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Inspiratory Work and Response Times of a Modified Pediatric Volume Ventilator during Synchronized Intermittent Mandatory Ventilation and Pressure Support Ventilation

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Volume ventilation by demand flow ventilators significantly increases work of breathing during inspiration. Although various ventilator modifications and different modes of ventilation have been developed, there have been few studies regarding imposed work of breathing in infants and children. This study was designed to evaluate several modifications of a commercially available demand flow ventilator designed to shorten response time (t_r) and decrease the imposed work (W_i) involved in opening the demand valve. Minimum withdrawal volume (V_{min}), maximum negative pressure (P_{mneg}), and t_r were measured. W_i was defined as the product of V_{min} and P_{mneg}. Seven Siemens Servo® 900C ventilators were tested under 16 different trial conditions with four variables: 1) mode of ventilation (synchronized intermittent mandatory ventilation [SIMV] *vs.* pressure support ventilation [PSV]); 2) caliber of circuit tubing (adult *vs.* pediatric); 3) location of airway pressure monitor (distal *vs.* proximal); and 4) ventilator trigger sensitivity (0 cm H_2O—high *vs.* −2 cm H_2O—low). V_{min}, P_{mneg}, and W_i were all decreased ($P < .05$) while t_r was unaffected by changing ventilator trigger sensitivity from low to high. W_i was decreased by pediatric tubing and proximal airway pressure monitoring only when low trigger sensitivity was used. PSV and proximal airway monitoring shortened t_r. The authors conclude that the use of pediatric circuit tubing and proximal airway pressure monitoring with a Siemens Servo® 900C ventilator significantly improved ventilator performance. (Key words: Equipment, ventilator. Muscle, respiratory: imposed work. Ventilation, mechanical: pediatric.)

PATIENT-INITIATED MODES of mechanical ventilation are widely used means of providing ventilatory support in the intensive care setting. Demand flow ventilators with intermittent gas flow significantly increase inspiratory work of breathing, compared with continuous flow systems.[1-8] Newer modes of mechanical ventilation have been developed in an attempt to minimize this imposed inspiratory workload.[9-13] Modifications to the ventilator circuit have been reported to shorten response time and improve patient-ventilator synchrony.[14] Infants and young children are particularly susceptible to the difficulties with demand flow ventilators. First, they have limited ability to respond to the imposed inspiratory work load and frequently develop worsening respiratory failure or apnea.[15,16] Second, their rapid respiratory rates along with the variable "sensing" capability of these ventilators can lead to patient-ventilator asynchrony and actually further increase the work of breathing.[17]

This study was designed to evaluate the effect of two modifications to a commercially available demand flow ventilator designed to shorten response time (t_r) and decrease the inspiratory work imposed (W_i). In addition, t_r and W_i were measured using two different ventilatory modes: synchronized intermittent mandatory ventilation (SIMV) and pressure support ventilation (PSV).

Methods

Seven ventilators (Siemens Servo® 900C, Siemens Elema Corp, Elma, Sweden) were randomly selected from a pool of routinely used ventilators. Each ventilator had undergone routine maintenance and calibration according to the manufacturer's specifications within a month prior to the study.

Circuit withdrawal volume, airway pressure, and ventilator response time were determined by the method reported by Epstein.[17] Minimum withdrawal volume (V_{min}) was defined as the volume of air that, when rapidly removed from the ventilator circuit, triggered the ventilator in nine of ten trials. The volume of air was first stored as a vacuum in a syringe and then instantaneously removed from the ventilator circuit by manually opening a three-way stopcock as rapidly as possible. Circuit pressure was measured by a differential pressure transducer (Validyne® MP-45) that was calibrated to a water manometer. Pressure-time tracings (fig. 1) were recorded at a paper speed of 50 mm/s (Hewlett Packard® 7754B). Maximum negative pressure (P_{mneg}) was defined as the peak negative pressure measured during a triggering maneuver. Response time was defined as the elapsed time from initiation of negative airway pressure to the attainment of 1 cm H_2O positive pressure during the triggered inspiration. Imposed work associated with opening the demand valve

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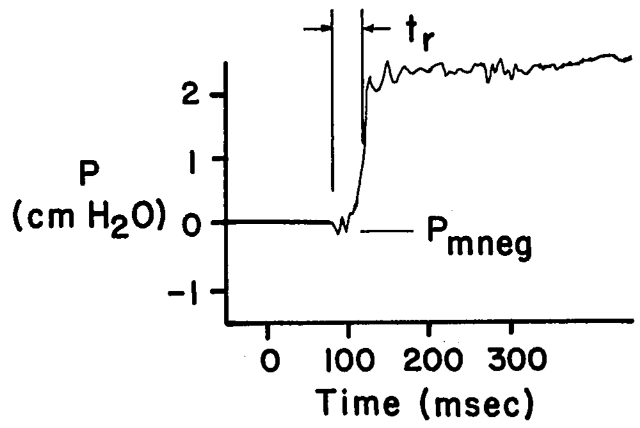

FIG. 1. Typical pressure-time tracing demonstrating how P_{mneg} and t_r were obtained.

and triggering the ventilator was defined as the product of V_{min} and P_{mneg}.

Each circuit contained a humidifier (Cascade I®, Bennett Corp., Kansas City, MO) at room temperature. Compressible volume was calculated for each circuit by injecting a known volume of air (200 ml) into the closed circuit and measuring the peak circuit pressure in ten trials. The volume of air was divided by the average peak circuit pressure to obtain the compressible volume in ml/cm H_2O.

Each ventilator was tested in both SIMV and PSV modes. During SIMV each ventilator was set to provide six breaths per minute, tidal volume of 200 ml, inspiratory flow of approximately 8 l/min, square inspiratory flow waveform, and zero-end expiratory pressure (baseline). During PSV, the pressure limit was set at 10 cm H_2O above baseline. Each ventilator was tested under 16 different trial conditions by the manipulation of four variables (table 1). These variables were:

Ventilator sensitivity setting. The ventilator was set to trigger when the circuit pressure was less than either 1) ambient pressure (high sensitivity); or 2) −2 cm H_2O (low sensitivity).

Sampling site of ventilator circuit pressure. 1)Distal—usual configuration with the sampling site located at the end of the exhalation limb of the ventilator circuit; and 2) Proximal—the sensing transducer was connected directly to the patient adapter by ¼-inch diameter, rigid tygon tubing.

Ventilator circuit characteristics. 1) Adult tubing—22-mm ID tubing with a total volume of 1740 ml and 2.20 ± .09 ml/cm H_2O compressible volume (Airlife breathing circuit, American Pharmaseal Corp.); and 2) Pediatric tubing—10-mm ID tubing with a total volume of 990 ml and 1.37 ± .04 ml/cm H_2O compressible volume (Siemens Elema Ventilatory Systems, Siemens Elema Corp.).

Mode of assisted ventilation. SIMV and PSV.

TABLE 1. List of Variables Used for All 16 Trial Conditions

Trial	Mode of Ventilation	Caliber of Tubing	Pressure Transducer Location	Ventilator Sensitivity
1	SIMV	adult	distal	high
2	PSV	adult	distal	high
3	SIMV	pediatric	distal	high
4	PSV	pediatric	distal	high
5	SIMV	adult	proximal	high
6	PSV	adult	proximal	high
7	SIMV	pediatric	proximal	high
8	PSV	pediatric	proximal	high
9	SIMV	adult	distal	low
10	PSV	adult	distal	low
11	SIMV	pediatric	distal	low
12	PSV	pediatric	distal	low
13	SIMV	adult	proximal	low
14	PSV	adult	proximal	low
15	SIMV	pediatric	proximal	low
16	PSV	pediatric	proximal	low

Mean ± SEM.

Under each trial condition, the initial withdrawal volume was 0.5 ml and was increased by 0.5 ml increments until nine of ten attempts triggered a ventilator cycle. Analysis of variance was used to compare results for V_{min}, P_{mneg}, t_r, and W_i under all 16 trial conditions. The Duncan multiple range test was used to determine significant differences ($P < .05$) between means.

Results

Values for V_{min} are summarized in table 2. When ventilator trigger sensitivity was decreased from high to low, V_{min} was increased independently of all other test variables. Pediatric circuit tubing and proximal airway monitoring decreased V_{min} only at a low trigger sensitivity. No differences in V_{min} was found between SIMV and PSV.

TABLE 2. Measured Withdrawal Volume, Maximum Negative Pressure, Imposed Work, and Mean Response Time under All 16 Trial Conditions

Trial	Withdrawal Volume (ml)	Maximum Negative Pressure (cm H_2O)	Imposed Work (mJ/l)	Mean Response Time (ms)
1	2.3 ± 0.4	0.75 ± 0.14	0.20 ± 0.06	127 ± 5
2	2.3 ± 0.4	0.73 ± 0.13	0.19 ± 0.06	109 ± 4
3	2.1 ± 0.6	1.56 ± 0.31	0.42 ± 0.16	120 ± 9
4	2.1 ± 0.5	1.68 ± 0.31	0.43 ± 0.15	109 ± 9
5	1.1 ± 0.4	0.50 ± 0.13	0.08 ± 0.04	112 ± 11
6	1.1 ± 0.3	0.49 ± 0.12	0.07 ± 0.04	93 ± 8
7	0.5 ± 0.0	0.70 ± 0.08	0.04 ± 0.05	102 ± 7
8	0.5 ± 0.0	0.71 ± 0.09	0.04 ± 0.01	89 ± 7
9	13.4 ± 1.6	3.42 ± 0.41	4.86 ± 1.13	169 ± 23
10	12.9 ± 1.9	3.30 ± 0.41	4.52 ± 1.11	131 ± 20
11	5.4 ± 1.2	3.27 ± 0.28	1.86 ± 0.55	111 ± 7
12	6.2 ± 1.2	3.83 ± 0.28	2.46 ± 0.59	101 ± 5
13	9.0 ± 2.2	2.53 ± 0.40	2.58 ± 1.18	132 ± 4
14	8.0 ± 2.2	2.55 ± 0.43	2.54 ± 1.25	100 ± 11
15	1.5 ± 0.5	1.87 ± 0.38	0.39 ± 0.20	86 ± 6
16	1.1 ± 0.3	1.67 ± 0.27	0.21 ± 0.08	79 ± 5

Mean ± SEM.

Values for P_{mneg} are in table 2. P_{mneg} was greater when ventilator trigger sensitivity was decreased from high to low. Proximal airway pressure monitoring decreased P_{mneg} except when adult circuit tubing and high ventilator sensitivity were used. Circuit tubing size and mode of ventilation had no influence on P_{mneg}.

Results for W_i are represented in table 2. The mode of ventilation had no effect on W_i (fig. 2 A). Pediatric tubing and proximal airway monitoring decreased W_i only at low trigger sensitivity (figs. 2 B and 2 C). In general, W_i was greater at low trigger sensitivity (figs. 2 A, 2 B, and 2 C) except when pediatric circuit tubing and proximal airway monitoring were used (fig. 2 A).

Table 2 shows the values for t_r. During PSV, t_r was shorter than during SIMV (fig. 3 A). Pediatric tubing decreased t_r only when ventilator sensitivity was low (fig. 3 B). Proximal airway pressure monitoring decreased t_r under all trial conditions (fig. 3 C).

Discussion

We assessed the performance of a commonly used ventilator under rigidly controlled and reproducible conditions that resemble the clinical situation in that a patient withdraws a small volume from the ventilator circuit, thus generating a negative pressure.[17] This method of gas withdrawal (stored vacuum in a syringe exposed as rapidly as possible to the circuit by manually opening a stopcock) produced a constant P_{mneg} at each level of withdrawal volume, indicating consistent technique. Unfortunately, in clinical situations the respiratory rates and inspiratory flows and volumes vary greatly; therefore, caution should be used when extrapolating these laboratory results to the clinical situation.

During mechanical ventilation, the work of breathing can be considered to be the sum of three components: lung work, chest work, and work imposed by the ventilator. Imposed work is defined as the work added to the chest/lung work as a result of the attachment of equipment to the airway composed of artificial airways[18-20] and ventilator circuitry.[1-3] This study estimated only one component of W_i, namely the work involved in opening the demand valve.

A typical clinical configuration in many ICU's for assisted ventilation includes: SIMV mode, adult circuit tubing, distal airway pressure monitoring, and low trigger sensitivity. In our study, this configuration was associated with a substantially greater W_i and significant prolongation of t_r when compared to the maximally sensitive configuration: PSV mode, pediatric circuit tubing, proximal airway pressure monitoring, and high trigger sensitivity (figs. 2 and 3). Although both W_i and t_r were minimal with high trigger sensitivity, this configuration is clinically impractical due to automatic cycling. The modifications

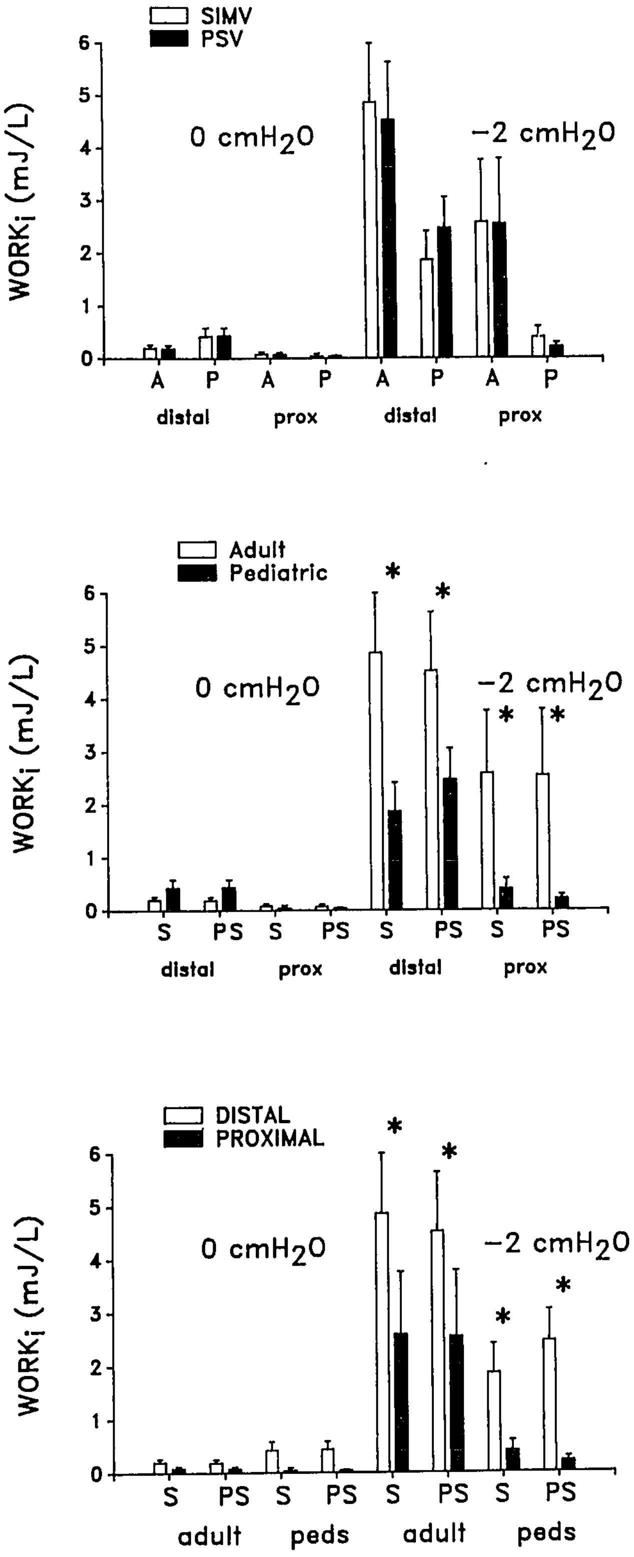

FIG. 2. Imposed work expressed in millijoules/liter (mean ± SEM). The three panels compare sets of variables which were tested: A) SIMV *versus* PSV; B) Adult *versus* pediatric circuit tubing; and C) Distal *versus* proximal airway pressure monitoring. (S = SIMV, PS = PSV, A = adult, P = pediatric, 0 cm H_2O = high sensitivity, −2 cm H_2O = low sensitivity, $^*P < 0.05$).

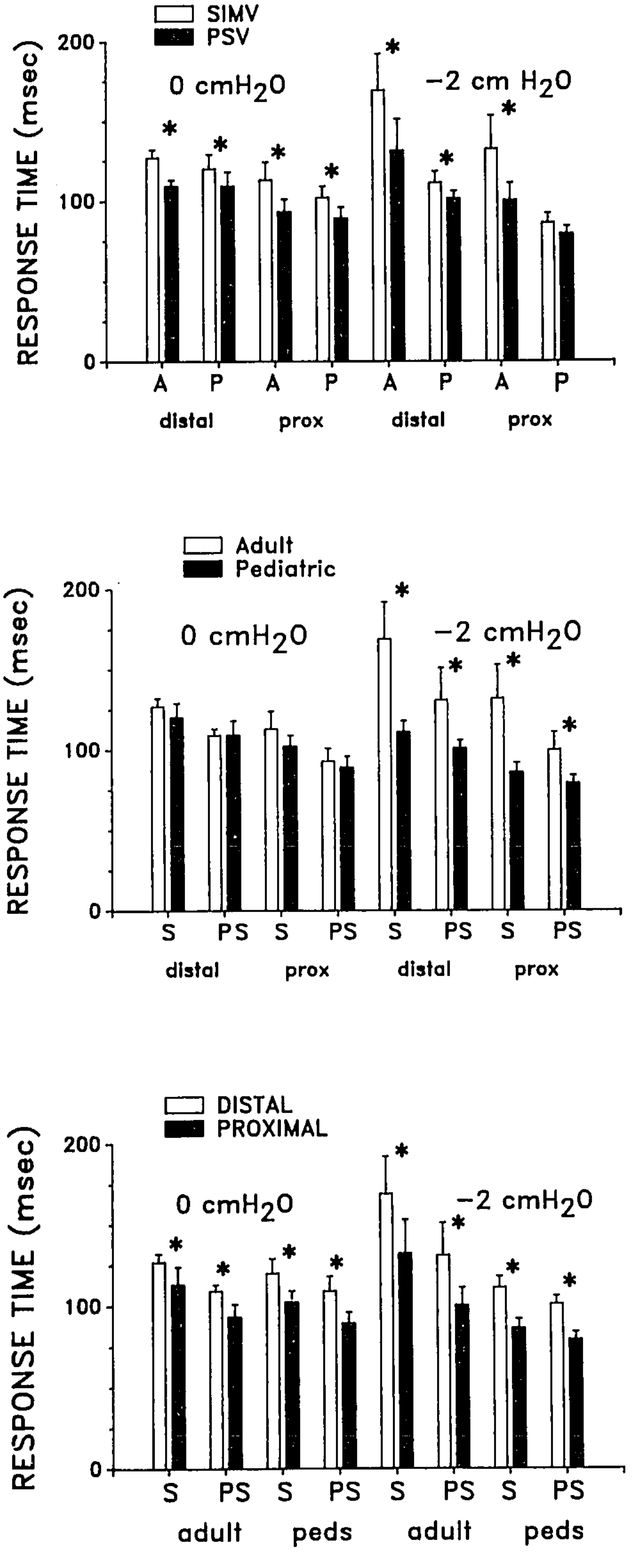

FIG. 3. Response time expressed in milliseconds (mean ± SEM). The three panels compare sets of variables which were tested: A) SIMV *versus* PSV; B) Adult *versus* pediatric circuit tubing; and C) Distal *versus* proximal airway pressure monitoring. (S = SIMV, PS = PSV, A = adult, P = pediatric, 0 cm H_2O = high sensitivity, −2 cm H_2O = low sensitivity, *$P < 0.05$).

used in this study (*i.e.*, pediatric circuit tubing and proximal airway pressure monitoring) can significantly decrease W_i and shorten t_r at a clinically useful ventilator sensitivity (−2 cm H_2O). These modifications result in decreased circuit compliance and compressible volume, thus allowing more rapid sensing of both the patient's inspiratory effort by the ventilator and more rapid delivery of the ventilator breath to the patient, leading to shorter t_r and decreased W_i.

Until a ventilator responds to an inspiratory effort, it imposes an inspiratory load on the patient. If the response time comprises a large portion of the inspiratory time, the patient will work against the obstruction until gas is delivered. Moreover, less time will be allowed for the delivery of the mechanical tidal volume necessitating faster flows and higher peak pressures. In patients with high airway resistance (*i.e.*, asthma, bronchopulmonary dysplasia) there may be an additional time lag between the initiation of inspiration as measured by muscle activity or change in pleural pressure and the development of negative airway pressure. Thus the total response time is longer, leading to patient-ventilator phase difference (asynchrony). An additional problem in infants and children is the irregular and rapid respiratory rates of this group of patients with pulmonary disease which makes them more susceptible to patient-ventilator asynchrony.[21,22] This asynchrony has been associated with deterioration in gas exchange and oxygenation[23,24] as well as an increased incidence of barotrauma.[22]

The responsiveness of modern demand flow volume ventilators is of major importance when attempting to assist ventilation in infants and small children. We have demonstrated that pediatric circuit tubing and proximal airway monitoring with a Siemens Servo® 900C volume ventilator significantly decreased t_r and W_i, thus improving responsiveness. This in turn might reduce the risk of complications such as asynchrony, respiratory fatigue, and pulmonary barotrauma in children.

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