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The Effectiveness of Pressure Support Ventilation for Mechanical Ventilatory Support in Children

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Background: **The rapid respiratory frequency of children may lead to patient–ventilator asynchrony and increase the work of breathing during mechanical ventilation, and the use of a small endotracheal tube and a demand valve can further increase this work of breathing. Although pressure support ventilation (PSV) is well known to reduce the work of breathing in adults, there are no reports regarding clinical studies of PSV in children. Therefore, the effect of PSV on breathing patterns and the work of breathing in children was studied.**

Methods: **Six children (3–5 yr of age) were studied in the immediate postoperative period. Three levels of PSV, 0, 5, and 10 cmH$_2$O, were employed. Airway pressure, flow, tidal volume, minute ventilation, and respiratory frequency were measured. To assess the work of breathing, the negative deflection of esophageal pressure (ΔPes) caused by inspiratory effort was measured. The inspiratory work of breathing was also estimated directly by measuring the esophageal pressure–volume loop using the Campbell technique.**

Results: **Although minute ventilation did not change with PSV, tidal volume increased and respiratory frequency decreased with increasing levels of PSV. The ΔPes decreased markedly from 8.9 cmH$_2$O with PSV of 0 cmH$_2$O to 5.7 cmH$_2$O with PSV of 5 cmH$_2$O and 2.7 cmH$_2$O with PSV of 10 cmH$_2$O. The mechanical work of breathing also decreased from 0.743 Joules/l with PSV of 0 cmH$_2$O to 0.463 Joules/l with PSV of 5 cmH$_2$O and 0.196 Joules/l with PSV of 10 cmH$_2$O.**

Conclusions: **It was concluded that PSV can effectively augment spontaneous breathing and reduce the work of breathing in children. (Key words: Muscle, respiratory: work of breathing. Ventilation, mechanical: children; pressure support.)**

PATIENT-TRIGGERED modes, such as synchronized intermittent mandatory ventilation (IMV) and pressure support ventilation (PSV), have been widely used as partial ventilatory support in adults.[1] However, in children, synchronized IMV has been relatively unsuccessful because of problems related to the time delay used to trigger spontaneous breathing.[2] This time delay may lead to asynchrony between the children and the ventilator because of their short inspiratory time and rapid respiratory frequency. Asynchrony may result in inefficient gas exchange and increased work of breathing. Therefore, nonsynchronized IMV with a continuous-flow system has been used instead of synchronized IMV with a demand-flow system in infants and children. However, in children, especially those over 3 yr of age, a negative deflection of airway pressure during inspiration cannot be avoided, even with the continuous flow system, because of their relatively large tidal volume (over 100 ml of tidal volume). This decrease in airway pressure increases the work of breathing imposed by the ventilator. In addition, the small-diameter endotracheal tubes required by children increase the airway resistance and, thus, add to the resistive work of breathing by the patient during spontaneous breathing *via* a ventilator.

Pressure support ventilation is well known to reduce the work of breathing with increased levels of PSV, and to improve patient–ventilator synchrony in adults.[3–8] Concerning PSV in children, Martin *et al.*[2] have reported that it shortened the response time of the demand valve when compared with synchronized IMV in a mechanical ventilatory model. However, there are no reports regarding clinical studies of PSV in children. We, therefore, investigated the effect of PSV on breathing patterns and the work of breathing in children.

Materials and Methods

Patients

With institutional approval and informed consent from their families, six children aged 3–5 yr were studied. Body weight ranged between 13.5 and 18.4 kg

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(average: 15.3 kg). All of the children had undergone cardiac surgery and were ready to begin the process of separation from mechanical ventilation with stable respiratory and hemodynamic conditions. They were sedated moderately with continuous infusion of chlorpromazine at a dose of 0.05–0.15 $\mu g \cdot kg^{-1} \cdot h^{-1}$. The endotracheal tubes used were between 4.5 and 6.0 mm in internal diameter. Although uncuffed tubes were used in three of six children (cases 1–3), there was no air leakage from the tube with less than 10 cmH_2O of airway pressure.

Protocol

Three levels of PSV (0, 5, and 10 cmH_2O) were employed in random order with a ventilator (7200a; Puritan-Bennett, Los Angeles, CA). The trigger sensitivity was set at −1.0 cmH_2O. Each level of PSV was utilized for 30 min, and measurements were performed in the last 10 min of each treatment period.

Measurements

Airway pressure and flow were measured at the proximal end of the endotracheal tube using a differential pressure transducer (pneumotachograph/pressure transducer system; Bicore, Irvine, CA). Tidal volume (V_T) and minute ventilation were obtained by integrating the flow signal. From the flow signal, the respiratory frequency, inspiratory time (T_I), and total respiratory cycle duration (T_{tot}) were measured. The duty cycle, which was defined as the T_I/T_{tot} ratio, and mean inspiratory flow (V_T/T_I) were calculated.[9]

To assess the work of breathing by the patient, esophageal pressure was measured using an esophageal balloon. The position of the esophageal balloon was confirmed by comparing the negative deflection of esophageal pressure and airway pressure during inspiration made against an occluded airway.[10] The negative deflection of esophageal pressure during inspiration (ΔPes) was calculated as the difference between the end-expiratory esophageal pressure and the lowest esophageal pressure. Changes in esophageal pressure follow those in pleural pressure;[11] therefore, the ΔPes value reflects the inspiratory work of breathing.

Table 1. Patient Characteristics

Case No.	Age (yr)	Sex (M/F)	Body Weight (kg)	Tube Diameter (mm)	Operation Performed
1	5	M	15.5	5.5	Fontan's operation
2	3	F	12.5	4.5	Total correction of TOF
3	5	M	15.5	5.5	Fontan's operation
4	5	M	16.2	5.5	Patch closure of ASD
5	5	M	18.4	6.0	Patch closure of ASD
6	5	F	13.9	6.0	Total correction of DORV

Tube diameter = internal diameter of endotracheal tube; TOF = tetralogy of Fallot; ASD = atrial septal defect; DORV = double-outlet right ventricle.

Table 2. Ventilatory Parameters and Blood Gas Tensions during Pressure Support Ventilation (PSV)

	PSV 0	PSV 5	PSV 10
$\dot{V}_E$ (L/min)	3.36 ± 0.77	3.26 ± 0.79	3.36 ± 0.88
V_T (ml)	112 ± 21	116 ± 80	137 ± 24*
f (breaths/min)	30 ± 4	28 ± 4	25 ± 6*
Duty cycle	0.36 ± 0.03	0.32 ± 0.02*	0.28 ± 0.04*
V_T/T_I	155 ± 40	168 ± 39*	200 ± 34*
ΔPes (cmH_2O)	8.9 ± 4.0	5.7 ± 3.1*	2.7 ± 2.3*
WOB (joules/L)	0.74 ± 0.29	0.46 ± 0.28*	0.20 ± 0.22*
Pa_{O_2} (mmHg)	128 ± 62	127 ± 60	135 ± 64
Pa_{CO_2} (mmHg)	44 ± 3	41 ± 3	41 ± 1

Values are means ± SD.

PSV 0, 5, 10 = pressure support ventilation of 0, 5, and 10 cmH_2O, respectively; $\dot{V}_E$ = minute ventilation; V_T = tidal volume; f = respiratory frequency; V_T/T_I = mean inspiratory flow; ΔPes = negative deflection of esophageal pressure during inspiration; WOB = mechanical inspiratory work of breathing.

* $P < 0.05$ *versus* PSV 0.

The work of breathing was also estimated directly by measuring the area enclosed between the esophageal pressure–volume loop during inspiration and the relaxation curve of the chest wall, using the Campbell technique (CP-100; Bicore).[12,13] Chest wall compliance was assumed to be 200 ml/cmH_2O. The mechanical work of breathing (WOB) by the patient was expressed as work per liter of ventilation.

Arterial blood samples were obtained *via* a catheter inserted in a radial artery, and were analyzed with a blood gas analyzer (ABL4; Radiometer, Copenhagen, Denmark).

All data are presented as mean ± SD. Statistical analysis was performed by analysis of variance for repeated measures and paired Student's *t* test with Bonferroni's correction. The α level was set at 0.05.

Results

Patients characteristics are described in table 1. Although minute ventilation did not change, tidal volume increased by 22% and the respiratory frequency decreased by 16% with PSV of 10 cmH_2O when compared

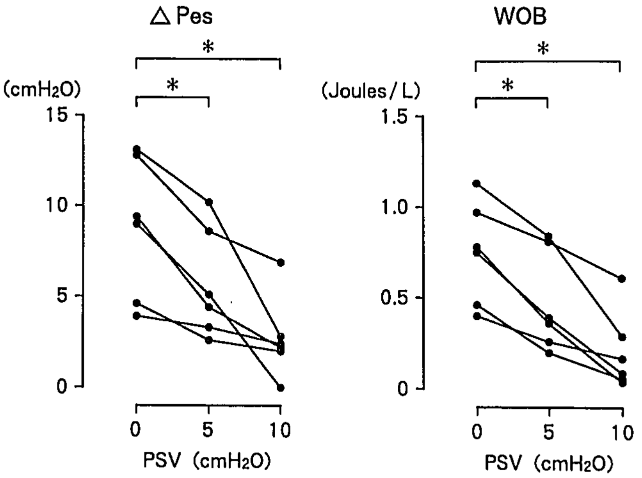

Fig. 1. Negative deflection of esophageal pressure and WOB during PSV of 0, 5, and 10 cmH_2O.

with PSV of 0 cmH_2O (table 2). The mean inspiratory flow increased by 8% with PSV of 5 cmH_2O and by 29% at 10 cmH_2O. In contrast, the duty cycle decreased by 11% with PSV of 5 cmH_2O and by 24% at 10 cmH_2O. Concerning the work of breathing, the mean ΔPes value decreased significantly from 8.9 cmH_2O without PSV to 5.7 cmH_2O with PSV of 5 cmH_2O and 2.7 cmH_2O with PSV of 10 cmH_2O (fig. 1). Work of breathing also decreased by 48% with PSV of 5 cmH_2O and by 73% with PSV of 10 cmH_2O. Arterial oxygen tension and Pa_{CO_2} did not change significantly.

Figures 2 and 3 show the airway pressure, flow, and esophageal pressure curves obtained at PSV levels of 0, 5, and 10 cmH_2O in cases 3 and 5, respectively. In both patients, the change in esophageal pressure during inspiration was greater without PSV than with PSV, and this decrease in esophageal pressure caused by inspiratory effort was reduced with increasing levels of PSV.

Discussion

The principal observations in this study were that PSV increased tidal volume and mean inspiratory flow in children, while decreasing respiratory frequency and duty cycle. Pressure support ventilation markedly reduced the work of breathing as estimated from the ΔPes and WOB data.

The potential advantage of PSV to reduce the work of breathing appeared to be the same in children as it is in adults.[3-8] As shown in case 3 (fig. 2), esophageal pressure did not decrease below the end-expiratory esophageal pressure level during inspiration with PSV of 10 cmH_2O. This suggests that PSV could both compensate for the resistive work imposed by a small endotracheal tube and also reduce the total work of breathing. Thus, the indications for PSV in children are

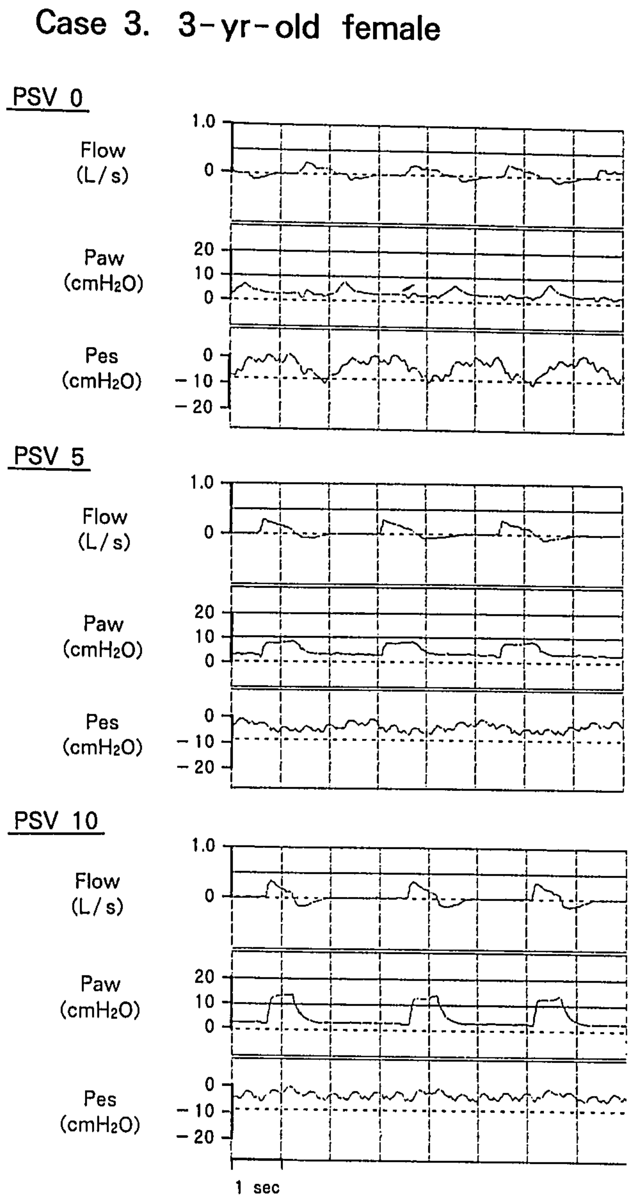

Fig. 2. Airway pressure (Paw), flow, and esophageal pressure (Pes) curves obtained during PSV of 0, 5, and 10 cmH_2O in case 3, a 3-yr-old girl with a 4.5-mm endotracheal tube. Without PSV, a 10-cmH_2O decrease in Pes was observed. However, the decrease in Pes was only 3–4 cmH_2O with PSV of 5 cmH_2 and the change in Pes was negligible with PSV of 10 cmH_2O.

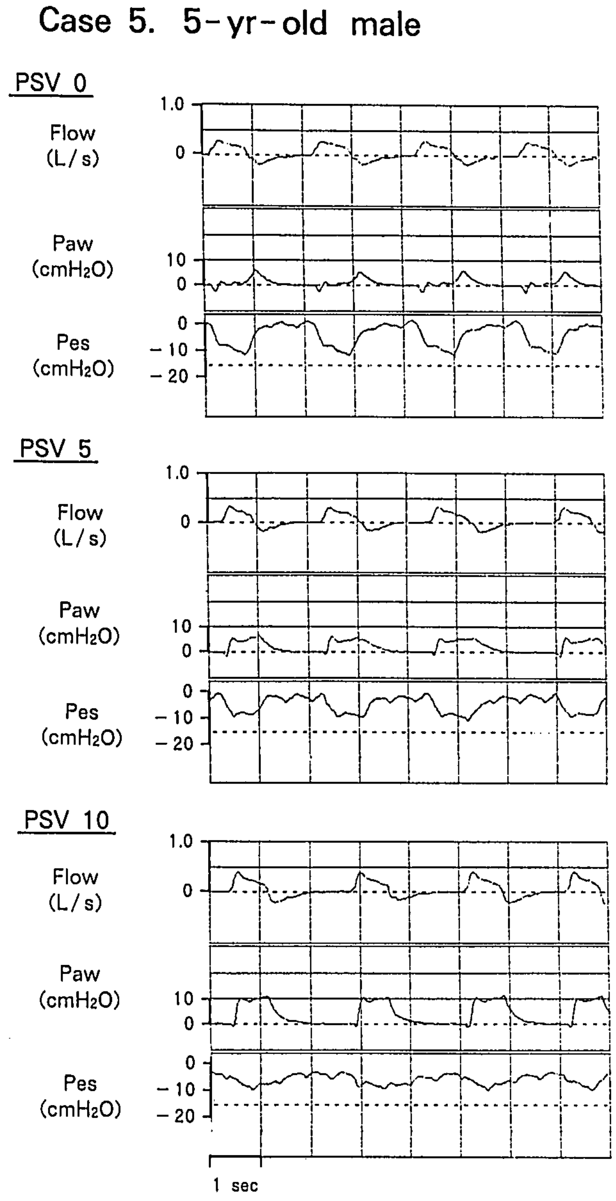

Fig. 3. Airway pressure (Paw), flow, and esophageal pressure (Pes) curves obtained during PSV of 0, 5, and 10 cmH$_2$O in case 5, a 5-yr-old boy with a 5.5-mm endotracheal tube. Without PSV, Pes decreased by 12–13 cmH$_2$O. With increasing levels of PSV, the decrease in Pes was reduced.

not only to overcome the resistive work in children breathing spontaneously through an endotracheal tube, but, also, to reduce the work of breathing during separation from ventilatory support.

Concerning its effect on the breathing pattern, PSV increased tidal volume and mean inspiratory flow, and decreased the respiratory frequency and duty cycle. These findings obtained in children are in agreement with those of our previous study performed in adults.[6] One of the real advantages of PSV is that it allows the patient's brainstem to regulate the ventilatory strategies in the patients. Duty cycle, respiratory frequency, and even tidal volume are ultimately patient determined during PSV. The decrease in respiratory frequency, along with the decrease in duty cycle, resulted in the prolongation of expiratory time from 1.3 s without PSV to 1.5 s with PSV of 5 cmH$_2$O and 1.8 s with PSV of 10 cmH$_2$O. This change made it easier for our children to synchronize with the ventilator. The decrease in respiratory frequency also reflects a decrease in the work of breathing, because children respond to inspiratory load with increased respiratory frequency.

A major problem with using PSV in small children is air leakage from the uncuffed endotracheal tube. Pressure support ventilation is terminated when the inspiratory flow decreases to 5 l/min or below, or if the airway pressure exceeds the preset PSV level by 1.5 cmH$_2$O with a Puritan-Bennett 7200a ventilator. Positive inspiratory pressure persists in the presence of an air leak when the expiratory criterion is not met.[14] Therefore, when an air leak is present with less than 10 cmH$_2$O of airway pressure, the endotracheal tube should be changed to a larger one to avoid massive air leakage. In our series, there was no need to cease PSV because of air leakage.

Our results may not apply to small infants who require a smaller endotracheal tube or to children with respiratory failure, because such patients may need higher levels of PSV to reduce the work of breathing. Thus, further studies are required to confirm these results in children receiving higher levels of PSV.

In conclusion, PSV can effectively augment spontaneous breathing and reduce the work of breathing in children during separation from mechanical ventilation.

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