A Pulse Method of Measuring Respiratory System Compliance in Ventilated Patients*

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We describe a method of measuring total static respiratory system compliance (Crs) in ventilated patients during inflation, which appears to detect relaxation of respiratory muscles and does not require an end-inspiratory pause or disconnection of a constant-flow intermittent mandatory ventilation (IMV) circuit. Flow is measured with a pneumotachometer attached to the endotracheal tube. Transhthoracic pressure is taken as the difference between mouth pressure measured at the proximal pneumotachometer port and body surface (atmospheric) pressure. Flow and transhthoracic pressure are displayed on separate channels of a strip chart recorder. The ventilator is adjusted to deliver a constant rate of air flow. When inflation begins, the pressure tracing shows an initial step rise related to the flow resistance of the subject followed by a section with a slower rise and a constant slope. Respiratory system compliance is calculated by dividing the flow rate in L/sec by the slope of the pressure tracing in cm H2O/sec. Pulse Crs was compared with static Crs measured with an end-inspiratory pause in nine subjects receiving mechanical ventilation. Correlation between pulse Crs and static Crs in nine ventilated patients was highly significant (r = .997, pulse Crs = 1.00 static Crs + 0.001). We conclude that with the pulse method, one can measure static Crs during inflation without an inspiratory pause and without disconnecting an IMV circuit.

Measurement of total respiratory system compliance (Crs) in ventilated patients is useful in adjusting ventilation and in following the course of patients' respiratory illness. For example, by maximizing static Crs with positive end-expiratory pressure (PEEP) in subjects with acute respiratory failure, one can optimize oxygen transport. Also abrupt changes in static Crs in ventilated patients have been associated with pneumothorax, atelectasis, pneumonia, bronchial intubation, and pulmonary edema.

There are several problems with the conventional methods of measuring static Crs. First, a 1 sec or longer end-inspiratory pause must be used at the end of each ventilation. Second, it is usually necessary to disconnect a constant-flow intermittent mandatory ventilation (IMV) circuit to eliminate air flowing into the patient during the end-inspiratory pause. Third, since static Crs can be altered by contraction of respiratory muscles, one must ensure that respiratory muscles are relaxed. This is particularly difficult in awake patients who are out of phase with the ventilator and in patients who breathe spontaneously with an IMV circuit.

We describe a method of measuring static Crs in ventilated patients that does not require an end-inspiratory pause or disconnecting an IMV circuit and that appears to detect respiratory muscle relaxation. The pulse method of measuring Crs is based on the principle that when a constant rate of airflow is blown into a container, the rate of change of pressure in the container is inversely proportional to the compliance of the container. This concept is developed in the following equations:

\[ \text{Compliance} = \frac{\Delta \text{Volume}}{\Delta \text{Pressure}} \]  

(1)

\[ \text{Compliance} = \frac{\Delta \text{Volume/time}}{\Delta \text{Pressure/time}} \]  

(2)

Therefore:

\[ \text{Compliance} = \frac{\dot{V}}{\Delta \text{Pressure/time}} \]  

(3)

Methods

Respiratory system compliance was measured in nine ventilated patients, five women and four men. Their ages ranged from 22 to 82 years, with a mean of 48 years. Three patients had pneumonia (Table 1), two had the adult respiratory distress syndrome, two had postoperative respiratory failure, one had a crush-skull injury, and one was quadriplegic from a C6-7 spinal cord injury. Three subjects were thought by their physicians to have obstructive lung disease, one had previous pulmonary function studies showing a forced expired volume in one second to forced expired volume ratio (FEV1/FVC) of 65 percent, and two others had 80 and 60 pack-year histories of smoking respectively.

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Ventilators used were the Servo 900-B in four patients, the Bennett MA1 in three patients, and the Bourns Bear-1 in two patients. An external constant-flow IMV circuit was used in all ventilators. The internal IMV circuit of the Bourns Bear-1 was not used because of difficulties we have had with its demand valve. All patients were receiving PEEP. The ventilators were adjusted to deliver a constant-flow wave pattern with a flow varying from 0.40 to 0.65 L/sec, the mean being 0.6 ± 0.10 SD L/sec. To determine the effect of flow rate on pulse Crs measurements in obstructive lung disease, in one patient with obstructive lung disease (patient 6, Table 1) the flow rate was transiently decreased from 0.65 L/sec to 0.35 L/sec while doubling the respiratory rate.

In six subjects, a heated pneumotachometer (Hewlett-Packard modified No. 1 Fleish attached to a Hewlett-Packard 47304A flow transducer) was placed between the endotracheal tube and the "Y" connector to which the inspiratory and expiratory ventilator tubing was attached (Fig 1). In the remaining three subjects, a heated pneumotachometer was placed in the inspiratory line near the endotracheal tube, and the ventilatory expiratory valve moved closer to the endotracheal tube (Fig 2). Transrespiratory pressure (Prs) was measured as the difference between mouth pressure, measured at the proximal pneumotachometer port, and body surface (atmospheric) pressure with a Hewlett-Packard 270 differential transducer. Flow and Prs were displayed against time on separate channels of a strip chart recorder. The pressure tracing during inspiration has three components—first, an initial step rise in pressure related to the flow resistance of the subject; second, a short slightly curved portion; and third, a longer section with a constant slope (Fig 3A). Respiratory system compliance is calculated by dividing the flow rate in L/sec by the slope of the constant-slope section of the pressure tracing in cm H2O/sec (equation 3).

To test the accuracy of pulse Crs measurements, pulse Crs was compared to static Crs measured in the same subjects. Static Crs was measured by dividing inspired volume integrated from the flow signal (Hewlett-Packard 8815A respiratory integrator) by the difference between Prs before inspiration and a "plateau" Prs at end inspiration. The "plateau" Prs was measured by creating a 1- to 2-sec end-inspiratory pause by obstructing the expiratory and inspiratory ventilator tubing within 15 cm of the "Y" connector. Dynamic Crs was also measured by dividing inspired volume by the difference between Prs before inspiration and the peak Prs that occurred during the ventilation.

Airway resistance was estimated by dividing the difference between peak Prs and "plateau" Prs at end inspiration by the flow rate at peak Prs.

**RESULTS**

Correlation between pulse Crs and static Crs was highly significant (r = .997, pulse Crs = 1.00 static Crs + .001). Table 1. The mean coefficient of variation was similar with both pulse Crs (8.8 percent) and static Crs (6.9 percent) measurements. Dynamic Crs was significantly lower than pulse Crs or Static Crs in all subjects (t = 3.23, p < .02).

In three nonsmoking patients (patients 2, 5, and 8), mean dynamic Crs/static Crs was 0.78 ± 0.049 SD, and mean resistance 10.8 ± 2.3 SD cm H2O/L/sec. In three patients with obstructive lung disease, mean dynamic Crs/static Crs was lower than in the nonsmoking patients, 0.64 ± 0.11 SD, and mean airway resistance higher, 15.9 ± 2.8 SD cm H2O/L/sec, but the differences were not significant.
A typical tracing from a relaxed subject is shown in Figure 3A. Shown in Figure 3B is an example of a tracing when a patient was not relaxed. There was an irregular line without a constant slope on the pressure time recording and occasionally on the flow recording. Some subjects could not relax during early inflation, but could relax toward the end of inflation (Fig 3C). In these subjects the initial portion of the pressure tracing and occasionally the flow tracing was irregular, but the latter portion was straight. Pulse Crs could be calculated in these subjects by measuring only the latter straight portions of the flow and pressure tracings.

The configuration of the pressure time curve generally differed in patients without obstructive lung disease from those with obstructive disease. In subjects with obstructive disease there was a larger step rise in pressure followed by a longer curved line and a shorter straight line (Fig 3D). Decreasing the flow rate from 0.65 to 0.35 L/sec in one subject with obstructive disease tended to normalize the configuration of the curve by decreasing the step rise and the length of the curved portion and lengthening the straight portion (Fig 3E). Changing the flow rate did not, however, change the value of pulse Crs.
MEASURING RESPIRATORY SYSTEM COMPLIANCE

We have shown that there is close correlation between Crs measured with the pulse method and with conventional static techniques. Although pulse Crs is measured during inflation, we have demonstrated that it reflects static rather than dynamic compliance. Because pulse Crs is measured during inflation, an inspiratory pause is not required, and thus if a constant-flow IMV circuit is in place, it does not have to be disconnected.

Pulse Crs has the added advantage of detecting relaxation of respiratory muscles. We have shown in a previous study that when there is a straight line on the pressure tracing, pulse Crs measurements are very reproducible, the mean coefficient of variation being 4.8 ± SD 2.6 percent. Reproducible measurements of static chest wall compliance measured with the relaxation method have previously been shown to correlate with an electrically silent diaphragm. We also demonstrated that values for Crs in normal subjects measured with the pulse technique were identical to those reported by Johnson and Mead in their highly trained subjects measured with the relaxation technique.

The close correlation of pulse and static Crs measurements in subjects with obstructive lung disease is at variance with previous studies of constant-flow inflation. Previous studies based on mechanical two-compartment lung models showed that when a resistance of 94 cm H2O/L/sec was inserted in the airway of one compartment, the airflow would principally enter the compartment without the resistance. Thus, measured compliance would reflect primarily the compliance of the low time constant (resistance × compliance) compartment. The close correlation of static and pulse Crs measurements in our patients with obstructive disease demonstrates that the time constants in the lungs of these patients were not diverse enough to significantly alter pulse Crs measurements.

To detect relaxation of respiratory muscles with the pulse method, ventilation must be delivered with a constant-flow pattern. Without a constant-flow pattern, the slope of the pressure time tracing in a relaxed subject would not be straight, the sign of a relaxed subject in this test. The majority of volume ventilators will deliver a constant flow pattern. These include the Bennett MAI and 2, the Servo 900-B, the Bourns Bear-1 and Pediatric Ventilator, the Forreger 210, the Gill 1, the Monaghan 225, and the Ohio 580 and CCV. A few ventilators, such as the Bennett MAI, cannot deliver a constant-flow pattern to patients with very low compliances. We generally ventilate such patients with more powerful ventilators, such as the Servo 900-B. Two volume ventilators that cannot deliver a constant airflow are the Emerson and Engstrom models.

When the pneumotachometer was placed between the patient and the ventilator tubing, all measured airflow entered the patient and dead space increased by 13 ml. If the pneumotachometer were left in this location in a patient with a productive cough, however, it could become partially or completely obstructed with sputum. This problem can be avoided by placing the pneumotachometer near the endotracheal tube in the inspiratory line and the ventilator expiratory valve near the endotracheal tube on the expiratory line. With this arrangement, all air flowing through the pneumotachometer during inflation will enter the patient, yet the IMV circuit can remain connected. With the Servo ventilator, however, the expiratory valve is in the ventilator and cannot be moved close to the endotracheal tube. The measured compliance with the Servo will thus reflect both the Crs of the patient and the compliance of the expiratory tubing. The patients’ Crs can be calculated, however, by subtracting the expiratory tubing compliance from the measured compliance.

The pulse technique lends itself to direct computer analysis. As we have shown previously, a microprocessor can sample the pressure and flow signals and calculate compliance for each inflation.

ACKNOWLEDGMENT: We wish to thank Mr. Robert Bageant for his advice, Drs. Dudley F. Rochester and C. Edward Rose for their helpful suggestions and criticism, and Mrs. Catherine Brock for help in preparing the manuscript.

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The American Heart Association will sponsor the Annual Conference on High Blood Pressure Research in Cleveland, September 23-25. For information, contact AHA Postgraduate Programs, Scientific Sessions, 7320 Greenville Avenue, Dallas 75231.

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