Pressure controlled-inverse ratio ventilation and pulmonary gas exchange during lower abdominal surgery

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Although pressure controlled-inverse ratio ventilation (PC-IRV) has been used successfully in the treatment of respiratory failure, it has not been applied to the treatment of respiratory dysfunction during anaesthesia. With PC-IRV the inspiratory wave form is fundamentally altered so that inspiratory time is prolonged (inverse I:E), inspiratory flow rate is low, and the peak inspiratory pressure is limited. Positive end-expiratory pressure (PEEP) can be applied and the mean airway pressure is higher than with conventional ventilation. To assess the clinical efficacy of this new mode of ventilation we studied ten patients having lower abdominal gynaecologic surgery in the Trendelenburg position under general anaesthesia. Pulmonary O_2 exchange was determined during four steady states: awake control (AC), after 30 and 60 min of PC-IRV during surgery, and at the end of surgery. Patients' lungs were ventilated with air/ O_2 by a Siemens 900C servo ventilator in the PC-IRV mode with an I:E ratio of 2:1 and 5 cm H_2O of PEEP. The FiO_2 was controlled at 0.5 and arterial blood gases were used to calculate the oxygen tension-based indices of gas exchange. There were significant increases of (A-a) DO_2 at 30 and 60 min (41 and 43%). These changes were less than those reported in a previous study using

conventional tidal volume ventilation ($7.5 \text{ ml} \cdot \text{kg}^{-1}$) and were similar to those in patients whose lungs were ventilated with high tidal volumes ($12.7 \text{ ml} \cdot \text{kg}^{-1}$). Thus, in this clinical model of compromised gas exchange, arterial oxygenation was better with PC-IRV than with conventional ventilation, but not better than with large tidal volume ventilation.

Bien que la ventilation à pression contrôlée avec rapport I/E inversé (PC-IRV) ait été utilisée avec succès pour traiter l'insuffisance respiratoire, on ne l'a appliquée jusqu'à maintenant au traitement du dysfonctionnement respiratoire peropératoire. Sous ce mode de ventilation, la courbe d'insufflation inspiratoire est altérée de sorte que la durée de la phase inspiratoire est prolongée (rapport I/E inversé), le débit inspiratoire est maintenu bas, et le pic inspiratoire est plafonné. Une pression positive expiratoire (PEP) peut être ajoutée. Sur les voies aériennes, la pression moyenne devient plus élevée qu'avec la ventilation conventionnelle. Pour évaluer l'efficacité de ce nouveau mode de ventilation sous anesthésie générale, nous avons étudié dix patientes subissant une chirurgie gynécologique en position de Trendelenburg. Pour l'oxygène, les échanges pulmonaires sont évalués à l'état d'équilibre à quatre moments : contrôle à l'état d'éveil, après 30 et 60 min de PC-IRV et après la chirurgie. Les poumons sont ventilés avec un mélange air/ O_2 par un ventilateur Siemens Servo 900C en mode IRV-PC avec un rapport I/E de 2/1 et un PEP de 5 cm H_2O . La FiO_2 est maintenue à 0,5 et la mesure des échanges gazeux se fait par les gaz artériels. Nous avons trouvé une augmentation importante de la (A-a) DO_2 à 30 et 60 min (41 et 43%). Ces changements sont moindres que ceux qui ont été rapportés dans une étude antérieure où on utilisait le mode ventilatoire avec volumes courants usuels ($7,5 \text{ m} \cdot \text{kg}^{-1}$) et étaient identiques à ceux de patients ventilés avec des volumes courants élevés ($12,7 \text{ ml} \cdot \text{kg}^{-1}$). Ainsi, avec ce modèle clinique présentant une situation d'échanges gazeux perturbés, les résultats de la mesure de l'oxygénation du sang artériel sont supérieurs avec PC-IRV que sous ventilation conventionnelle mais identiques à ceux qu'on obtient avec une ventilation à grands volumes courants.

Key words

LUNG: gas exchange, shunting;
VENTILATION: artificial, tidal volume, oxygen tension (gradients), inverse ratio, pressure controlled;
OXYGEN: blood levels, gradients, tension.

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Pressure controlled-inverse ratio ventilation (PC-IRV) has been used in the treatment of severe respiratory failure.^{1,2} It permits delivery of a pre-determined tidal volume (V_T) with a limited peak inspiratory pressure (PIP), high mean airway pressure (AWP), and variable positive end-expiratory pressure (PEEP). Boros³ has shown that the beneficial effect of positive pressure ventilation in neonatal respiratory failure is directly related to the level of mean AWP, and this may explain the efficacy of PC-IRV in severe respiratory failure. Some manifestations of pulmonary dysfunction during anaesthesia, such as atelectasis⁴ and shunting of pulmonary venous blood,⁵ are similar to those of respiratory failure. We therefore undertook a clinical trial, in patients known to be at high risk for pulmonary dysfunction, to assess the effect of PC-IRV on gas exchange during anaesthesia and surgery.

Methods

The protocol for this study was approved by Departmental and Institutional Ethics Review Committees.

The methods were similar to those reported previously.⁶ Subjects for this study were ten adult ASA physical status I or II females having elective intra-abdominal gynaecological surgery through lower abdominal incisions. Various degrees of intra abdominal packing, retraction, and supine Trendelenburg (head down) positioning were common to all.

Routine preanaesthetic workup included history, physical examination and chest radiograph. None was grossly obese, a cigarette smoker, or had symptomatic pulmonary disease.

A 20-gauge teflon cannula was inserted, with the patient's consent and the aid of local anaesthesia, in a radial artery. After premedication with lorazepam or midazolam, all had total intravenous general anaesthesia with tracheal intubation as previously described.⁶ While lying supine before induction of anaesthesia they breathed air/O₂ ($FiO_2 = 0.5$) for five minutes from the ventilator circuit via a tight fitting mask (AC condition). After tracheal intubation and four or five manual inflations they were connected to the Siemens 900C servo ventilator in the PC-IRV mode with a rate of 10 min⁻¹, an I:E ratio of 2:1 and 5 cm H₂O of PEEP. The fresh gas mixture was air/O₂ and the inspiratory O₂ concentration (FiO_2) of 0.5 was monitored continuously by the Siemens oxygen analyzer. Tidal volume (V_T) was set by adjusting peak inspiratory pressure (PIP) so that end-tidal CO₂ ($FETCO_2$) was between 4.5 and 5.0% (V_T of 7–8 ml · kg⁻¹). During the study only the V_T was adjusted to maintain near constant $FETCO_2$.

After five minutes of AC breathing, at 30 and 60 min of anaesthesia, and during abdominal closure, an anaerobic arterial blood sample was drawn from the radial artery

cannula, placed on ice, and analyzed within three minutes in a Nova Stat Profile Blood Gas Analyzer at 37° C. The analyser was calibrated as previously described. Heart rate (HR) and blood pressure (BP) were measured by a Dinamap Automatic BP Monitor at three-minute intervals.

The calculation of alveolar oxygen tension was based on the formula adopted by Pappenheimer *et al.*:⁷

$$PAO_2 = FiO_2(PB - PAH_2O) - PaCO_2[FiO_2 + (1 - FiO_2)/RQ]$$

Since Singapore is at sea level the barometric pressure PB was assumed to be 760 mmHg and alveolar water vapour partial pressure (PAH_2O) to be 47 mmHg. Day to day variation in barometric pressure in Singapore is less than one percent.* If FiO_2 and RQ are assigned constant values of 0.5 and 0.9† respectively the Pappenheimer formula reduces to:

$$PAO_2 = 357 - (PaCO_2 \times 1.06)$$

Pulmonary gas exchange was assessed by calculating the alveolar-arterial oxygen tension difference, (A-a) DO₂, that is the calculated PAO₂ minus the temperature corrected PaO₂.

Because the data did not meet the requirements of normal distribution and equal variances non-parametric analysis was used. Two sample comparisons were by the Wilcoxon signed rank test for paired data and the Mann-Whitney u test for unpaired data.

Results

The demographic data are shown in Table I, PC-IRV column. These patients were similar to those of a previous study⁶ (Table I).

During PC-IRV average V_T was 8 ml · kg⁻¹, PIP was 14–15 cm H₂O and mean AWP was 12–13 cm H₂O. There were no differences among the four study conditions in pH, PAO₂, Bp, or temperature, and PaCO₂ remained constant during controlled ventilation (Table II).

There were increases in (A-a) DO₂ at 30 and 60 min compared with AC (41% and 43% respectively, $P < 0.05$). During abdominal closure, that is after removal of packs and retractors and return to the supine position, (A-a) DO₂ was not different from AC.

These results were compared with those of a previously reported study,⁶ in which the lungs of similar patients had been ventilated with conventional tidal volumes (CVT, 7.5 ml · kg⁻¹) or high tidal volumes (HVT, 12.7 ml · kg⁻¹) (Table I). The increase in (A-a)DO₂ with PC-IRV was less than that during CVT ventilation and similar to that found with HVT.

*Personal communication, The Meteorological Service of Singapore.

†Value obtained from previous metabolic studies during anaesthesia in this Department.

TABLE 1 Pulmonary gas exchange during anaesthesia: comparison of three modes of ventilation

	Ventilatory group		
	CVT ⁶	HVT ⁶	PC-IRV
<i>Comparative data: mean ± SD (range)</i>			
<i>n</i>	12	12	10
Age yr	46.7 ± 11.8 (21–69)	43.8 ± 9.7 (26–64)	45.7 ± 7.1 (38–63)
Weight kg	61.3 ± 10.4 (47–84)	59.5 ± 10.6 (43–73)	58.1 ± 10 (47–70)
ASA I/II	8/4	7/5	7/3
Cigarette smokers	2/12	1/12	0/10
<i>Gas exchange: mean ± SEM</i>			
FiO ₂	0.50	0.50	0.50
Awake cont. (A-a) DO ₂	82 ± 7	77 ± 10	65 ± 6
% Increase at 30 min	126 ± 31%	48 ± 32%*	41 ± 13%*

**P* < 0.05 compared with the increase during CVT by the Mann-Whitney *u* test for unpaired data.

TABLE 2 Pressure controlled-inverse ratio ventilation (mean ± SEM, *n* = 10)

	Study conditions			
	AC	30 min	60 min	CL
<i>Controlled variables</i>				
VT ml · kg ⁻¹		8.1 ± 0.4	7.7 ± 0.4	8.0 ± 0.4
FiO ₂	0.50	0.50	0.50	0.50
PAO ₂ mmHg	314 ± 2	319 ± 1	319 ± 1	319 ± 1
Temp °C	37.0 ± 0	36.3 ± 0.2	36.2 ± 0.2	35.8 ± 0.3
<i>Cardiovascular</i>				
Syst BP mmHg	122 ± 5	111 ± 6	105 ± 5	107 ± 4
Diast BP mmHg	70 ± 3	64 ± 4	63 ± 4	63 ± 3
<i>Airway Pressures</i>				
PIP cm H ₂ O		14.5 ± 0.7	14.7 ± 0.5	14.2 ± 0.6
Mean AWP cm H ₂ O		12.1 ± 0.6	12.3 ± 0.4	12.1 ± 0.5
PEEP cm H ₂ O		5.0	5.0	5.0
<i>Arterial blood gases</i>				
pH	7.37 ± 0.02	7.40 ± 0.01	7.40 ± 0.01	7.38 ± 0.01
PaCO ₂ mmHg	41 ± 2	36 ± 1*	36 ± 1*	36 ± 1*
PaO ₂ mmHg	249 ± 7	228 ± 12	224 ± 11	237 ± 13
Bicarb mEq · L ⁻¹	23.3 ± 0.4	23.3 ± 0.3	22.9 ± 0.4	22.2 ± 0.4
<i>Pulmonary ventilation and gas exchange</i>				
VE ml · kg ⁻¹ · min ⁻¹		81 ± 4	77 ± 4	80 ± 4
(A-a)DO ₂	65 ± 6	91 ± 12*	95 ± 11*	82 ± 13
% Change from AC		41 ± 13*	43 ± 15*	26 ± 13

AC – awake control; CL – abdominal closure; PIP – peak inspiratory pressure; mean AWP – Mean airway pressure; PEEP – positive end expiratory pressure.

* *P* < 0.05 compared with AC by the Wilcoxon signed rank test for paired data.

Discussion

In this sample of patients there was considerable worsening of gas exchange during lower abdominal surgery, when the effects of packs, retractors and positioning were maximal. During abdominal closure, when these factors were removed, oxygenation was not different from control,

suggesting that the gas exchange dysfunction was largely due to surgical and positional factors. We believe that these factors impede diaphragmatic excursion, and that this is a model of compression atelectasis with pulmonary venous shunting.

This is a descriptive study with historical controls. In

comparison with the previous study, PC-IRV provided protection against hypoxaemia about equal to that of HVT ventilation.

We have also investigated time cycled-inverse ratio ventilation (TC-IRV), without PEEP, in a group of orthopaedic patients and found no difference between it and conventional ventilation.⁸ However, the orthopaedic patients were not subjected to compressive and positional forces, as were the gynaecological subjects, and therefore were not at the same risk for compression atelectasis. In addition, although both modes of ventilation increased mean AWP, there was a fundamental difference between them. With PC-IRV the increased airway pressure was sustained throughout the respiratory cycle, with TC-IRV it was not. We suggest that continuous positive airway pressure is more effective to increase resting lung volume (FRC) and improve $\dot{V}_A/\dot{Q}$ matching in patients with pulmonary dysfunction during anaesthesia.

Gas exchange impairment occurs during general anaesthesia in obese patients, cigarette smokers, and those with pre-existing lung disease, but only minimally in healthy young non-smokers.⁹ The FRC and total pulmonary compliance are reduced with onset of general anaesthesia. When FRC is reduced to below awake closing capacity (CC), Dueck *et al.* found physiological shunting in dependent areas of the lung.¹⁰ Hedenstierna *et al.* have also found venous shunting in anaesthetized patients, and have demonstrated dependent atelectasis, in both the supine and lateral positions, by CT scanning.¹¹⁻¹³ Although we have not examined the pathophysiology of impaired gas exchange in our patients, the evidence cited above supports our contention that it can be reasonably ascribed to increased intra-abdominal pressure, cephalad shift of the diaphragm, compression atelectasis, and venous shunting. We propose that PC-IRV increases resting lung volume, that is FRC, and prevents compression atelectasis under these circumstances.

Continuous positive pressure ventilation (CPPV) and conventional ratio ventilation with PEEP have also been shown to improve oxygenation in some, but not all, studies.¹⁴⁻¹⁶ Thus, PC-IRV can be viewed as another form of CPPV, but with higher mean AWP and a prolonged inspiratory waveform.

The present studies show that, in patients at risk for compression atelectasis and pulmonary venous shunting, impairment of O_2 exchange can be reduced by PC-IRV, which combines high mean AWP with PEEP. However, PC-IRV at the pressures and ratios that we have used does not appear to be superior to ventilation with large tidal volumes of 12–13 ml $\cdot$ kg⁻¹.

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References

- 1 Tharratt RS, Allen RP, Albertson ET. Pressure controlled inverse ratio ventilation in severe adult respiratory failure. *Chest* 1988; 94: 755–62.
- 2 Abraham E, Yoshihara G. Cardiorespiratory effects of pressure controlled inverse ratio ventilation in severe respiratory failure. *Chest* 1989; 96: 1356–9.
- 3 Boros SJ. Variations in inspiratory:expiratory ratio and airway pressure wave form during mechanical ventilation: the significance of mean airway pressure. *J Pediatr* 1979; 94: 114–7.
- 4 Hedenstierna G. Gas exchange during anaesthesia. *Br J Anaesth* 1990; 64: 507–14.
- 5 Price HL, Cooperman LH, Warden JC, Morris JJ, Smith TC. Pulmonary hemodynamics during general anaesthesia in man. *Anesthesiology* 1969; 30: 629–36.
- 6 Tweed WA, Phua WT, Chong KY, Lim E, Lee TL. Large tidal volume ventilation improves pulmonary gas exchange during lower abdominal surgery in Trendelenburg's position. *Can J Anaesth* 1991; 38: 989–95.
- 7 Pappenheimer JR, Comroe JH, Cournand A, *et al.* Standardization of definitions and symbols in respiratory physiology. *Fed Proc* 1950; 9: 602–5.
- 8 Tweed WA, Lee TL. Time-cycled inverse ratio ventilation does not improve gas exchange during anaesthesia. *Can J Anaesth* 1991; 38: 311–7.
- 9 Rehder K, Knopp TJ, Sessler AD, Didier EP. Ventilation-perfusion relationships in young healthy awake and anesthetized paralyzed man. *J Appl Physiol* 1979; 47: 745–53.
- 10 Dueck R, Prutow RJ, Davies NJH, Clausen JL, Davidson TM. The lung volume at which shunting occurs with inhalation anaesthesia. *Anesthesiology* 1988; 69: 854–61.
- 11 Gunnarsson L, Strandberg A, Brismar B, *et al.* Atelectasis and gas exchange impairment during enflurane/nitrous oxide anaesthesia. *Acta Anaesthesiol Scand* 1989; 33: 629–37.
- 12 Klingstedt C, Hedenstierna G, Lundquist H, *et al.* The influence of body position and differential ventilation on lung dimensions and atelectasis formation in anesthetized man. *Acta Anaesthesiol Scand* 1990; 34: 315–22.
- 13 Klingstedt C, Hedenstierna G, Baehrendtz S, *et al.* Ventilation-perfusion relationships and atelectasis formation in the supine and lateral positions during conventional ventilation and differential ventilation. *Acta Anaesthesiol Scand* 1990; 34: 421–9.
- 14 Wyche MQ, Teichner RL, Kallos T, Marshall BE, Smith TC. Effects of continuous positive pressure breathing on functional residual capacity and arterial oxygenation during intra-abdominal operations. *Anesthesiology* 1973; 38: 68–74.
- 15 Bindsløv LG, Hedenstierna G, Santesson J, Gottlieb I,

- Carvallhas A.* Ventilation-perfusion distribution during inhalation anaesthesia. *Acta Anaesthesiol Scand* 1981; 25: 360-71.
- 16 *Visick WD, Fairley HB, Hickey RF.* The effects of tidal volume and end-expiratory pressure on pulmonary gas exchange during anesthesia. *Anesthesiology* 1973; 39: 285-90.