Intensive Care Med (1992) 18:69–75

Intensive Care Medicine

Originals

Continuous positive airway pressure (CPAP) vs. intermittent mandatory pressure release ventilation (IMPRV) in patients with acute respiratory failure *

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Received: 3 June 1991; accepted: 31 December 1991

Abstract. Intermittent Mandatory Pressure Release Ventilation (IMPRV) is a positive pressure spontaneous breathing ventilatory mode in which airway pressure is released intermittently and synchronously with patient's spontaneous expiration in order to provide ventilatory assistance. Eight critically ill patients free of any factor known to alter chest wall mechanics (group 1) and 8 critically ill patients whose spontaneous respiratory activity was markedly altered by a flail chest, or by a C_5 quadraplegia and/or by the administration of opioids (group 2) were studied prospectively. CPAP and IMPRV were administered to each patient in a random order during a 1 h period using a CESAR ventilator. Gas flow, tidal volume, tracheal pressure, esophageal pressure, end-expiratory lung volume and hemodynamic parameters were measured. In group 1 patients, the ventilatory assistance provided by IMPRV was associated with a significant decrease in spontaneous tidal volume whereas all other respiratory parameters remained unchanged. In group 2 patients, IMPRV increased minute ventilation from 8.0 ± 2.6 l/min to 12.2 ± 1.8 l/min ($p < 0.05$), decreased $PaCO_2$ from 46 ± 7.3 mmHg to 38 ± 6.8 mmHg ($p < 0.05$) and reduced respiratory frequency from 21 ± 10 bpm to 14 ± 5.7 bpm ($p < 0.07$). These results show that IMPRV provides significant ventilatory assistance to patients with mild acute respiratory failure either by decreasing patient's contribution to minute ventilation or by increasing alveolar ventilation in presence of respiratory depression of central or peripheral origin.

Key words: Ventilation – Airway pressure release ventilation – Continuous positive airway pressure – Positive end-expiratory pressure

In patients with acute respiratory failure, one of the therapeutic goals of mechanical ventilation is to re-expand collapsed alveoli by increasing intrathoracic pressure. A strong relationship exists between mean airway pressure and arterial oxygenation, whatever the method used to increase intrapulmonary pressure [1–3]. Because it increases mean airway pressure without markedly increasing peak airway pressure, Continuous Positive Airway Pressure (CPAP) has been advocated as an attractive ventilatory mode to treat patients with mild acute respiratory failure. However its use is limited in clinical practice, because of a high incidence of discomfort and respiratory muscle fatigue which rapidly results in alveolar hypoventilation. Recently, Stock and Downs have shown that alveolar ventilation can be maintained by intermittently releasing airway pressure in anesthetized dogs with acute lung injury [4]. For delivering Airway Pressure Release Ventilation (APRV), they used a modified CPAP breathing circuit in which the CPAP level could be modified by opening or closing a release valve connected to a timer. Although this simple system is efficient in paralyzed animals or patients [5, 6], it can have an uncomfortable effect in spontaneously-breathing subjects because of the difficulty of synchronizing pressure release with spontaneous expiratory efforts. We describe here another form of pressure release ventilation, Intermittent Mandatory Pressure Release Ventilation (IMPRV), specifically designed to support alveolar ventilation of spontaneous breathing patients. This ventilatory mode has been integrated in a commercially available ventilator which includes alarms and respiratory monitoring. We hypothesized that IMPRV could be an efficient method to increase alveolar ventilation of spontaneously breathing patients with mild acute respiratory failure, if intermittent pressure release was not associated with alteration in arterial oxygenation. Therefore, a pro-

* Presented in part at the 32th Congrès National d'Anesthésie-Réanimation, Paris, September 24, 1990 and at the Annual Meeting of the American Society of Anesthesiologists, Las Vegas, Nevada, October 22, 1990

spective and randomized study was untertaken to compare CPAP and IMPRV in two groups of critically ill patients.

Methods

Patients

Sixteen patients were included in the study after informed consent had been obtained either from the patient or from the closest relative. Authorization was given by the Ethical Committee of La Pitié-Salpêtrière hospital. The patients were selected as follows: between July 1988 and May 1989, 41 patients were admitted to the Surgical Intensive Care Unit (SICU) of La Pitié Hospital (Department of Anesthesiology) following either multiple trauma ($n = 28$), major surgery ($n = 10$) or acute medical disease ($n = 3$). All were in acute respiratory failure, defined as the presence of bilateral lung opacities on chest X-ray with bilateral hyperdensities on lung CT scan associated with a $PaO_2 < 100$ mmHg at FiO_2 0.5. Within 48 h following admission to the SICU, pulmonary artery and systemic arterial catheters were inserted and the following parameters were measured during intermittent positive pressure ventilation using an FiO_2 of 1 in order to quantify the severity of acute repiratory failure: PaO_2, pulmonary shunt ($\dot{Q}s/\dot{Q}t$), mean pulmonary arterial pressure (MPAP), pulmonary wedge pressure (PWP), alveolar dead space (V_{DA}) and static respiratory compliance (Crs.). V_{DA}/V_T was calculated as:

$$V_{DA}/V_T = \frac{PaCO_2 - PetCO_2}{PaCO_2}$$

where $PetCO_2$ (end-tidal carbon dioxide tension) is measured using the capnographic method (47210A capnometer, Hewlett-Packard) and $PaCO_2$ is simultaneously measured from an arterial blood sample. Because many instances of acute respiratory failure are associated with pulmonary arterial occlusion by local thrombi, V_{DA} is a better index of these vascular lesions than physiologic dead space calculated from the Bohr equation which takes into account the anatomical dead space. Crs was measured using the giant syringe method. Patients were anesthetized using fentanyl and vecuronium and their endotracheal tube disconnected from the ventilator to enable functional residual capacity to be reached, following which 100 ml injections of oxygen were made at 2 s intervals. The pressure-volume curve on the inflation limb between 0 and 30 cmH_2O was directly recorded using an X–Y recorder. Static respiratory compliance was considered as the slope of the curve between 500 and 1500 ml.

Initial respiratory measurements were used to quantify the severity of acute respiratory failure. Patients with $PaO_2 < 100$ mmHg, MPAP > 30 mmHg, $V_{DA} > 40\%$ and Crs < 50 ml/cmH_2O were considered as having a severe form of acute respiratory failure and were excluded from the study. Patients with chronic obstructive pulmonary disease, cardiogenic pulmonary edema, head injury and circulatory shock were also excluded. Finally, 16 patients with mild acute respiratory failure ($PaO_2 > 100$ mmHg, MPAP < 30 mmHg, $V_{DA} < 40\%$ and Crs > 50 ml/cmH_2O) were prospectively identified and included. The 16 patients were divided into two groups according to their spontaneous breathing capacity. Group 1 included 8 patients whose spontaneous respiratory activity efficiency was altered only by their acute lung disease. All were free of chest wall trauma, neuromuscular disease and recent thoracic or upper abdominal incisions. They were all conscious and none was receiving sedative drugs. Group 2 included 8 patients whose spontaneous respiratory activity was markedly altered not only by their acute lung disease but also by a large and mobile flail chest associated with pulmonary contusion (patients 9, 10, 14), or by a C5 quadraplegia (patients 11, 12, 13), or by the continuous intravenous administration of 2000 µg/day of fentanyl (patients 9, 10, 14, 15, 16). The administration of large doses of fentanyl was required because of pain (patients 9, 10), agitation (patients 14 and 16), and because of severe tachypnea of central origin in patient 15. Clinical characteristics and pre-study respiratory parameters during Intermittent Positive Pressure Ventilation are summarized in Table 1.

Equipment and cardiopulmonary measurements

The ventilator. The lungs of each patient were mechanically ventilated using a CESAR ventilator (TAEMA, Air liquide, France) in which all ventilatory functions are controlled by a central microprocessor which is connected to a flow generator, to the pressure transducer and to the PEEP valve. The flow generator is composed of a proportional valve directed by a step-by-step motor and can deliver a maximal inspiratory flow of 180 l/min in less than 100 ms. The PEEP valve is made of a collapsible tube mounted on the expiratory circuit which can be obstructed by a mechanical roller system driven by a step-by-step motor, itself connected to the microprocessor. This entirely original PEEP valve acts as a threshold-resistor expiratory pressure valve of the low-flow-resistant type and enables the changing of end-expiratory pressure from one respiratory cycle to another, thus providing airway pressure changes always synchronized with patient's spontaneous expiratory activity. The ventilator is equipped with a large screen on which expired tidal volume, airway pressure and gas flow are continuously displayed. Trends of the main respiratory parameters can be reviewed and recorded over a period of time ranging from half an hour to 72 h.

Measurements of gas flow, tidal volume an pressures. Inspiratory and expiratory gas flows ($\dot{V}$) delivered by the ventilator were measured using two calibrated hot wires placed on inspiratory and expiratory circuits. Expired tidal volume (V_T) was measured by integrating the expiratory flow signal. Respiratory frequency (F), inspiratory time (T_I), total respiratory cycle duration (T_{TOT}) and duty cycle (T_I/T_{TOT}) were measured from the flow signal. Airway pressure was measured at the proximal end of the endotracheal tube using a solid state pressure transducer. Peak inspiratory pressure (PIP) and PEEP were directly measured whereas mean airway pressure ($\overline{Paw}$) was obtained by planimetry. Esophageal pressure (Peso) was measured using a fluid-filled 2 mm internal diameter silicone tube positioned in the middle third of the esophagus [7]. Mean esophageal pressure was obtained by planimetry and mean transpulmonary pressure (P_{TP}) was measured as $\overline{Paw}$ minus mean esophageal pressure over a ten respiratory cycle period. Minute ventilation ($\dot{V}_E$) was defined as the sum of the expired tidal volumes during 1 minute.

Measurement of changes in end-expiratory lung volume. Increase in end-expiratory lung volume above apneic functional residual capacity (EELV) was measured using an indirect spirometric method, previously described in detail [8]. Briefly, changes in rib cage and abdominal circumferences were measured with differential linear transformers mounted on flexible belts positioned around the patient's thorax and abdomen at the nipple and umbilicus levels. Because variations in thoracoabdominal partitioning could not easily be obtained by voluntary maneuvers in our patients, the individual breath method was used for calibration [9]. This method is based on the fact that in spontaneous breathing there is enough variability between breaths to determine the volume-motion coefficients. Points were taken along 15 different breathing cycles on both rib cage and abdominal tracings, as well as on direct spirometric tracings during expiratory phases. Volume-motion coefficients were calculated by multiple linear regression and were used for measuring changes in end-expiratory lung volume.

Hemodynamic measurements. Systolic, diastolic, mean arterial pressures (SAP, DAP, MAP), right atrial pressure (RAP), mean pulmonary arterial pressure (MPAP) and pulmonary wedge pressure (PWP) were measured using a calibrated quartz pressure transducer (1290 A Hewlett-Packard) positioned at the midaxillary line. Cardiac output was measured by serial determinations using the thermodilution technique and a bedside computer (15055 A Hewlett-Packard). Three serial injections of 10 ml of iced 5% dextrose were made during different moments on the ventilatory cycle in order to average the variations in cardiac output related to pressure release. Heart rate (HR) was measured from ECG. Systemic and pulmonary arterial blood samples were drawn simultaneously within 1 minute following the measurements of cardiac output. PaO_2, $P\bar{v}O_2$, $PaCO_2$, pH, hemoglobin concentration and oxygen saturations (SaO_2 and $S\bar{v}O_2$) were measured with an Hemoximeter OSM_3. Calculations with conventional formulas were used to

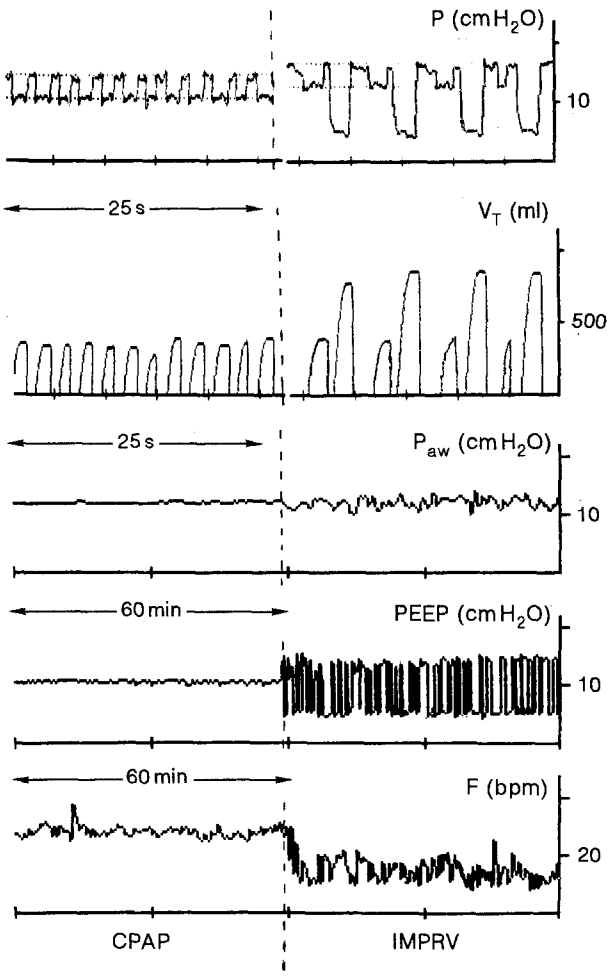

Fig. 1. Comparative recordings of CPAP and IMPRV modes in a patient of group 2. CPAP was first administered (left part of the figure) using a PEEP of 10 cmH_2O and a pressure support of 5 cmH_2O. IMPRV was then administered for a 60-min period (right part of the figure) using a pressure release of 9 cmH_2O every two spontaneous breaths, and a pressure support of 5 cmH_2O. As shown in the figure, both ventilatory modes were compared at the same level of mean airway pressure (*Paw*), and IMPRV markedly reduced respiratory frequency (*F*). These tracings were obtained directly from the CESAR ventilator: on the upper part of the figure, airway pressure (*P*) and expired tidal volume (*VT*) are displayed during a 25-s period; on the lower part of the figure, trends of Paw, PEEP and F over a 60-min period in each ventilatory mode are represented

derive the following: cardiac index (CI), pulmonary shunt ($\dot{Q}s/\dot{Q}t$), oxygen consumption ($\dot{V}O_2$), oxygen delivery ($\dot{D}O_2$) and oxygen extraction (EaO_2).

Procedure

CPAP and IMPRV were sequentially administered to each patient in a random order for a one-hour period. During the study period, group 1 patients and patients 11, 12 and 13 of group 2 did not receive sedative drugs, whereas patients 9, 10, 14, 15, and 16 of group 2 were receiving a continuous intravenous infusion of fentanyl 2000 µg/day. Ventilatory parameters were adjusted before begining the study in order to obtain the same level of mean airway pressure in each mode (Fig. 1). During both modes: trigger sensitivity was set between -0.5 and -1 cmH_2O; a 5 cmH_2O of pressure support was added to each spontaneous breath, in order to suppress the patient's extra-work of breathing due to the endotracheal tube and the ventilator tubings [10]; FIO_2 0.6 was used; mean airway pressure was adjusted in order to obtain a $PaO_2 > 100$ mmHg using FIO_2 0.6. During both ventilatory modes, $\overline{Paw}$ was obtained by changing the PEEP level. During IMPRV, a 8–10 cmH_2O of pressure release was generated every two spontaneous expirations by decreasing the PEEP level. These ventilatory settings were not changed throughout the study period. At the end of the one-hour period of CPAP or IMPRV, the following parameters were simultaneously recorded on a Gould ES 1000 recorder: hemodynamic pressures (arterial pressure, pulmonary arterial pressure, capillary wedge pressure, right atrial pressure), airway pressure, esophageal pressure, thoracoabdominal displacements, gas flow delivered by the ventilator, and expired tidal volumes resulting either from patient's spontaneous inspiratory efforts (V_T spont) or from airway pressure release (V_T rel). At the end of a 5-min period of recording, cardiac output was measured and arterial and pulmonary arterial blood samples were withdrawn for blood gas analysis. For measuring changes in end-expiratory lung volume, the patient was disconnected from the ventilator and ΔEELV was defined as end-expiratory lung volume measured during CPAP or IMPRV minus end-expiratory lung volume measured during spontaneous breath. ΔEELV was calculated as:

$$\Delta EELV = Krc\ RC + Kab\ AB$$

where RC and AB are the rib cage and abdominal motion changes following the disconnection from the ventilator, and Krc and Kab are the volume motion coefficients obtained from the calibration procedure.

Statistical analysis

All data obtained were expressed as mean ± SD. Initial clinical status of the 2 groups of patients were compared using Mann-Whitney's U test. Comparison of each parameter between CPAP and IMPRV in the groups was made using a student t-test for paired data. Comparison of respiratory and hemodynamic data between groups and ventilatory modes was made using Kruskall and Wallis H test and Mann-Whitney's U test. $p < 0.05$ was considered significant.

Results

Comparison between groups

As shown in Table 1, the two groups did not differ significantly as far as etiology of respiratory failure, PaO_2, static respiratory compliance, alveolar dead space, pulmonary shunt, mean pulmonary arterial pressure and pulmonary wedge pressure. This result suggests that patients of each group had a similar degree of acute respiratory failure. However, group 1 patients had a lower $PaCO_2$ than group 2 patients, during CPAP (Table 2). This difference clearly reflects the fact that in group 2 patients spontaneous breathing activity was less efficient than that in group 1 patients.

Ventilatory settings used during CPAP and IMPRV

As shown in Table 2, similar levels of $\overline{Paw}$ were applied during both ventilatory modes in each group. During CPAP, this was obtained by applying a PEEP of 10.4 ± 0.7 cmH_2O in group 1 patients and a PEEP of 11.7 ± 1 cmH_2O in group 2 patients. During IMPRV, this was obtained by changing PEEP every two spontaneous expirations from 14.6 ± 0.9 cmH_2O to 5.6 ± 0.9 cmH_2O in group 1 patients and from 14.11 ± 1.5 cmH_2O to 5.1 ± 1.2 cmH_2O in group 2 patients. Each spontaneous respiratory cycle was assisted by a 5 cmH_2O of pressure support and the trigger sensitivity was set at minus 0.5 – 1 cmH_2O.

Table 1. Clinical characteristics and pre-study ventilatory parameters of patients with acute respiratory failure. (Intermittent positive pressure ventilation, FiO_2 1)

Patients	Sex*	Age (yrs)	Outcome**	Initial diagnosis	Acute respiratory failure	$PaCO_2$ (mmHg)	PaO_2 (mmHg)	Crs (ml/cmH_2O)	V_{DA}/V_T (%)	Qs/Qt (%)	MPAP (mmHg)	Pwp (mmHg)	PIP (cmH_2O)
Group 1													
1	M	18	D	Mutiple trauma	Pulmonary contusion	38	330	78	18	18	18	8	20
2	M	70	D	Med. disease	Inhalation pneumonia	42	300	105	21	18	12	9	15
3	F	40	S	Delivery	Amiotic embolism	37	218	80	35	34	27	7	22
4	M	72	D	Aortic surgery	Bacterial pneumonia	43	126	77	20	30	24	8	25
5	F	26	S	Multiple trauma	Pulmonary contusion	32	212	67	21	35	14	4	36
6	F	45	S	Multiple sclerosis	Bacterial pneumonia	41	293	65	25	37	28	11	36
7	F	41	S	Multiple trauma	Pulmonary contusion	44	269	78	29	35	22	6	25
8	F	54	D	Multiple trauma	Pulmonary contusion	38	201	50	30	25	21	11	41
Mean ± SD		46 ± 18				39 ± 4	244 ± 62	75 ± 15	25 ± 6	29 ± 7	21 ± 5	8 ± 2	28 ± 9
Group 2													
9	M	68	D	Multiple trauma	Pulmonary contusion	37	263	65	40	28	22	13	33
10	M	60	S	Multiple trauma	Pulmonary contusion	37	238	90	18	28	15	6	16
11	M	33	S	Multiple trauma	Bacterial pneumonia	43	399	105	12	20	14	9	15
12	M	19	S	Multiple trauma	Bacterial pneumonia	40	205	50	23	28	19	8	40
13	M	27	S	Multiple trauma	Pulmonary contusion	39	395	103	22	22	20	10	12
14	M	32	S	Multiple trauma	Pulmonary contusion	37	355	96	26	27	17	14	39
15	M	60	S	Rhombo-encephalitis	Inhalation pneumonia	42	335	90	29	24	13	7	20
16	M	71	D	Peritonitis	Pulmonary edema	38	101	60	25	33	12	2	39
Mean ± SD		46 ± 19				39 ± 2	261 ± 102	77 ± 21	24 ± 8	26 ± 4	17 ± 3	9 ± 4	27 ± 11

* F, female; M, male; ** S, survived; D, deceased

Table 2. Respiratory effects of CPAP and IMPRV in the 2 groups of patients (mean ± SD)

	Group 1 ($n = 8$)		Group 2 ($n = 8$)	
	CPAP	IMPRV	CPAP	IMPRV
$PaCO_2$ (mmHg)	34 ± 3.1	33 ± 3.5	46 ± 7.3 $^{+}$	38 ± 6.8*
$\dot{V}E$ (l/min)	9.7 ± 2.4	10.6 ± 1.4	8.0 ± 2.6	12.2 ± 1.8*
VT spont (ml)	379 ± 106	202 ± 84**	367 ± 140	432 ± 261 $^{++}$
VT rel (ml)	–	817 ± 133	–	1159 ± 178
F (bpm)	26 ± 4.3	23 ± 4.3	21 ± 10	14 ± 5.7 $^{++}$
T_I (sec)	0.93 ± 0.3	1 ± 1.4	1.3 ± 0.5 $^{+}$	1.6 ± 0.6 $^{++}$
T_E (sec)	1.4 ± 0.4	1.6 ± 0.6	2.7 ± 1.4 $^{+}$	3.3 ± 1.4 $^{++}$
T_I/T_{TOT} (%)	40 ± 8.8	40 ± 7.3	34 ± 8.9 $^{+}$	34 ± 11 $^{+}$
Paw (cmH_2O)	11.9 ± 0.7	11.9 ± 0.6	12.4 ± 1.4	12.5 ± 1.3
EELV (ml)	636 ± 224	851 ± 211	736 ± 152	1101 ± 471
PIP (cmH_2O)	16 ± 0.8	20 ± 1.6**	17 ± 1.4	20 ± 1.7**
Peso (cmH_2O)	3.8 ± 2.8	3.2 ± 1.4	4.2 ± 2	4.4 ± 2.3
P_{TP} (cmH_2O)	7 ± 2.6	8.7 ± 1.7	8.2 ± 2.8	8.0 ± 2.7

* $p < 0.05$ IMPRV vs CPAP in the same group
** $p < 0.01$ IMPRV vs CPAP in the same group
$^{+}$ $p < 0.05$ group 1 vs group 2 in the same ventilatory mode
$^{++}$ $p < 0.01$ group 1 vs group 2 in the same ventilatory mode

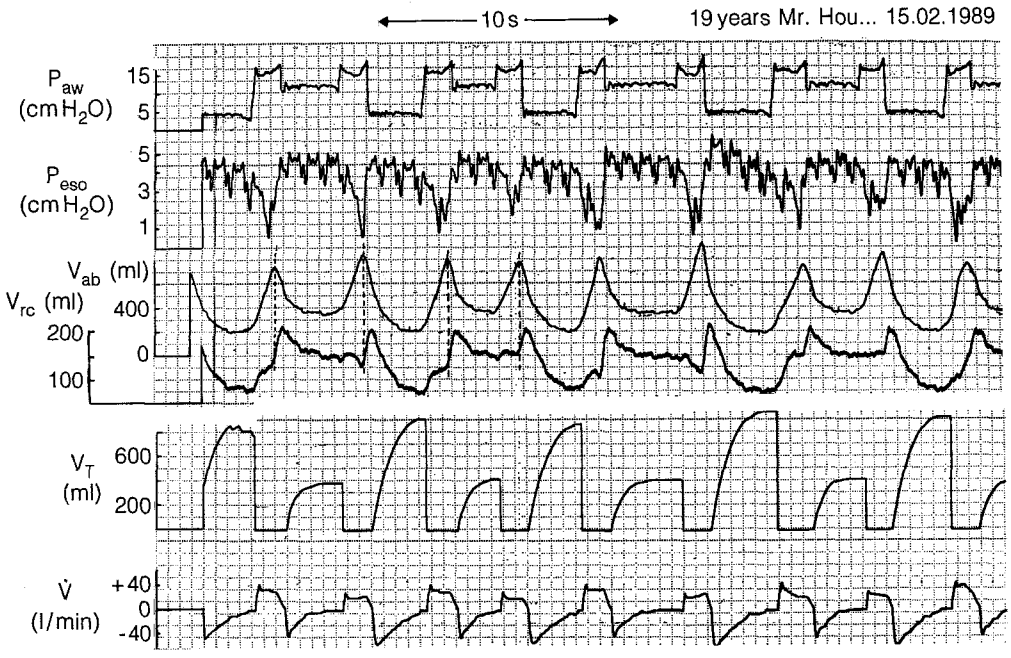

Fig. 2. Changes in airway pressure (*Paw*), esophageal pressure (*Peso*), expired tidal volume (*VT*), rib cage contribution to tidal volume (*Vrc*), abdominal contribution to tidal volume (*Vab*) and gas flow delivered by the ventilator ($\dot{V}$) during IMPRV in patient 13 (C_5 quadraplegia). The patient is ventilated using a CESAR ventilator with the following IMPRV settings: trigger sensitivity minus 1 cmH_2O, high PEEP level 12 cmH_2O and low PEEP level 5 cmH_2O, pressure support 5 cmH_2O, PEEP change every two spontaneous breaths. The patient's respiratory frequency is of 16 bpm and, consequently airway pressure is released 8 times per min

Respiratory and hemodynamic effects of IMPRV

Changes in respiratory pressure, lung volumes and gas flow during IMPRV are illustrated in Fig. 2. When considering esophageal pressure, it is evident that IMPRV is a spontaneous breathing mode: when esophageal pressure decreases with patient's spontaneous inspiratory effort, airway pressure slightly decreases, which in turn triggers inspiratory flow. While esophageal pressure continues to decrease, inspiratory flow and airway pressure rapidly increase up to the preset pressure support level. Then inspiratory flow starts decreasing in order to maintain a pressure plateau in the airways. When esophageal pressure reincreases with patient's spontaneous expiration, airway pressure slightly increases, which in turn stops inspiratory flow. Then expiration occurs (negative flow), airway pressure rapidly decreases to PEEP level and tidal volume is expired. Pressure release always occurs during the early phase of expiration and is associated with changes in end-expiratory lung volume. When PEEP is changed every two spontaneous breaths, inspiratory flow and expiratory flow characterizing a given respiratory cycle, are not equal. The inspiration preceding an expiration at the low PEEP level is made of an inspiratory flow smaller than the expiratory flow, because lung volume decreases. The inspiration preceding an expiration at the high PEEP level is made of an inspiratory flow greater than the expiratory flow because lung volume reincreases. Finally, IMPRV induced mechanical assistance results of variable inspiratory flows delivered by the ventilator.

As shown in Table 2, IMPRV significantly increased minute ventilation in group 2 patients. Spontaneous V_T did not change, respiratory frequency decreased and pressure release was associated with a threefold increase in tidal volume (V_T rel). As shown in Fig. 3, IMPRV decreased $PaCO_2$ in each individual of group 2. In contrast, minute ventilation, respiratory rate and $PaCO_2$ were similar during CPAP and IMPRV in group 1 patients. Whereas patient's spontaneous tidal volumes were significantly reduced during IMPRV in group 1 patients, inspiratory and expiratory times were significantly shorter than in group 2 patients during both ventilatory modes, whereas T_I/T_{TOT} was lengthened. Although patient's spontaneous T_I/T_{TOT} varied with time and from one respiratory cycle to another during IMPRV, the ob-

Table 3. Hemodynamic and metabolic effects of CPAP and IMPRV in the 2 groups of patients (mean ± SD)

	Group 1 ($n = 8$)		Group 2 ($n = 8$)	
	CPAP	IMPRV	CPAP	IMPRV
MAP (mmHg)	86 ±12	84 ±15	80 ±14	85 ±13
HR (b/min)	101 ±20	99 ±21	94 ±13	91 ±16
CI (l/min/m^2)	4.5±1	3.8±0.8	4.2±0.7	4.0±0.7
POD (mmHg)	8.3±4.2	8.5±3.3	6.9±3.2	6.8±4.1
PAP (mmHg)	21 ±5	18 ±4	17 ±8.8	14.3±7.3
PWP (mmHg)	10 ±2.9	10.8±3	8.5±3.4	8.8±4.1
$\dot{V}O_2$ (ml/min/m^2)	145 ±29	142 ±8	148 ±36	159 ±26
$\dot{D}O_2$ (ml/min/m^2)	461 ±125	355 ±98	542 ±193	496 ±79
EaO_2 (%)	32.3±5.1	34 ±6.4	28.5±5.8	32.3±3.6

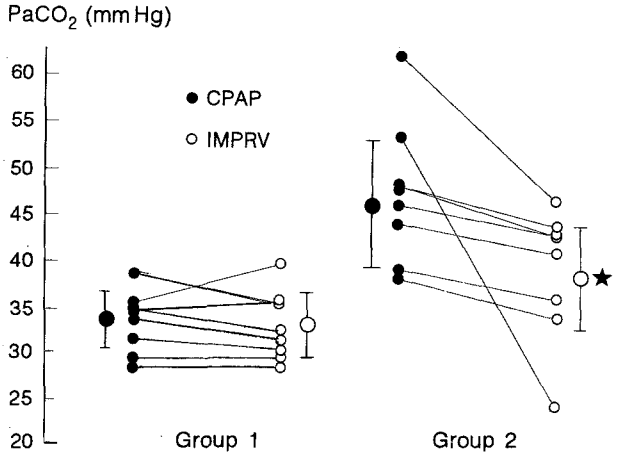

Fig. 3. Individual changes in $PaCO_2$ during CPAP and IMPRV in both groups of patients. Group 1 is composed of 8 patients free of any factor known to alter ventilatory mechanics. Group 2 is composed of 8 patients whose spontaneous respiratory activity is markedly altered by a flail chest, or by a C_5 quadraplegia or/and by the administration of fentanyl

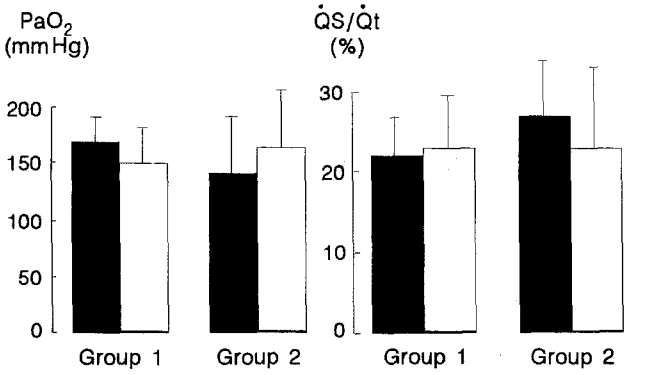

Fig. 4. Changes in PaO_2 and $\dot{Q}s/\dot{Q}t$ during CPAP and IMPRV in both groups of patients (mean ± SD). During both ventilatory modes a FiO_2 of 0.6 is used (■ CPAP □ IMPRV)

served changes in expiratory time were not great enough to significantly influence $\overline{Paw}$. Mean airway pressure and ΔEELV were comparable in both groups of patients during both ventilatory modes. During IMPRV, pressure release, which induced a comparable decrease in ΔEELV in both groups (from 851 ± 211 ml to 277 ± 90 ml in group 1 patients and from 1101 ± 471 ml to 369 ± 138 ml in group 2 patients) was not associated with deterioration in PaO_2 and $\dot{Q}s/\dot{Q}t$ (Fig. 4). In both groups of patients peak inspiratory pressure was slightly but significantly increased during IMPRV. Mean esophageal and mean transpulmonary pressures were comparable in both groups during both ventilatory modes.

As shown in Table 3, all hemodynamic and metabolic parameters were comparable in both groups and ventilatory modes.

Discussion

This study shows that IMPRV can improve the alveolar ventilation of critically ill patients who are hypercapnic during CPAP, without markedly increasing peak airway pressure, as observed in pressure support ventilation [11] or assisted mechanical ventilation. In addition, the intermittent decrease in end-expiratory lung volume associated with pressure release does not impair arterial oxygenation in hypoxemic patients with mild acute respiratory failure.

During IMPRV, minute ventilation is equal to the product of tidal volume by respiratory frequency. Respiratory frequency depends on patient's spontaneous inspiratory activity and tidal volume is the sum of the spontaneous tidal volume generated by the patient and of the pressure release induced change in lung volume. In this study, one spontaneous breath out of two was assisted by a 8 – 10 cmH_2O pressure release. In group 1 patients who could achieve a normal $PaCO_2$ during CPAP, minute ventilation did not increase during IMPRV, and $PaCO_2$ remained stable: the increase in tidal volume induced by intermittent pressure release was counterbalanced by a decrease in spontaneous tidal volume, the respiratory frequency remaining unchanged. In other words, in the group of patients able to achieve normal alveolar ventilation during CPAP, the ventilatory assistance provided by IMPRV was associated with a significant reduction in spontaneous inspiratory activity. In group 2 patients who were hypercapnic during CPAP because of mechanical chest wall impairment and/or drug induced respiratory depression, IMPRV significantly increased minute ventilation and tended to reduce $PaCO_2$ and respiratory frequency. As shown in Fig. 3, a marked decrease in $PaCO_2$ was observed in 2 patients severely hypercapnic during CPAP, whereas in the 6 others with mild alveolar hypoventilation during CPAP, improvement in $PaCO_2$ was slight although observed in each individual. This result suggests that the greater is alveolar hypoventilation during CPAP, the more efficient is IMPRV. Nevertheless, the underlying mechanism for hypoventilation during CPAP likely influences the ability of IMPRV to improve alveolar ventilation. Hypoventilation secondary to peripheral factors will benefit from IMPRV to a greater extent that might a similar degree of hypoventilation due to central factors.

IMPRV and Airway Pressure Release Ventilation (APRV) are two forms of pressure release ventilation designed to augment minute ventilation when spontaneous breathing activity becomes insufficient to ensure adequate alveolar ventilation. In both modes, pressure release induced ventilatory assistance depends on the amount of pressure release and on the frequency of pressure release. For a given amount of pressure release, the higher the respiratory compliance, the greater the ventilatory assistance. Although based on the same concept, IMPRV and APRV differ in several ways. During APRV, the frequency of pressure release is predetermined by setting pressure release time between 1 and 1.5 seconds [4, 6]. As a consequence, pressure release is not automatically synchronized with spontaneous respiratory efforts and ventilatory assistance is not influenced by the patient's spontaneous respiratory frequency. In the absence of spontaneous respiratory activity, this results in duty cycles above 50% (inverse I/E ratio) [4, 5]. In contrast, during IMPRV, pressure release occurs according to pa-

tient's spontaneous respiratory frequency: positive end-expiratory pressure can be changed each 2, 3, 4, 5 or 6 spontaneous expiratory efforts, thus providing a smooth and progressive assistance of minute ventilation [12] without discoordination between patient's spontaneous breathing and pressure release. The more rapid the patient's respiratory frequency, the greater the ventilatory assistance. As shown in Table 2, duty cycle is in the physiological range of 25–45%. Since the IMPRV mode is provided by a conventional ICU ventilator, a 4–5 cmH_2O of pressure support can be added to each spontaneous respiratory cycle, in order to suppress the extra work of breathing caused by artificial airway resistance [13–16]. This small pressure support, which is critical to avoid respiratory fatigue during the long-term use of CPAP and IMPRV, cannot be added when a high continuous flow device equipped with a solenoid valve is used to deliver CPAP or APRV [4, 5, 17]. These potential advantages of IMPRV over APRV remain speculative and require further studies to be confirmed.

Because pressure release is basically designed to assist alveolar ventilation, a decrease in patient's respiratory frequency should be expected during IMPRV. In fact, the increased respiratory frequency observed in patients with acute respiratory failure can be of several origins. It can be a compensatory mechanism to maintain minute ventilation when the patient is unable to achieve adequate tidal volumes. In these patients, the ventilatory assistance provided by pressure release tends to decrease respiratory frequency. Such a phenomenon was observed in 2 patients of group 1 and in 6 patients of group 2. However, the increased respiratory frequency can also be due to the bronchial lesions which characterize many acute respiratory failures. If this mechanism is predominant, then no significant decrease in respiratory frequency can be expected from pressure release induced ventilatory assistance.

It is highly likely that identical therapeutic end points could have been achieved by increasing pressure support level above 5 cmH_2O. In fact, pressure support and IMPRV provide ventilatory assistance either by increasing inspiratory airway pressure or by decreasing end-expiratory airway pressure. How they differ in terms of barotrauma and respiratory work of breathing is not known. In patients with acute respiratory failure, a decrease in peak airway pressure could be potentially beneficial in terms of barotrauma. Further studies are required to verify this assumption.

In conclusion, this study shows that an increase in minute ventilation and in CO_2 elimination occurs when ventilatory assistance in the form of IMPRV is provided as opposed to CPAP alone in patients with hypercapnic respiratory failure. In patients with large and mobile flail chest, in quadraplegic patients, in patients receiving intravenous opioids, CPAP often results in a marked elevation of $PaCO_2$ and IMPRV provides the possibility of increasing alveolar ventilation without markedly increasing peak airway pressure. Whether this type of ventilatory assistance has any advantage over constant positive airway pressure with increasing level of pressure support, remains to be determined.

Acknowledgement. We thank the nursing staff of the Surgical Intensive Care Unit for their patience and active cooperation, the Air Liquide CFPO Company for providing the CESAR ventilator,, C. Mataguez and J. Liaudet for preparing the manuscript and G. Debrabander for technical assistance.

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