$

where He_c = corrected helium reading; He_d = direct helium reading; F_{O_2} = oxygen fraction of the gas mixture.

A similar instrument in this department delivered a correction formula different from that above, and both corrections are different from that proposed by Colgan.[3] We therefore believe that each catharometer should be tested for the conductivity deflections due to oxygen in nitrogen so that adequate corrections are made for the helium readings.

MEASUREMENT

The circuit is filled with a helium–oxygen–nitrogen mixture resulting in a helium concentration of 5–7 per cent. Because no oxygen is added during the measurement, the beginning oxygen concentration is set approximately 10 per cent higher than the value used in ventilating the patient's lungs prior to the FRC determination. The gases are mixed in the circuit using the circulation motor and several deflations of the bag. At end-expiration, the patient connection is changed from the ventilator to the closed FRC circuit by simultaneous rotation of both two-way valves. The gas mixture in the circuit is equilibrated with the lung volume. Equilibration can be recognized by a slowly increasing helium concentration due to the oxygen consumption from the circuit. During this equilibration period, which lasts 4–7 minutes, the patient's ventilator drives the "bag-in-the-box," thus assuring ventilatory patterns similar to those prior to the test period. The patient can also initiate the inspiratory ventilator phase during this time. At termination, direct patient contact with the ventilator is re-established by reversing both two-way valves to their original positions at end-expiration.

FRC is then calculated with the classic formula:

$$FRC = \frac{He\ 1}{He\ 2} \times V_1 - V_2$$

where He 1 = initial helium concentration; He 2 = final helium concentration; V_1 = initial spirometer volume + apparatus deadspace; V_2 = final spirometer volume + apparatus deadspace.

RELIABILITY

When tested on an artificial lung with a volume of 1,400 ml, repeated volume measurements with different levels of end-expiratory pressure yielded results with a coefficient of variation of 0.7 per cent. Duplicate determinations were done under identical ventilatory conditions in 30 patients requiring mechanical ventilation for acute respiratory failure. The second value differed from the first by 1.5 ± 0.2 per cent (mean ± SE), while the measured FRC's in these patients ranged from 640 to 4,600 ml.

In conclusion, a simple apparatus for FRC determination for use in patients requiring mechanical ventilation is described. The measurement can be made while the conditions of ventilation are similar to those provided by the ventilator, including determinations during PEEP. The results obtained in awake, non-curarized patients are repeatable within narrow limits.

REFERENCES

1. Meneely GR, Kaltreider NL: The volume of the lung determined by helium dilution. Description of the method and comparison with other procedures. J Clin Invest 28:129–139, 1949
2. Laws AK: Effects of induction of anaesthesia and muscle paralysis on functional residual capacity of the lungs. Can Anaesth Soc J 15:325–331, 1968
3. Colgan FD, Whang TB: A method for measuring the functional residual capacity and dynamic lung compliance during oxygen and halothane inhalation. ANESTHESIOLOGY 28: 559–563, 1967