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A New Method for Measurement of Airway Occlusion Pressure*

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Airway occlusion pressure correlates with central respiratory drive. The airway occlusion pressure (P0.1) may be an excellent predictor of the ability of patients with obstructive lung disease to wean from mechanical ventilation. We describe a new method for measuring P0.1 using digitized signals generated from standard respiratory equipment and a computer program to automatically determine P0.1 values. The accuracy of this new method was tested by comparison with standard analog recorder methods using a mechanical lung model, in ventilated patients in an intensive care unit, and in normal volunteers. In all settings, excellent correlation was obtained between P0.1 measurements by the digital Servo and standard analog methods ($r = 0.99$). This new method permits accurate and automatic

Airway occlusion pressure (P0.1) is the airway pressure that is generated 100 ms after the start of inspiration against a closed system and indirectly correlates with respiratory drive from central nervous system centers.¹⁻³ Airway occlusion pressure has been used in physiologic studies for a number of years. Occlusion pressure has been shown to be a predictor of the ability of patients with obstructive lung disease to wean from mechanical ventilation.^{4,5} High levels of P0.1 in ventilated patients are associated with increased respiratory effort and predict an inability to successfully breathe independently. Conversely, lower values of P0.1 generally predict a greater likelihood of effective weaning.

The use of P0.1 for physiologic weaning assessment in ventilated patients has been limited primarily to research centers because measurement of P0.1 is technically complex and requires specialized equipment. We sought to develop a method for measuring P0.1 using standard respiratory equipment that is simple, accurate, and reproducible.

The method was validated using a mechanical lung model. Airway occlusion pressures were then measured in ventilated patients using these newly described

determination of P0.1 in ventilated patients using standard respiratory equipment. The rapid response and ease of use of this method should enable evaluation of a number of physiologic variables involved in respiratory control in ventilated and nonventilated patients.

(*Chest* 1990; 98:421-27)

P0.1 = airway occlusion pressure; CPAP = continuous positive airway pressure; cm H₂O = pressure in centimeters of water; SCM900 = Servo computer module 900 analog to digital converter; COPD = chronic obstructive pulmonary disease; CPAP-0 cm H₂O = continuous positive airway pressure of 0 centimeters water; PEEP = positive end-expiratory pressure; IMV = intermittent mandatory ventilation

methods and compared with the values obtained using standard measurement techniques. Additionally, non-ventilated normal subjects were studied with this system (using a mouthpiece and ventilator in the continuous positive airway pressure (CPAP) 0 cm H₂O mode) to obtain P0.1 values.

METHODS

Occlusion Pressure Measurements

Analog Pressure Recording Standard Methods: The standard method for measuring P0.1 employed a ± 10 cm pressure transducer (model MP45-1, Validyne Co, Northridge, CA) with a probe placed in the respiratory tubing at the endotracheal tube connector site. The pressure transducer was connected to a carrier demodulator (model CD19, Validyne Co, Northridge, CA). The demodulator outputs were sent to an X-Y recorder (model 750A, Cardio-Pulmonary Instruments, Houston, TX). The pressure transducer was calibrated prior to each set of measurements with a water manometer. Pressures were measured directly from the analog recording.

Digital Methods: Digital pressure recording from the Servo 900C ventilator and Servo computer module converter (model SCM 990, Siemens Life Support Systems, Schaumburg, IL) were obtained by connecting the serial output of the RS232 port to a computer (IBM). Standard communications software (Procomm v.2.3, PIL Software Systems, Columbia, MO) directed pressure and flow sampling outputs at 10 ms intervals. The SCM990 converter has the capabilities for sampling up to four channels at 0.005-s intervals (200 Hz). Up to 6,000 sampling points (1,500 points on each channel) can be stored in the SCM990 memory buffer for transfer to the peripheral computer. Following transfer to the IBM computer, the digital pressure signals were stored on disk. The continuous data string file was then converted to columns of individual sampling transducer data points using a command macro to search and replace inspiratory and expiratory signals as row separators (Word Perfect v-5.0, Word Perfect Co, Orem, UT). A basic program was developed to read to

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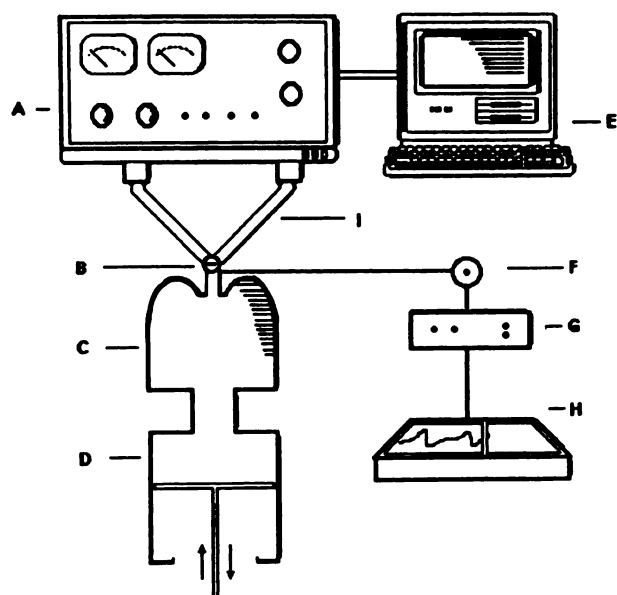


FIGURE 1. Mechanical lung model for measurement of *in vitro*. A, Servo 990 ventilator with 990SCM analog to digital converter. B, Three-way stopcock. C, Lung tank with endotracheal tube. D, Adjustable inspiratory flow piston source. E, IBM computer. F, ± 10 cm H₂O pressure transducer. G, carrier demodulator. H, X-Y recorder.

the column data and convert them to pressure and flow curves that were displayed graphically (appendix 1). The program then placed computer-directed markers at sites of onset of inspiration based on the pressure and flow curves using Servo ventilator manufacturer-supplied conversion factors for pressure and flow readings. The algorithm selected marker sites to fit the criteria of 0 flow, and pressures decreasing from a 0 value to negative values. The last point in a series of consecutive eligible points was chosen as the baseline marker site. The baseline marker pressure was then subtracted from the pressure reading 100 ms later as the P0.1. Appropriateness of marking positions was confirmed by visual inspection or readjusted to the point where pressures begin to fall from a flat baseline (with 0 flow) by shifting the markers (appendix 1). A digital readout of P0.1 was then generated.

Lung Model

The accuracy of the P0.1 measurement was validated using a mechanical lung model (Fig 1). A piston compressor delivered carefully controlled inspiratory and expiratory flows into a 1.5-L, poorly compliant lung tank (compliance 18 ml/ml H₂O). The mechanical lung model was connected to the Servo ventilator through a three-way valve system and standard Servo respiratory tubing circuit (250 ml volume, 3 ml/L/cm H₂O compliance (Siemens Life Support Systems, Schaumburg, IL).

Inspiration and expiration were performed over a range of rates into the Servo system generating P0.1 values ranging from 1.5 to 10 cm H₂O. Occlusion pressure was measured by standard methods² with occlusion at the proximal three-way valve (connected at the site of the endotracheal tubing).

The series of lung model breaths were then repeated using the Servo ventilator digital occlusion method and compared with those obtained by the standard method. With the digital method, the inspiratory and expiratory valves of the Servo ventilator occluded the system in the ventilator distal to the airway tubing circuitry (in contrast to the standard method where the three-way valve occluded directly adjacent to the endotracheal tube).

Nonventilated Controls

Three nonventilated normal subjects were also evaluated with

this technique. The three normal subjects were supine and resting. A noseclip was placed and mouthpiece was inserted. The Servo ventilator was set in the CPAP mode at 0 cm H₂O pressure. A three-way valve (T-shaped stopcock, model 021043, internal diameter $\frac{1}{8}$ "", dead space 44 ml, Collins Co, Braintree MA) was placed adjacent to the endotracheal tube in the inspiratory flow circuit. A drape was placed between the patient and the valve. Random valve occlusions were performed over the sampling period. Multiple measurements were obtained when the airway was occluded proximally by the three-way valve using standard P0.1 methods. Repeated P0.1 values were then obtained by the Servo ventilator method (with occlusion distally in the Servo ventilator).

Ventilated Patients

Patients receiving mechanical ventilatory support in the medical/surgical intensive care unit were eligible for the study. Patients with primary respiratory problems as well as patients with routine postoperative ventilatory support were included. The protocol was approved by the Human Subjects Committee St. Joseph Hospital, Orange, Calif. Informed consent was obtained from all patients enrolled in the study.

Occlusion pressure measurements were performed while patients were resting in a supine position and breathing normally. The inspiratory tubing was connected directly to the inspiratory outflow connector (temporarily bypassing the heating and humidification module) during the P0.1 measurements. The inspiratory tubing was reconnected through the heater-humidifier immediately following the P0.1 measurement procedure. Similarly, the bacterial filter on the expiratory limb was temporarily bypassed during the measurements. All patient P0.1 measurements were performed in patients on the ventilator using standard noncompliant Siemens ventilator circuitry (250 ml volume, 3 ml/L/cm H₂O compliance). Three to 5 P0.1 determinations were obtained on each patient under a variety of ventilator settings (intermittent mandatory ventilation [IMV], continuous positive airway pressure [CPAP], pressure support, and positive end-expiratory pressure [PEEP]). Occlusion pressure measurements were performed by depressing the expiratory pause button on the Servo ventilator. The inspiratory scissors valve remained closed on end expiration and the flap valve closes on the expiratory side, resulting in inspiratory effort against a closed system. Once the initial inspiratory effort was completed, the inspiratory button was released and normal respirations resumed. Measurements of P0.1 were obtained concurrently by the analog methods along with the measurements from the Servo 900C ventilator digital system.

Data Analysis

Occlusion pressure regression values obtained from the lung model by the Servo ventilator method and standard methodologies were determined by linear regression analysis. Correlations between P0.1 values in ventilated patients from servo ventilator methods in comparison with standard methods were also determined by linear regression.

RESULTS

Lung Model Results

The mechanical lung model was used to generate breathing patterns with P0.1 values ranging from 1.5 to 10.5 cm H₂O. Occlusion pressure values obtained by the servo ventilator method at the same lung model flow settings correlated extremely well with those obtained by the standard method ($r=0.99$, slope = 1.00, $p<0.001$) (Fig 2). Using the standard analog measurement methods and proximal airway

Mechanical Lung Model

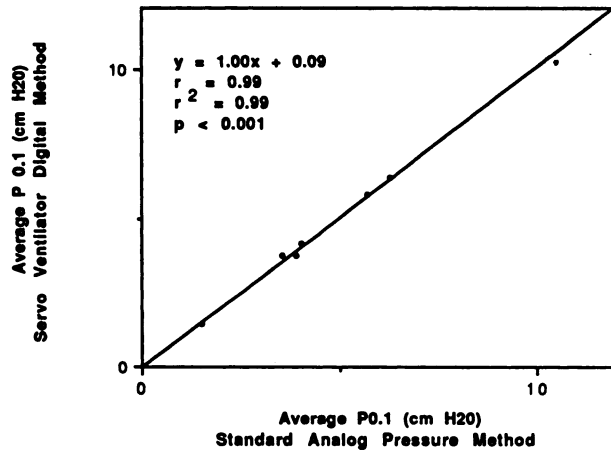


FIGURE 2. Correlation between P0.1 measurements obtained by Servo ventilator methods (vertical axis) and standard analog methods (horizontal axis) using the mechanical lung model. Least squares linear regression line is shown.

tubing occlusion, P0.1 values obtained at each pressure level yielded an average variance of 0.067 cm H₂O. Average variance obtained from the servo method was 0.079 cm H₂O.

Digital Pressure Curves

In all cases (lung model, ventilated patients, and normal subjects), the pressure curves constructed from

the digital Servo-ventilator outputs were virtually identical to the curves obtained by the analog X-Y recordings (Fig 3)

Ventilated Patients

Fifty individual measurements comparing P0.1 by standard vs Servo ventilator methods were obtained. Underlying conditions requiring ventilatory support in these patients included pneumonia, congestive heart failure with pulmonary edema, chronic obstructive pulmonary disease (COPD) exacerbation, Guillian-Barré syndrome, and uncomplicated postabdominal surgery.

Measurements were made on four consecutive days in one patient. In a second patient, measurements were made on two consecutive days. Measurements were made on only one day in the other patients. Sets of measurements were made with two different ventilator settings in four patients. Ventilator settings used in the P0.1 evaluations included volume control, volume control plus pressure support, IMV, IMV plus pressure support, CPAP, and PEEP. An average of four P0.1 measurements was obtained on each patient for each ventilator setting. Occlusion pressure ranged from 0.2 to 4.7 cm H₂O by the standard method, and from 0.2 to 5.3 cm H₂O by the Servo method. There was an excellent correlation between servo and standard methods with a correlation coefficient value of 0.99 (slope = 1.09, p < 0.001) (Fig 4). The average

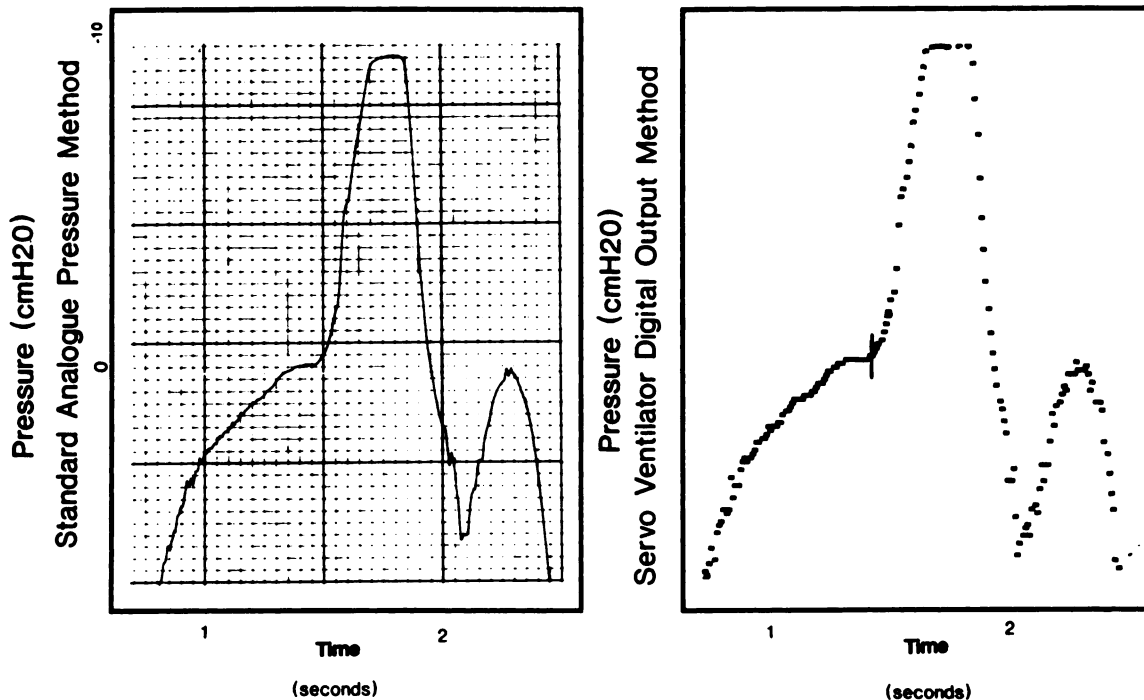


FIGURE 3. Airway pressure obtained by standard analog pressure and X-Y recorder (left graph) methods compared with pressures obtained with the Servo ventilator digital output method (right graph). Pressure in cm H₂O is shown on the vertical axis, time in seconds on the horizontal axis. This is a representative tracing from a ventilated patient. Tracings obtained from the Servo ventilator method are virtually identical to standard analog methods. The position of the computer-generated P0.1 position is indicated by the vertical marking on the Servo digital output curve.

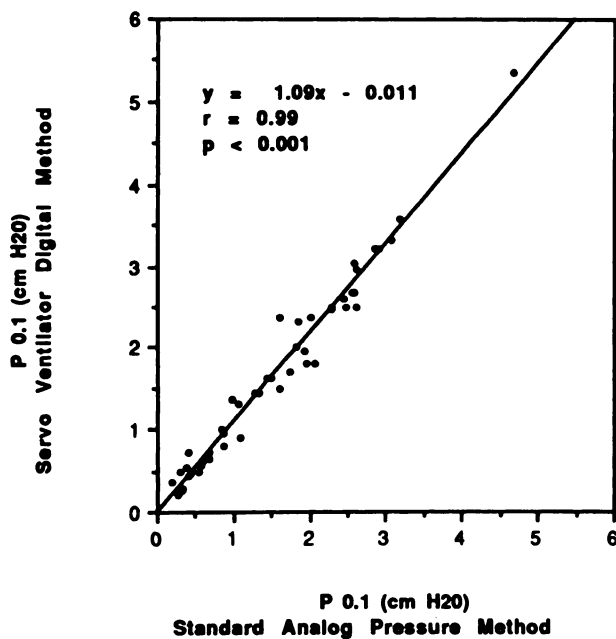


FIGURE 4. Correlation between P0.1 measurements obtained by Servo ventilator methods (vertical axis) and standard analog methods (horizontal axis) in ventilated patients.

variance for P0.1 was 0.80 cm H₂O by the standard method and 0.20 cm H₂O by the servo method. No point differed by more than 0.38 cm H₂O between

Servo Ventilator 900 C

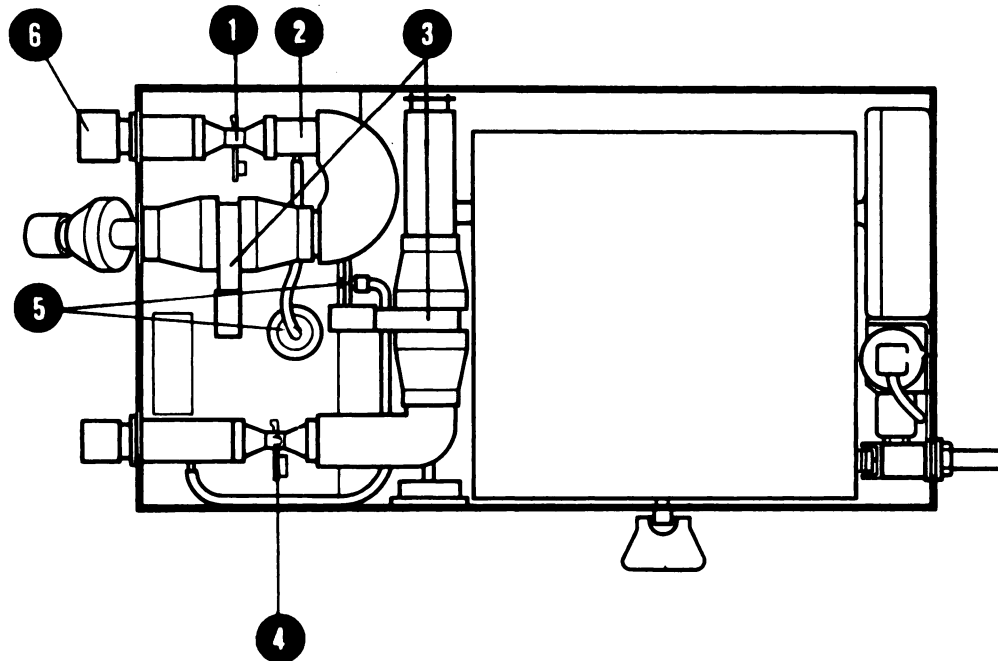


FIGURE 5. Servo ventilator breathing circuitry and airway control valves. 1, Expiratory scissor valve. 2, Expiratory pressure transducer inlet site. 3, Inspiratory and expiratory flow transducers. 4, Inspiratory scissor valve. 5, Inspiratory and expiratory pressure transducers. The inspiratory and expiratory airway flow control scissor valves are shown. Note that the pressure and flow transducers are located within the airway circuitry on both the inspiratory and expiratory flow limbs. The scissor valves and one way expiratory flow flap valve remain closed at end expiration when the expiratory pause button on the ventilator is depressed.

servo and standard methods.

The 50 measurements consisted of 13 different sets of measurements from five patients. When the individual P0.1 values were averaged for each set of measurements in patients, a correlation coefficient of 0.99 was obtained between servo and standard P0.1 methods ($r^2 = 0.99$, slope 0.98, $p < 0.001$). The maximum difference in average P0.1 values between Servo method measurements and standard methods was 0.20 cm H₂O.

Normal Control Subjects

Two female subjects and one male nonventilated subject were studied using a mouthpiece and the servo ventilator set at CPAP 0 cm H₂O. An average of seven measurements was obtained in each control subject. Again, excellent agreement was found between P0.1 obtained by the servo method and standard methods. No difference was found between measurement means obtained by the two methods. The maximum difference obtained between the two methods in normal subjects was 0.23 cm H₂O.

DISCUSSION

Airway occlusion pressure appears to correlate well with the ability of patients with lung disease to tolerate weaning from mechanical ventilation.^{4,5} The use of

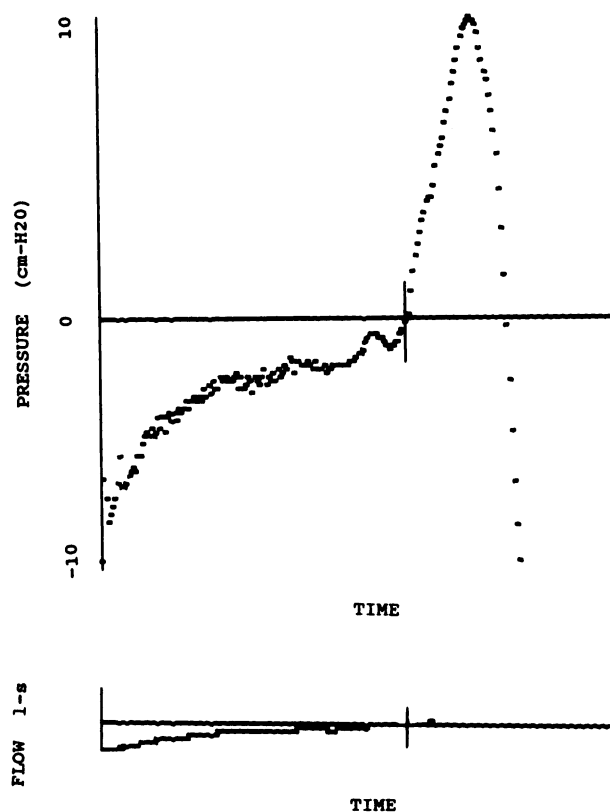


FIGURE 6. Simultaneous digital output curve generated of airway pressure and flow during airway occlusion maneuver by the Servo ventilator. Airway pressures in cm H₂O are graphed on the vertical axis, time in seconds on the horizontal axis (upper curve). The computer-generated P0.1 position is indicated by the vertical marking on the digital output curve. The position of the computer-selected P0.1 marker can be confirmed or readjusted. The simultaneous airway flow curve is reconstructed on computer (lower tracing). Absence of airway flow at the time of airway occlusion measurement is demonstrated with this tracing.

P0.1 in ventilated patients has been limited by technical complexity of the measurement procedure. We have developed a new method for measuring P0.1 using standard ventilatory equipment. This method is accurate in a mechanical lung model, in patients receiving ventilatory support in the intensive care unit, and in nonventilated patients.

Standard methods for measuring P0.1 in ventilated patients require the use of a valve system to rapidly terminate airflow at end expiration. A three-way valve or pneumatic occlusion valve is usually employed on the inspiratory circuit on the inflow side with a one-way valve on the expiratory side.^{2,4} A pressure transducer is placed in the airway system. A fall in airway pressure is measured as the patient attempts to inhale against the closed valve system. The inspiratory pressure is measured and recorded 1/10 of a second after the start of the inspiratory effort. Following the brief occlusion, the inspiratory valve must be quickly opened to allow the patient to continue the inspiratory cycle with minimal distress. This method requires the specialized transducing and recording equipment, as

well as the mechanical valves. A degree of skill is required to turn and release the valves rapidly and silently to obtain accurate P0.1 values.¹

We have used the capabilities of the ventilator and SCM990 analog to digital internal converting capabilities to develop a simplified method for measuring P0.1. The Servo ventilator has an inspiratory and expiratory flow circuit with scissors and flap valves capable of shutting off flows on both limbs of the flow circuit (Fig 5). These valves are microprocessor controlled with feedback from pressure and flow transducers within the airway tubing circuitry. Flow, pressure, and time algorithms are used by the Servo ventilator to recognize the components of the respiratory cycle. The expiratory pause button on the ventilator causes the inspiratory valve to remain closed at end expiration; the flap valve does not allow retrograde flow from the expiratory side. The expiratory scissors valve closes when airway pressures are negative and both scissors valves remain closed from end expiration until the expiratory pause button is released. Pressure transducers between both scissor valves and the patient continuously monitor pressure. The signals are converted to digital codes for analysis. In this manner, the Servo ventilator system has the ability to perform all the necessary functions for obtaining accurate P0.1 measurements.

The validity of the Servo ventilator system for measuring P0.1 is dependent on a number of factors. The scissors valves must properly recognize expiration, and the inspiratory scissors valve must remain closed during the inspiratory effort. The inspiratory scissors and the expiratory flap valve closure must be complete, blocking all airflow. Closure must be undetected by the patient until inspiration begins. Finally, the pressure recorded by the transducers within the Servo system must be accurate within the range of the P0.1 measurements. The digital sampling intervals must be sufficiently short to generate a smooth curve in the region of the P0.1 measurement.

The valves for the Servo ventilator system are located within the ventilator. In contrast, the standard three-way valve system is placed close to the patient's endotracheal tube. Thus, the compliance of the airway tubing system must be low enough that no significant inspiratory pressure is dissipated within the tubing. This was confirmed with the mechanical lung model. Lung model P0.1 measurements correlated extremely closely when airway tubing was occluded adjacent to the endotracheal tube with the three-way valve (standard analog method) in comparison with distal occlusion at the scissors valves over a wide range of pressures (Servo ventilator method) (Fig 2). This confirmed the accuracy of the valve closure and showed that there was no significant damping of the inspiratory pressure signals due to the compliance of the airway tubing for

P0.1 as high as 10 cm H₂O.

Continuous digital flow recordings demonstrate complete occlusion by the scissor valves. These flow readings also confirm correct timing of closure of the scissors valves at end-expiration (Fig 6).

The pressure transducer within the servo ventilator generated digital pressure curves that were virtually identical to the standard X-Y recorder analog curves, although there was a baseline shift of up to 1 cm H₂O (depending on individual ventilator transducers). The baseline shift was corrected by subtracting the baseline pressure value from the pressure 100 ms following the start of inspiration. The digital signal had the advantage of exact and instantaneous readout capabilities.

The accuracy of this method for measurement of P0.1 in intubated patients was demonstrated under a variety of ventilatory modes (CPAP, pressure support, PEEP, IMV). There was an extremely strong correlation between P0.1 measured by the Servo ventilator and P0.1 measured by traditional pressure transducer and analog X-Y recorder methods in all ventilatory modes.

A relatively simple computer program may be written to automatically select P0.1 values from digital signal pressure curves. Additionally, this system can be used with a mouthpiece in nonintubated patients (in the CPAP mode) to determine P0.1 in spontaneously breathing patients. In our studies, P0.1 values obtained with this system in nonventilated patients also correlated very closely with P0.1 values obtained from standard X-Y recordings.

Previous studies have demonstrated the feasibility of digitizing airway pressure signals from patients for computerized analysis of P0.1.^{5,6} However, they have not used standard respiratory equipment available to most clinical centers.

Thus, we have described a highly accurate method for the measurement of P0.1 using standard Servo ventilator respiratory equipment. Routine and investigational measurements of P0.1 as a weaning parameter may be facilitated with this system. The rapid response and ease of use of the system should enable evaluation of many physiologic variables involved in respiratory control in ventilated and nonventilated subjects.

APPENDIX

Transducer Specifics

The Servo 900C ventilator inspiratory pressure transducers have a pressure range (-)20 cm H₂O to (+)120 cm H₂O with accuracy ± 5 percent (manufacturer's specifications). Analog sample processing range is (-)10 V to (+)9.99 V with 4.883 mV/bit resolution and accuracy of 0.2 percent of readings. Digital SCM990 signals are optocoupled connections to the

RS232 output port.

Data Analysis

The data analysis for generation of airway occlusion pressures is performed in two steps. The first step is the conversion of continuous string data generated by the Servo SCM990 into discreet data points. The second step is analysis of the data graphically and selection of P0.1 points. The two steps are accomplished currently in the following manner:

Program 1: Conversion of the string to discreet columns of individual data is easily accomplished since the servo SCM990 precedes each data point with a letter (I, E, or P) designating inspiratory, expiratory, or pause cycles. We have chosen to read columnar data rather than string data to avoid any misreading if an error occurs in any data signal transmission point.

Data files from the servo SCM990 are named 1, 2, 3, etc. A batch file was created that performs the following functions: (a) opens Word Perfect (v-5.0); (b) opens the first file; (c) calls up a macro that converts all inspiratory, expiratory, and pause markers to carriage returns; (d) saves the file in ASCII format; and (e) opens the second file and repeats the preceding sequence until all files have been converted.

Program 2: The data processing program was written in Quick Basic (v-4.5. Microsoft Co., Redmond, WA). The program performs the following functions: (a) data are read into the program; (b) four-digit codes are converted to pressures and flows using conversion factors for each channel supplied by the manufacturer (Siemens).

Conversion information:
channel 00 airway flow gain 1.0 offset 2.0 scale 9.7656E-4
channel 02 airway pressure gain 1.0 offset 200.0 scale 9.7656E-2

(c) the program then graphically displays the pressure and flow curves; (d) the computer then selects proposed marker points for the start of airway occlusion maneuvers by the following criteria:

- (1) Search for the first point where flow is 0 L/s* and inspiratory pressure is at least -2cm magnitude (to eliminate noise variations).
- (2) From this point the data points are scanned retrograde in time to a point where the pressure is 0* (and flow is still 0). This then is proposed as the potential point for the start of the inspiratory occlusion maneuver. A marker is placed on the computer screen at this site.

*The baseline values for pressure and flow criteria are chosen as 0 mm Hg and 0 l/s, respectively. However, in cases where there has been a baseline pressure transducer shift, or if some PEEP is present, a correction of the baseline may be needed. Baseline adjustments can be entered into a set-up criteria at the start of the program run.

Copies of this program will be made available to anyone who is interested. The program runs on IBM compatible computers with EGA, VGA, or CGA graphics.

- (3) The operator is queried as to the appropriateness of the marker site. The marker site can then be approved or shifted in either direction. After each shift of the marker, confirmation is requested from the operator.
- (4) Once an appropriate marker site has been approved, the P0.1 is determined. This is done by finding the pressure 100 ms following the point of the marker. The flow is checked at this point to ensure it is still 0. The pressure at the start of the maneuver (initial marker) is subtracted from the pressure 100 ms later.
- (5) The P0.1 is displayed on screen.
- (6) The curve is then searched for further points that meet criteria.

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