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Effect of Synchronized Intermittent Mandatory Ventilation on Respiratory Workload in Infants after Cardiac Surgery

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Background: **Synchronized intermittent mandatory ventilation (SIMV) is commonly used in infants and adults. However, few investigations have examined how SIMV reduces respiratory workload in infants. The authors evaluated how infants' changing respiratory patterns when reducing SIMV rate increased respiratory load. The authors also investigated whether SIMV reduces infant respiratory workload in proportion to the rate of mandatory breaths and which rate of SIMV provides respiratory workloads similar to those after tracheal extubation.**

Methods: **When 11 post–cardiac surgery infants aged 2–11 months were to be weaned with SIMV, the authors randomly applied five levels of mandatory breathing: 0, 5, 10, 15, and 20 breaths/min. All patients underwent ventilation with SIMV mode: pressure control ventilation, 16 cm H_2O; inspiratory time, 0.8 s; triggering sensitivity, 0.6 l/min; and positive end-expiratory pressure, 3 cm H_2O. After establishing steady-state conditions at each SIMV rate, arterial blood gases were analyzed, and esophageal pressure, airway pressure, and airflow were measured. Inspiratory work of breathing, pressure–time products, and the negative deflection of esophageal pressure were calculated separately for assisted breaths, for spontaneous breaths, and for total breaths per minute. Measurements were repeated after extubation.**

Results: **As the SIMV rate decreased, although minute ventilation and arterial carbon dioxide tension were maintained at constant values, spontaneous breathing rate and tidal volume increased. Work of breathing, pressure–time products, and negative deflection of esophageal pressure increased as the SIMV rate decreased. Work of breathing and pressure–time products after extubation were intermediate between those at a SIMV rate of 5 breaths/min and those at 0 breaths/min.**

Conclusion: **When the load to breathing was increased progressively by decreasing the SIMV rate in post–cardiac surgery infants, tidal volume and spontaneous respiratory rate both increased. In addition, work of breathing and pressure–time products were increased depending on the SIMV rate.**

PATIENT-TRIGGERED ventilation (PTV), which includes synchronized intermittent mandatory ventilation (SIMV), assist control ventilation, and pressure support ventilation, is commonly used in adults because patient–ventilator synchrony is thought to enhance patient acceptance of mechanical ventilation and decrease the work of breathing (WOB).[1,2] SIMV assists the spontaneous breathing of the patient with a preset number of ventilator-delivered breaths each minute. Because it can flexibly provide ventilatory support over a range of levels, SIMV has two main indications: as a primary means of ventilatory support and as a weaning tool.[1] Weaning involves a gradual decrease in the number of mandatory breaths and an increase in the proportion of the ventilatory requirement assumed by the patient. Recently, SIMV using continuous flow, time- and patient-cycled, pressure-limited ventilation has been applied to infants and children.[3–5] SIMV is superior to conventional intermittent mandatory ventilation because it improves patient breathing patterns and oxygenation.[4–7] However, reports about the effects of SIMV on the respiratory workloads of infants are few.[8] It remains to be clarified whether infants respond by increasing tidal volume as well as the frequency of spontaneous breaths when we progressively increase the load to breathing, in this case by decreasing SIMV rates. Given the difference in respiratory control mechanisms between adults and infants,[9] this answer is not obvious.

In adults, WOB decreases as the SIMV rate increases.[1,10–12] When SIMV is used to wean adult patients from mechanical ventilation, the rate of SIMV is usually decreased gradually, depending on the patient's tolerance. Extubation is performed when the SIMV rate is successfully reduced to less than 5 breaths/min.[2] However, no study has shown that this protocol is similarly valid when weaning infants from the ventilator. We tested the hypothesis that pressure control SIMV reduces the respiratory workloads of infants in proportion to the SIMV rate and examined which SIMV rate in infants provides respiratory workloads most similar to those after extubation.

Subjects and Methods

The study was approved by the ethics committee of the National Cardiovascular Center (Osaka, Japan), and written informed consent was obtained from the parents of each patient.

Patients

Eleven infants who had undergone cardiac surgery to repair congenital heart disease were included in this study (table 1). Enrollment criteria were: (1) corrective surgery for cardiac anomalies; (2) stable hemodynamics;

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Table 1. Patient Profile

No.	Age (months)	BW (kg)	Height (cm)	Gender	Diagnosis	Operation	CPB (min)	ETT Size (mm ID)	C_{RS} (ml · cm H_2O^{-1} · kg^{-1})	C_{CW} (ml · cm H_2O^{-1} · kg^{-1})	F_{IO_2}	Length of MV (h)
1	10	8.10	67	F	VSD	VSD closure	91	4.0	1.00	5.67	0.4	3
2	11	10.6	81	M	VSD	VSD closure	80	4.5	1.26	3.65	0.35	4
3	2	4.46	57	M	VSD	VSD closure	80	4.0	0.64	2.94	0.4	5
4	7	4.78	64	F	ASD	ASD closure	37	3.5	1.26	7.39	0.4	6
5	3	3.37	59	M	VSD, ASD	VSD and ASD closure	82	3.5	1.13	7.52	0.4	7
6	7	4.32	61	F	VSD, MR	VSD closure, MVP	91	4.0	0.67	2.53	0.4	4
7	11	8.45	74	F	VSD	VSD closure	75	4.5	0.98	3.45	0.5	7
8	5	4.46	59	F	VSD, ASD	VSD and ASD closure	56	4.0	1.36	4.00	0.4	5
9	6	3.42	57	F	VSD	VSD closure	137	3.5	0.99	4.90	0.4	5
10	11	9.00	71	F	VSD	VSD closure	73	4.5	0.83	4.75	0.4	5
11	7	6.14	68	F	VSD	VSD closure	80	3.5	0.78	2.68	0.5	5
Mean	7.3	6.10	65				80.2		0.99	4.50	0.41	5.1

BW = body weight; CPB = duration of cardiopulmonary bypass; ETT = endotracheal tube; C_{RS} = compliance of the respiratory system; C_{CW} = compliance of the chest wall; F_{IO_2} = inspired oxygen fraction; MV = mechanical ventilation; VSD = ventricular septal defect; ASD = atrial septal defect; MR = mitral regurgitation; MVP = mitral valve plasty.

and (3) leakage around the uncuffed endotracheal tube (3.5–4.5 mm ID) of less than 5% of the inspired tidal volume (V_T). We excluded candidates if they had chronic lung disease, central nervous system disorders, postoperative phrenic nerve damage, or any metabolic disorder. We diagnosed phrenic nerve damage if (1) the attempt to wean infants from mechanical ventilation was unsuccessful, (2) abnormal elevation of the unilateral diaphragm was noted on the chest radiograph during continuous positive airway pressure or after extubation, and (3) paradoxical movement of the affected hemidiaphragm was confirmed by fluoroscopic imaging. All patients were kept in the supine position during the measurements. Arterial blood pressure, heart rate, central venous pressure, and pulse oximeter signal (PM-1000; Nellcor Inc., Hayward, CA) were monitored continuously in all patients. No sedatives or opioids were administered during the measurement, although fentanyl (23–47 μg/kg total) and midazolam (0.36–1.61 mg/kg) had been administered during the surgery (145–375 min). We did not use neuromuscular blocking agents or any reverse.

Measurements

Flow, volume, and airway pressure (Pao) were measured at the airway opening. A heated pneumotachometer (range, 0–35 l/min; model 3500; Hans-Rudolph Inc., Kansas City, MO) was placed at the proximal end of the endotracheal tube. The pressure difference across the pneumotachometer was measured with a differential pressure transducer (TP-602T, ±5 cm H_2O; Nihon Kohden, Tokyo, Japan), amplified (AR-601G; Nihon Kohden), and converted to flow values. Volume was calculated from digital integration of flow using data acquisition software (Windaq; Dataq Instruments Inc., Akron, OH). Intrapleural pressure was estimated from esophageal pressure (Pes). An esophageal balloon (6 French; Bicore, Irvine, CA) was introduced transnasally and positioned in the lower third of the esophagus. The balloon was inflated with 0.2 ml air at the start of each measurement. The position of the esophageal balloon was adjusted using an occlusion technique when the patients regained spontaneous breathing.[13,14] We compared the maximal deflection in Pes with the maximal deflection in Pao while the infants made respiratory effort against occlusion of the airway opening. When the ratio of Pes to airway pressure was maximal (> 0.95), we secured the position of the balloon. Pes and Pao at the proximal end of the endotracheal tube were measured using differential pressure transducers (TP-603T, ±50 cm H_2O; Nihon Kohden) and amplified (AR-601G). Respiratory inductive plethysmography (RIP; SY07 Respitrace Plus; NIMS, Miami Beach, FL) was used to estimate inspiratory time (T_I), V_T, and asynchrony between the rib cage and the abdomen. A rib cage band was positioned at the nipple line, and an abdomen band was positioned 0.5 cm below the umbilicus. Baseline calibrations for RIP were made using the qualitative diagnostic calibration procedure.[15] Maximum compartment amplitude (MCA) was calculated as the sum of the absolute value from trough to peak of the rib cage and abdominal compartments, regardless of their timing in relation to the sum signal.[15] When the motions of the rib cage and the abdomen are in phase, the ratio of MCA/V_T is equivalent to 1.0, where V_T is calculated from the summed signal of the rib cage and the abdomen. When the motions are out of phase, the ratio of MCA/V_T exceeds 1.0. The airway and esophageal pressure transducers were simultaneously calibrated at 20 cm H_2O using a water manometer. Flow was calibrated at 10 l/min with a calibrated flowmeter (P/N 9220; Bird Corp., Palm Springs, CA) using a gas mixture with exactly the same oxygen concentration for each patient. Volume was calibrated with a 50-ml calibration syringe.

Study Protocol

We used V.I.P. Bird ventilators (Bird Corp.) with continuous flow, time- and patient-cycled, pressure-limited ventilation. Initial ventilatory settings were as follows: assist control mode; positive end-expiratory pressure, 3 cm H_2O; pressure control ventilation, 16 cm H_2O; T_I, 0.8 s; continuous flow, 20 l/min; and triggering sensitivity, 0.6 l/min. The inspired oxygen fraction (F_{IO_2}) was adjusted by attending physicians to maintain an arterial oxygen pressure (Pa_{O_2}) greater than 100 mmHg.

We started taking measurements when the patients had recovered spontaneous breathing in the surgical intensive care unit and had satisfied our weaning criteria: ratio of Pa_{O_2} to F_{IO_2} greater than 200; pH greater than 7.30; V_T greater than 5 ml/kg; and respiratory rate less than 50 breaths/min at a backup ventilatory rate of 6 breaths/min and a pressure control of 7 cm H_2O.[14] Next, we measured compliance of the respiratory system (C_{RS}) and chest wall (C_{CW}). After hyperventilating the patients for 2 or 3 min to lessen their inspiratory efforts, we switched ventilatory settings to T_I of 1.5–2 s, respiratory rate of 10 breaths/min, and pressure control of 16 cm H_2O. At the end-inspiratory phase, conditions of zero gas flow to permit the measurement of quasi-static compliance were confirmed on the computer display that we used to monitor data acquisition (fig. 1). Compliance was calculated using the following formulas[16]:

$$C_{RS} = V_T/(\text{end-inspiratory Pao} - \text{end-expiratory Pao})$$

$$C_{CW} = V_T/(\text{end-inspiratory Pes} - \text{end-expiratory Pes})$$

We repeated the measurements five times and averaged them.

Then, we switched the ventilatory mode to SIMV. Five levels of mandatory breathing (0, 5, 10, 15, and 20 breaths/min) were applied in random order, with pressure control ventilation of 16 cm H_2O, T_I of 0.8 s, positive end-expiratory pressure of 3 cm H_2O, continuous flow of 20 l/min, triggering sensitivity of 0.6 l/min, and termination sensitivity of 5% of the peak inspiratory flow. Randomization was performed using computer-generated numbers. A setting of zero-rate SIMV is equivalent to a continuous positive airway pressure of 3 cm H_2O. After establishing steady-state conditions (approximately 15 min), airflow, Pao, Pes, rib cage signals, and abdominal signals of RIP were recorded. All these signals were digitally recorded at a sampling rate of 100 Hz for each parameter (Windaq) during the last 5 min at each setting. Arterial blood samples were analyzed with a calibrated blood gas analyzer (ABL 505; Radiometer, Copenhagen, Denmark).

All subjects underwent successful extubation 90 min after completion of all measurements. After extubation, we waited at least 60 min and repeated the measurement of Pes, rib cage signals, and abdominal signals of RIP and arterial blood gas analysis during quiet breathing. We did not measure the flow directly after extubation because it was likely that the stimuli of face masks would alter the patients' inspiratory patterns. Instead, we computed the volume using RIP signals.[14,15]

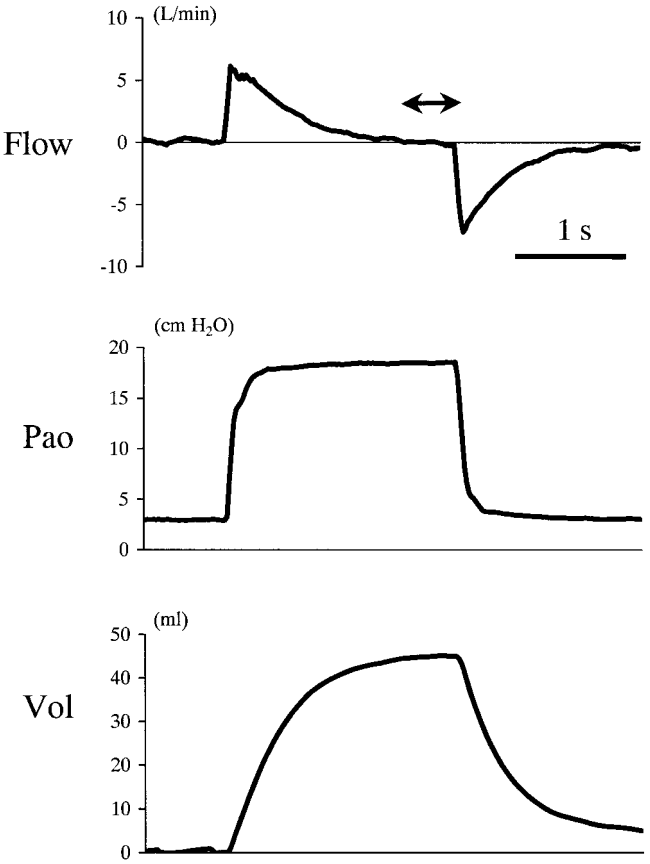

Fig. 1. Quasi-static measurement of compliance. Flow, airway pressure (Pao), and volume (Vol) tracings in patient 5 after hyperventilation. At the end-inspiratory phase, conditions of zero gas flow were observed. See text for details. Ventilatory settings: inspiratory time of 2 s, respiratory rate of 10 breaths/min, and pressure control of 16 cm H_2O.

Data Analysis

The respiratory workload was assessed at mandatory rates of 0, 5, 10, 15, and 20 breaths/min and during unassisted breathing after extubation. The onset of inspiration was defined as the point at which Pes started to decrease. The end of inspiration was determined in two ways: (1) as the zero crossing of inspiratory flow during mechanical ventilation (fig. 2) or (2) as the peak of the RIP value after extubation. We confirmed that the values of each definition of T_I were equivalent during mechanical ventilation (precision and bias, 0.01 ± 0.04 s). T_I, the ratio of inspiratory time to total respiratory cycle time (T_I/T_T), and respiratory rate were calculated using the flow or RIP signal. V_T and minute ventilation were obtained from the expiratory flow.

Inspiratory WOB done by the patient was computed as previously described.[7,11,17] First, we established a Campbell diagram, which consisted of the inspiratory Pes/V_T

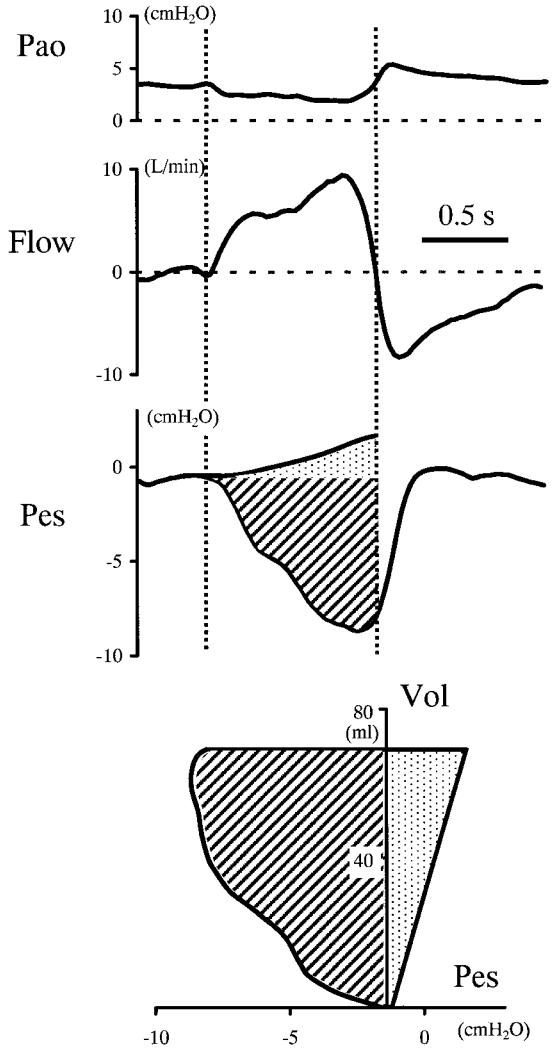

Fig. 2. Airway pressure (Pao), flow (inspiration upward), and esophageal pressure (Pes) tracings in patient 10. Pressure–time product was calculated using the integral of the difference between Pes and the chest wall recoil pressure. Work of breathing was calculated using the Campbell diagram. See text for details. The first and second vertical broken lines show the start and end of inspiration. The hatched area represents integration of the Pes *versus* either time or volume. The dotted area shows contribution of the chest wall recoil pressure to pressure–time product or work of breathing.

curve and chest wall compliance curve (fig. 2, bottom). Then we evaluated WOB per breath during each respiratory cycle by computing the area bound by the two curves. WOB per liter of ventilation (WOB/l; J/l) was computed as WOB per breath divided by the breath's tidal volume. WOB/l was expressed separately for assisted breaths and for spontaneous breaths. WOB per minute (WOB/min; $J \cdot min^{-1} \cdot kg^{-1}$) was calculated as the total inspiratory work done by the patient during both assisted and spontaneous cycles in 1 min and was normalized by body weight.

The pressure–time product (PTP) is regarded as an index of oxygen cost of breathing of the respiratory muscles as well as WOB[17–19]: here, we used the PTP of Pes to estimate the inspiratory muscle load. The PTP for each respiratory cycle was calculated as the area subtended by the Pes tracing and the chest wall static recoil pressure for inspiratory time (fig. 2). The chest wall static recoil pressure curve was obtained from values for C_{CW} and volume. The PTP per breath (PTPb; cm $H_2O \cdot s$) was calculated both for assisted and for spontaneous breaths. The PTP per minute (PTP/min; cm $H_2O \cdot s \cdot min^{-1}$) was obtained in the same manner as was WOB/min. Negative deflection of esophageal pressure (ΔPes) was also measured as the maximal negative excursion from the baseline over breath. After extubation, values for V_T, minute ventilation, WOB, PTP, and MCA/V_T were calculated from the volume obtained by the RIP.

All recorded breaths for 5 min were analyzed at each SIMV rate. The values of respiratory rate, V_T, ΔPes, WOB, and PTP were averaged separately for assisted breaths, for spontaneous breaths, and for the total of all breaths.

Statistical Analysis

Data are presented as mean ± SD. Using repeated-measures analysis of variance, mean values were compared across different levels of ventilatory support (SIMV rate of 0, 5, 10, 15, and 20 breaths/min, and after extubation). When significance was observed, multiple comparison testing of means was performed using the paired Student *t* test with Bonferroni correction. Comparisons between data for the spontaneous and assisted cycles at each SIMV rate were made by the two-tailed Student *t* test. Statistical significance was set at $P < 0.05$.

Results

The infants ranged in age from 2 to 11 months (median, 7 months), and body weight ranged from 3.37 to 10.6 kg (table 1). Mean duration of cardiopulmonary bypass was 80 min (table 1). In six patients with a body weight less than 5 kg, blood priming and modified ultrafiltration (150–1,170 ml) were applied during cardiopulmonary bypass. All patients underwent successful extubation within 7 h after the study, and no side effects were noted through this study. Table 2 shows respiratory parameters under each ventilatory setting. As the SIMV rate was reduced, the frequency of spontaneous breaths and total breaths increased without significant change in T_I/T_T. The minute ventilation was kept stable within the range of 221–254 $ml \cdot min^{-1} \cdot kg^{-1}$ at all SIMV rates. At each SIMV rate, V_T was greater in assisted breaths than in spontaneous breaths ($P < 0.01$). As the SIMV rate decreased, V_T increased significantly both during spontaneous breaths and during assisted breaths ($P < 0.01$). pH, arterial carbon dioxide pressure ($Paco_2$), Pao_2, heart rate, arterial blood pressure, and central venous pressure were not affected significantly by the SIMV setting.

Table 2. Parameters at Each Ventilatory Setting

	SIMV Rate (breaths/min)					
	20	15	10	5	0	After Extubation
Respiratory rate (breaths/min)	22.8 ± 4.2	24.4 ± 5.6	26.2 ± 5.3	28.3 ± 4.9*	28.4 ± 6.0*	31.1 ± 6.7*†‡
SB rate (breaths/min)	2.8 ± 4.3	9.2 ± 5.6*†	16.2 ± 5.4*†	23.3 ± 4.8*†‡	28.4 ± 6.0*†‡§	31.1 ± 6.7*†‡§
SIMV rate (breaths/min)	20.0 ± 0.2	15.1 ± 0.3	10.1 ± 0.2	5.0 ± 0.1	ND	ND
Inspiratory time (s)	0.89 ± 0.07	0.88 ± 0.07	0.84 ± 0.09	0.80 ± 0.10	0.80 ± 0.14	0.66 ± 0.11*†‡§
T_I/T_T	0.34 ± 0.07	0.35 ± 0.08	0.36 ± 0.05	0.37 ± 0.04	0.37 ± 0.04	0.33 ± 0.05
Minute ventilation (ml · min^{-1} · kg^{-1})	254 ± 37	239 ± 36	233 ± 38	225 ± 40	221 ± 43	229 ± 54
Tidal volume						
SB (ml/kg)	4.4 ± 0.9	5.2 ± 0.8	6.0 ± 1.1	6.7 ± 1.2*†	7.8 ± 0.9*†‡§	7.4 ± 1.0*†
SIMV (ml/kg)	12.1 ± 2.0	12.6 ± 1.9	13.4 ± 2.2	13.9 ± 2.2*†	ND	ND
pH	7.43 ± 0.04	7.42 ± 0.04	7.41 ± 0.03	7.41 ± 0.03	7.41 ± 0.04	7.41 ± 0.04
$Paco_2$ (mmHg)	40.1 ± 4.3	42.2 ± 3.9	42.7 ± 4.8	43.2 ± 5.0	43.2 ± 4.8	41.7 ± 4.4
Pao_2 (mmHg)	172 ± 24	162 ± 29	167 ± 27	160 ± 24	159 ± 29	189 ± 85
Heart rate (beats/min)	146 ± 13	147 ± 15	147 ± 15	146 ± 17	146 ± 17	143 ± 13
Systolic BP (mmHg)	101 ± 13	99 ± 12	101 ± 12	101 ± 13	102 ± 15	100 ± 8
Mean BP (mmHg)	74 ± 10	74 ± 9	74 ± 8	75 ± 7	75 ± 9	75 ± 6
CVP (mmHg)	7.8 ± 2.6	7.8 ± 2.4	8.0 ± 2.1	7.7 ± 2.1	8.2 ± 2.4	7.5 ± 1.9

After extubation, volume was measured by respiratory inductive plethysmography.

* $P < 0.05$ *versus* SIMV 20. † $P < 0.05$ *versus* SIMV 15. ‡ $P < 0.05$ *versus* SIMV 10. § $P < 0.05$ *versus* SIMV 5.

SIMV = synchronized intermittent mandatory ventilation; SB = spontaneous breath; ND = not detected; T_I/T_T = a ratio of inspiratory time to total respiratory cycle time; $Paco_2$ = arterial carbon dioxide tension; Pao_2 = arterial oxygen tension; BP = blood pressure; CVP = central venous pressure.

Figure 3 is a representative tracing of the Pes for mandatory breaths and for spontaneous breaths at five levels of SIMV and breathing after extubation. Reducing the SIMV rates resulted in greater negative deflection in Pes both for mandatory breaths and for spontaneous breaths. After extubation, the negative deflection in Pes was smaller than at the SIMV rate of 0 breaths/min (table 3).

Work of Breathing and Pressure–Time Products

As the SIMV rate was decreased, WOB increased in proportion on both a per-liter basis (fig. 4) and a per-minute basis (table 3). After extubation, WOB was larger than at SIMV rates of 15 and 20 breaths/min ($P < 0.05$); WOB after extubation was equivalent to a value intermediate between that at 0 breaths/min SIMV and that at 5 breaths/min SIMV. Similarly, the values of PTP/min increased in accordance with withdrawal of SIMV rates (fig. 5 and table 3). After extubation, values of PTP/min were equivalent to values intermediate between those at 0 and 5 breaths/min SIMV and were significantly larger than at SIMV rates of 15 and 20 breaths/min ($P < 0.05$). The values of MCA/V_T observed in RIP were approximately equal to 1.0 at high rates of SIMV, whereas they tended to increase when the SIMV rate was decreased (table 3).

Discussion

The main findings of this study are: (1) when the rate of assisted breaths during SIMV was decreased, V_T during spontaneous breaths increased, the respiratory rate increased, and minute ventilation and $Paco_2$ remained constant; (2) in proportion to the rate of assisted breaths, SIMV reduced WOB, PTP, and ΔPes; and (3) WOB and PTP values after extubation were intermediate to those found between 5 and 0 breaths/min SIMV.

Clinical Implications

In adults, increasing the SIMV rate decreases respiratory work.[1,10–12] This finding has been empirically extrapolated to infants, and applying SIMV and then gradually decreasing the SIMV rate has been used as a means of weaning infants from mechanical ventilation.[3] We undertook this study because in the absence of an extensive body of experimental evidence, it was difficult to be confident about how effective the SIMV weaning strategy is for infants. Our findings show that the respiratory workload of infants decreases directly in proportion to the SIMV rate. WOB and PTP values increased in a linear manner as the rate of SIMV was decreased from 20 to 0 breaths/min. When the SIMV rate was reduced, V_T increased, respiratory rate increased, and the same minute ventilation was maintained. These results suggest that SIMV may be effective as a weaning strategy for infants.

Patient-triggered Ventilation and SIMV

In adults, SIMV, pressure support ventilation, assist control ventilation, and other types of PTV have been widely used. These types of PTV are reported to provide good patient–ventilator interaction and to give good results when weaning from mechanical ventilation.[2] Although technological innovation, in particular of the sensors and microprocessors that control ventilators, has made it possible to extend PTV to pediatric patients, there are few reports of experimental investigations into

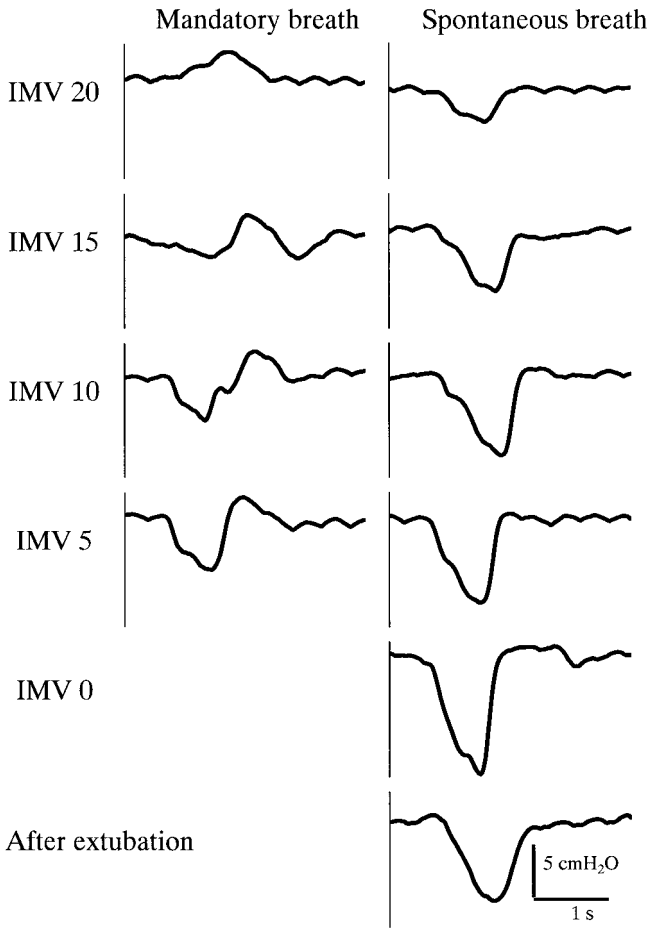

Fig. 3. Representative tracings of esophageal pressure. (*Left*) Mandatory breath. (*Right*) Spontaneous breath. (*Top to bottom*) Synchronized intermittent mandatory ventilation (IMV) rates of 20, 15, 10, 5, and 0 breaths/min, and after extubation.

the application of PTV to small children. Greenough *et al.*[20] evaluated the triggering function of PTV machines in neonates, while Bernstein and Cleary[4–6] evaluated patient–ventilator synchrony during PTV. Jarreau *et al.*[7] demonstrated that PTV with peak inspiratory pressures of 10 and 15 cm H_2O reduces WOB in infants more than conventional intermittent mandatory ventilation does. Dimitriou *et al.*[8] suggested that assist control ventilation provides faster weaning compared with SIMV, although they did not evaluate WOB. SIMV has proved superior to conventional intermittent mandatory ventilation because of its delivery of a larger and more consistent tidal volume,[4] improved oxygenation in neonates with respiratory distress syndrome,[5] and reduction of mean airway pressure at similar oxygenation index values.[6] In these studies, the focus has been on neonate–ventilator synchrony and on gas exchange. For infants, we could find only limited information regarding (1) how infants change respiratory pattern when increasing respiratory load during SIMV, (2) whether infants' WOB is reduced in proportion to the SIMV rate, and (3) the SIMV rates at which infants should undergo extubation. To our knowledge, the current study is the first to evaluate respiratory workloads in infants from near-full SIMV support to post-extubation spontaneous breathing.

We found that respiratory workload was reduced in proportion to the level of SIMV, which is not the case in adults.[10,11] In these post–cardiac surgery infants, we detected small amounts of respiratory work at a high level of SIMV, whereas in ventilator-dependent adults, WOB was found to be high at all levels of SIMV.[10,11] Leung *et al.*[12] recently found that increasing levels of SIMV and pressure support ventilation cause progressive and proportional decreases in the PTP/min values of adults. Our protocol involved infants who had undergone cardiac surgery. When the lungs of such patients are inflated with relatively high peak inspiratory pressure (19 cm H_2O) during SIMV, the Hering-Breuer reflex may suppress their inspiratory efforts more efficiently than it does in adults. In fact, we found that inspiratory effort was less at high SIMV rates and that this resulted in greater triggering delay and longer inspiratory time (table 2). Second, the infants in our study showed near-normal lung mechanics[21] (respiratory system compliance of healthy infants at

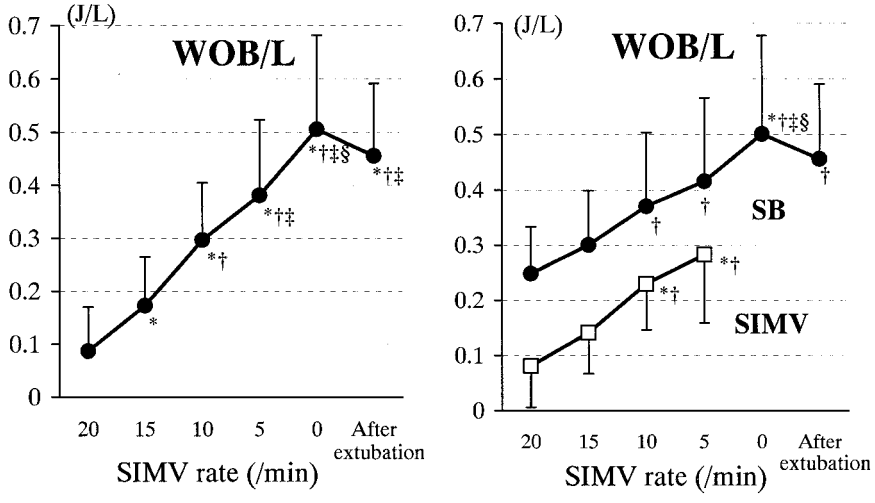

Fig. 4. Work of breathing per liter (WOB/l) at synchronized intermittent mandatory ventilation (SIMV) rates of 20, 15, 10, 5, and 0 breaths/min, and after extubation. (*Left*) Mean WOB/l for all breaths. (*Right*) WOB/l presented separately for spontaneous (SB) and assisted breaths (SIMV). **P* < 0.05 *versus* SIMV rates of 20 breaths/min; †*P* < 0.05 *versus* 15 breaths/min; ‡*P* < 0.05 *versus* 10 breaths/min; §*P* < 0.05 *versus* 5 breaths/min.

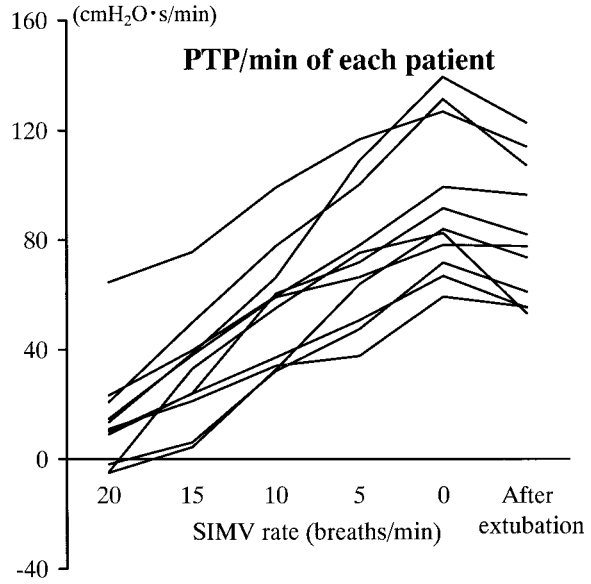

Fig. 5. Pressure–time products per minute (PTP/min) for each patient. The values are presented after combining spontaneous and assisted breaths. SIMV = synchronized intermittent mandatory ventilation.

1–12 months, 1.3–2.1 ml · cm H_2O^{-1} · kg^{-1}) and gas exchange status (table 1), whereas in previous reports on adults,[10,11] the patients were dependent on mechanical ventilation because of acute lung disease in the medical intensive care unit[10] or acute exacerbation of chronic obstructive pulmonary disease.[11] The normal lung mechanics and lower respiratory drives of the infants in our study may have reduced the SIMV requirement. Infants and children with primary lung diseases would respond differently to decreases in SIMV rates. Third, our protocol was conducted with continuous flow and flow-triggered SIMV, whereas previous reports used pressure triggering without continuous flow. During pressure-triggered SIMV, insufficient flow delivery during early inspiration may increase WOB during spontaneous breathing cycles because the demand valve circuitry is not responsive enough for efficient synchronization.[1] In contrast, continuous flow and flow triggering may require less absolute work during spontaneous cycles and may provide more efficient support at low SIMV rates than demand valve systems.[22–24] Fourth, we applied a mode of pressure control ventilation, whereas previous reports on adults used volume-controlled ventilation with a fixed flow supply profile. Pressure control ventilation reduces breathing effort more effectively than volume-controlled ventilation does when used in conjunction with flow triggering.[23,24] The flow profile during pressure target ventilation may provide better synchrony from a low level to a high level of SIMV support.

Extubation

In the infants we studied, who had relatively normal lung mechanics and gas exchange status, WOB, PTP, and ΔPes values after extubation were intermediate between those at SIMV of 5 and 0 breaths/min. During continuous positive airway pressure, although values for WOB and PTP tended to be higher than at SIMV of 5 breaths/min and after extubation, the differences did not reach significance. Provided that clinical and gas exchange levels are satisfactory, low levels of SIMV may indicate the feasibility of extubation.

Table 3. Respiratory Workloads at Each Ventilatory Setting

	SIMV Rate (breaths/min)					
	20	15	10	5	0	After Extubation
WOB/l (J/l)	0.09 ± 0.08	0.17 ± 0.09*	0.30 ± 0.11*†	0.38 ± 0.14*†‡	0.50 ± 0.18*†‡§	0.46 ± 0.14*†‡
SB (J/l)	0.25 ± 0.08	0.30 ± 0.10	0.37 ± 0.13†	0.42 ± 0.15†	0.50 ± 0.18*†‡§	0.46 ± 0.14†
SIMV (J/l)	0.08 ± 0.07	0.14 ± 0.07	0.23 ± 0.08*†	0.28 ± 0.12*†	ND	ND
WOB/min (J · min^{-1} · kg^{-1})	0.023 ± 0.022	0.042 ± 0.023	0.070 ± 0.028*	0.088 ± 0.036*†	0.112 ± 0.041*†	0.103 ± 0.031*†
SB (J · min^{-1} · kg^{-1})	0.007 ± 0.009	0.017 ± 0.012	0.038 ± 0.021	0.068 ± 0.030*†	0.112 ± 0.041*†‡§	0.103 ± 0.030*†‡
SIMV (J · min^{-1} · kg^{-1})	0.020 ± 0.016	0.027 ± 0.013	0.031 ± 0.011	0.020 ± 0.008	ND	ND
PTP/min (cm H_2O · s · min^{-1})	14.1 ± 19.2	32.2 ± 20.1*	55.8 ± 21.1*†	74.3 ± 25.5*†‡	93.8 ± 27.4*†‡§	81.8 ± 25.2*†‡‖
PTPb (cm H_2O · s)						
SB (cm H_2O · s · $breaths^{-1}$)	1.6 ± 0.5	2.0 ± 0.7	2.6 ± 0.9	2.8 ± 1.0†	3.4 ± 1.2*†‡	2.7 ± 1.1‖
SIMV (cm H_2O · s · $breaths^{-1}$)	0.4 ± 0.5	0.9 ± 0.5	1.5 ± 0.6*†	1.9 ± 0.9*†	ND	ND
ΔPes (cm H_2O)	0.9 ± 1.1	2.0 ± 1.2*	3.5 ± 1.5*†	4.6 ± 1.9*†‡	6.0 ± 2.4*†‡§	5.1 ± 2.1*†‖
SB (cm H_2O)	3.1 ± 1.3	3.8 ± 1.5	4.7 ± 1.8	5.1 ± 1.9†	6.0 ± 2.4†‡	5.1 ± 2.1‖
SIMV (cm H_2O)	0.6 ± 0.8	1.1 ± 0.8	1.8 ± 1.1*†	2.5 ± 1.8*†	ND	ND
MCA/V_T	1.05 ± 0.05	1.08 ± 0.06	1.08 ± 0.05	1.11 ± 0.09	1.13 ± 0.12	1.13 ± 0.15

After extubation, volume was measured by respiratory inductive plethysmography.

* $P < 0.05$ *versus* SIMV 20. † $P < 0.05$ *versus* SIMV 15. ‡ $P < 0.05$ *versus* SIMV 10. § $P < 0.05$ *versus* SIMV 5. ‖ $P < 0.05$ *versus* SIMV 0.

SIMV = synchronized intermittent mandatory ventilation; WOB = work of breathing; SB = spontaneous breath; ND = not detected; PTP = pressure–time product; PTPb = pressure–time product per breath; ΔPes = negative deflection of esophageal pressure; MCA/V_T = maximum compartment amplitude/tidal volume.

Limitations

The current study has several limitations. First, after tracheal extubation, we used RIP to calculate tidal volume, PTP, and WOB. The accuracy of RIP calibration may have been less precise because the chests of post–cardiac surgery patients are typically covered with chest tubes and bandages. Second, the patients in our study had relatively normal lung mechanics after corrective surgery for congenital heart diseases. Several patients had retarded gain of body weight, probably due to proceeding heart failure, although lung mechanics seemed normal for the body weight. The response of more seriously compromised patients to machine support may be quite different. Further studies are needed to corroborate the relevance of our findings for acutely ill and ventilator-dependent infants. Third, the number of patients was small, and the values of WOB and PTP included wide variations (table 3). However, in each patient, these parameters showed consistent changes in response to reducing the SIMV rate (fig. 5). Finally, because we did not measure the electrical activity of respiratory muscles, this report says nothing about the role of inspiratory neuromuscular output relating to the external inspiratory force.[11]

In conclusion, after cardiac surgery, for infants with healthy lungs, SIMV reduces WOB and PTP in proportion to the level of assisted breathing. The analysis of WOB and PTP shows that low levels of SIMV may indicate the feasibility of tracheal extubation.

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