Comparison of automated and static pulse respiratory mechanics during supported ventilation

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ABSTRACT

Objective: To compare respiratory mechanics estimated by the pulse technique in spontaneously breathing patients during proportional assist ventilation (PAV) with load-adjustable gain factor (PAV+) mode with those measured using the flow-interruption technique during controlled ventilation.

Design, participants and setting: Observational study of 21 haemodynamically stable post-cardiac surgery patients with routine weaning from mechanical ventilation (Puritan–Bennett 840 ventilator) in the intensive care unit of a tertiary hospital.

Main outcome measures: Bland–Altman and linear correlation of respiratory system compliance and inspiratory resistance estimated during PAV+ (C_{pulse} and R_{pulse}) with that measured during controlled mechanical ventilation (C_{int} and R_{int}).

Results: C_{pulse} overestimated C_{int} (67.4 [SD, 27.7] v 51.6 [SD, 9.7] mL/cmH_2O; $P = 0.02$), although the correlation between C_{int} and C_{pulse} was strong. Using the Bland–Altman method, the bias and limits of agreement were outside a clinically useful range. R_{pulse} underestimated R_{int} (9.3 [SD, 3.0] v 11.5 [SD, 3.0] cmH_2O/L/s; $P = 0.02$), with a weak positive correlation. Although the bias calculated by the Bland–Altman method was small, the limits of agreement were too large to be clinically useful.

Conclusion: Based on these data, respiratory mechanics estimated from the pulse technique are too inaccurate to be clinically useful.

Crit Care Resusc 2012; 14: 130–134

Respiratory system compliance (C_{int}) and inspiratory resistance (R_{int}) can be easily estimated from airway pressure using flow interruption in a relaxed, usually paralysed, patient. In patients with respiratory failure, this allows both greater insight into the mechanical problem faced, and an opportunity to monitor response to treatment. However, as ventilatory support is increasingly provided by patient-triggered modes, and paralysis is infrequently used in most intensive care units, estimates of respiratory mechanics require specific expertise and use of an oesophageal balloon to account for respiratory muscle effort. Consequently, measures of respiratory mechanics are infrequently available for use in routine clinical care.

The Puritan–Bennett 840 ventilator (Carlsbad, Calif, USA) offers proportional assist ventilation (PAV)[1] with a load-adjustable gain factor (PAV+) option that uses estimates of compliance and resistance, derived using the pulse technique,[2-4] to adjust the flow- and volume-assist settings during PAV. One proposed advantage of the pulse technique is that mechanics can be estimated without respiratory muscle relaxation. Intermittent increases in ventilatory support theoretically minimise respiratory muscle pressure (P_{mus}) by minimising neural drive, and this increase in support is followed by 300 ms of flow interruption to allow estimation of compliance (C_{pulse}) and resistance (R_{pulse}). Resistance and compliance are calculated at random intervals of 4–10 breaths. In a single-centre study, the PAV+ mode was shown to increase the probability of remaining on spontaneous breathing and to have better patient–ventilator synchrony than the pressure-support mode.[5]

The aim of our study was to compare respiratory mechanics estimated by conventional static methods to those estimated using an automated pulse method.[6] We propose that independent of PAV itself, an automated, valid estimate of these parameters would be clinically useful;[2,3] however, this technique has not been independently validated.

Abbreviations

C_{int}	Respiratory system compliance
C_{pulse}	Estimation of compliance
PAV	Proportional assist ventilation
PAV+	Proportional assist ventilation with a load-adjustable gain factor
PEEP	Positive end-expiratory pressure
P_{mus}	Respiratory muscle pressure
R_{int}	Inspiratory resistance
R_{pulse}	Estimation of resistance

Methods

The study was performed in a 32-bed general ICU of a tertiary care hospital. Twenty-one consecutive haemodynamically stable post-cardiac surgery patients admitted to our unit between February and June 2008 were included in

Table1. Demographics of 21 post-cardiac surgery patients who were mechanically ventilated

Age	Sex	Procedure	Predicted weight	Hours of ventilation	Bronchodilator use	Endotracheal tube internal diameter
65 years	Male	CABG	58 kg	9	No	8 mm
75 years	Male	CABG	70 kg	25	Yes	9 mm
67 years	Female	AVR	60 kg	16	No	7 mm
83 years	Male	CABG	74 kg	90	No	8 mm
50 years	Male	CABG	70 kg	6	Yes	9 mm
55 years	Male	CABG	70 kg	6	No	8 mm
69 years	Male	CABG	65 kg	11	No	9 mm
70 years	Male	MVR	75 kg	17	No	9 mm
70 years	Male	CABG	70 kg	7	Yes	9 mm
57 years	Male	AVR	64 kg	12	No	9 mm
52 years	Male	CABG	80 kg	9	No	9 mm
60 years	Female	CABG	60 kg	22	No	7 mm
76 years	Male	CABG	70 kg	15	No	8 mm
61 years	Male	CABG	71 kg	10	No	8 mm
48 years	Male	CABG	70 kg	7	No	9 mm
65 years	Female	MVR	60 kg	11	No	8 mm
80 years	Female	CABG	41 kg	17	No	8 mm
82 years	Male	CABG	70 kg	8	No	8 mm
54 years	Male	CABG	70 kg	6	No	8 mm
55 years	Male	AVR	80 kg	22	Yes	9 mm
71 years	Male	CABG	75 kg	19	No	9 mm

AVR = aortic valve replacement. CABG = coronary arteries bypass graft. MVR = mitral valve repair or replacement.

the study. The study was approved by the Flinders Clinical Research Ethics Committee (approval no. 64/08); the need for informed consent was waived because clinical management was unchanged.

Protocol

Medical staff looking after these patients were trained to carry out the study protocol before commencement, and were assisted with data collection by one of the investigators.

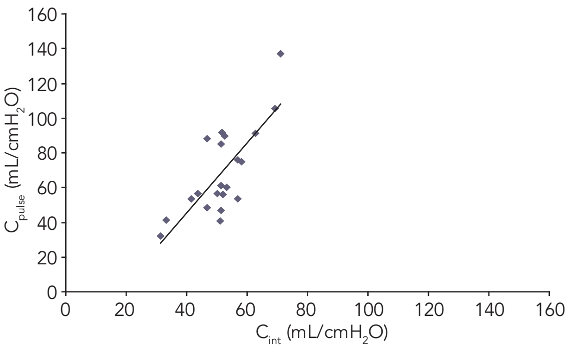
Haemodynamically stable post-cardiac surgery patients with no known chronic respiratory disease were included in the study, presuming that they would undergo routine ventilator weaning. Exclusion criteria included known chronic lung disease, chest wall abnormality, repeat sternotomy, pneumothorax, haemothorax, air leak, and inability to proceed to weaning from controlled ventilation as expected.

After enrolment, the following data were recorded: patient demographic characteristics, indication and type of surgery, underlying medical conditions, and physiological and ventilatory parameters, including endotracheal tube size and doses and timing of bronchodilator therapy. Before connecting a patient to a ventilator, body weight was predicted from the patient's height and sex and entered into the ventilator software along with the endotracheal tube size.

We used Puritan–Bennet 840 ventilators with an option for PAV and the software upgrade (PAV+) for its enhanced graphic displays and continuous monitoring capabilities. PAV+ software can estimate the inspiratory resistance of both the artificial airway and the patient's airway, and can estimate respiratory compliance every 4–10 breaths by applying random brief inspiratory pauses (duration, 0.3 s). The PAV+ software also estimates flow and volume every 5 ms. Based on the above estimates and the percentage support setting, the software computes the support to be applied at the wye for each supported breath.

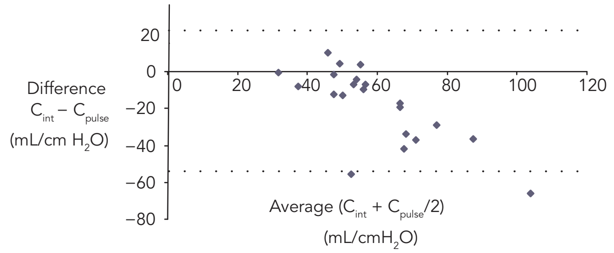
Controlled mechanical ventilation was delivered on arrival to the ICU. Once stable and starting to rouse, all patients were weaned using PAV+. Three measures, about 30 minutes apart, of interrupter resistance and compliance were recorded using a 0.5 s inspiratory pause soon after arrival from the operating theatre when the patient had no detectable respiratory effort. Peak and plateau airway pressure, extrinsic positive end-expiratory pressure (PEEP), intrinsic PEEP (after a 5–6 s end-expiratory hold manoeuvre performed before the inspiratory pause), and set inspiratory flow rate were recorded to allow calculation of respiratory system compliance and resistance using standard formulae.[7,8] Similarly, three measures of pulse resistance and compliance were

Figure 1. Comparison of respiratory system compliance (C_{int}) and estimation of compliance (C_{pulse})



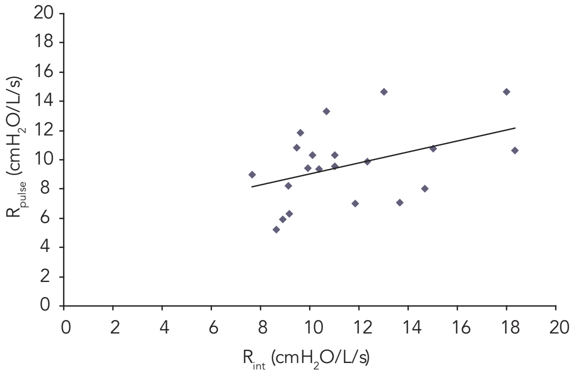
A linear correlation was present ($R^2 = 0.578$; $P < 0.001$).

Figure 2. Bland–Altman comparison of respiratory system compliance (C_{int}) and estimation of compliance (C_{pulse})



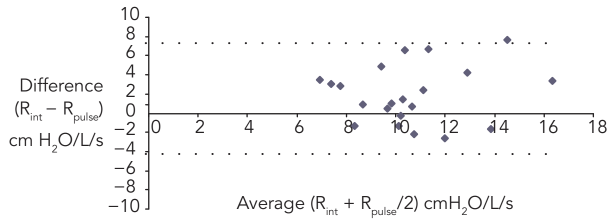
Bias = − 17.3 mL/cmH_2O. Limits of agreement = 22 to − 55 mL/cmH_2O. A strong inverse relationship was found ($R^2 = 0.752$; $P < 0.001$) between the average values and their differences.

Figure 3. Relation between inspiratory resistance (R_{int}) and estimation of resistance (R_{pulse})



A weak correlation was found between R_{int} and R_{pulse} ($R^2 = 0.170$; $P = 0.06$).

Figure 4. Bland–Altman comparison of inspiratory resistance (R_{int}) and estimation of resistance (R_{pulse})



Bias = 1.9 cmH_2O/L/s. limits of agreement = 7.9 to − 4.1 cmH_2O/L/s. Correlation was found between the average values and their differences ($R^2 = 0.017$; $P = 0.56$).

recorded about 30 minutes apart during stable PAV+. The averaged values were used for comparison.

Statistical analysis

The interrupter and pulse estimates of resistance and compliance were compared using the paired *t* test, and using the Bland–Altman method.[9] In addition, correlation between the two measures was performed to allow comparison with previous data.[2,3,10] Four patients received nebulised bronchodilator therapy during the study, so the data were analysed both including and excluding them.

Results

All included patients underwent primary median sternotomy. Sixteen of the 21 patients studied underwent coronary artery bypass grafting and the remainder had isolated heart valve surgery. All patients were successfully weaned using the PAV+ mode. The median duration of mechanical ventilation in the ICU was 11 hours (range, 6–90 hours) (Table 1).

C_{pulse} overestimated C_{int} (67.4 [SD, 27.7] v 51.6 [SD, 9.7] mL/cmH_2O; $P = 0.02$), although the correlation between C_{int} and C_{pulse} was strong (Figure 1), and at compliance values of around 50 mL/cmH_2O, the two estimates were similar. A Bland–Altman plot of the average of the two estimates and their difference is presented in Figure 2 along with the bias and limits of agreement.

R_{pulse} underestimated R_{int} (9.3 [SD, 3.0] v 11.5 [SD, 3.0] cmH_2O/L/s; $P = 0.02$), with a weak positive correlation of values, although at a resistance of around 8 cmH_2O/L/s the values were similar (Figure 3). A Bland–Altman plot of the average of the two estimates and their difference is presented (Figure 4) along with the bias and limits of agreement.

These results did not change when patients who received nebulised bronchodilators during study period were excluded.

Discussion

As readily available, valid respiratory mechanics during patient-triggered respiratory support would be clinically useful, we aimed to independently validate estimates of respiratory compliance and inspiratory resistance that are easily available when PAV+ is used as a mode of ventilatory assistance. Although the pulse technique has been suggested as being suitable for this purpose,[2,3] the excessive bias and limits of agreement we found suggest that the method used during PAV+ does not yield clinically useful measures. While our results are consistent with data from Ruiz-Ferron and colleagues,[11] Grasso and co-workers reported strong correlations between different measures of mechanics and concluded that the results were reliable.[10] We also found a strong correlation between C_{int} and C_{pulse}; however, using the Bland–Altman method, we found clinically important differences between the two measures. Correlation of data from one method of measurement with another does not prove equivalence, and was an important basis for the analytic approach suggested by Bland and Altman.[9]

On average, C_{pulse} overestimated C_{int} by 16 mL/cmH_2O. This is similar to the bias calculated using the Bland–Altman method, which also found that the limits of agreement were large (22 to − 55 mL/cmH_2O). As the respiratory system compliance in a ventilated patient without lung or chest wall abnormality is 60–100 mL/cmH_2O,[12] we suggest that C_{pulse} data are unreliable for clinical decision making. For example, a C_{pulse} reading of 60 mL/cmH_2O might equate to compliance between 88 mL/cmH_2O, which is still in the normal range, to 5 mL/cmH_2O, which suggests an extremely stiff respiratory system seen only with the most severe restrictive disease. However, the range of compliance values examined was limited and did not adequately explore the relationship at low levels of compliance, as may be seen among patients with severe acute respiratory distress syndrome. R_{pulse} underestimated R_{int} by around 2 cmH_2O/L/s, which is similar to the bias calculated using the Bland–Altman method. As the normal inspiratory resistance of an intubated patient ranges from 5 to 10 cmH_2O/L/s, this does not seem excessive. However, the limits of agreement were 7.9 to − 4.1 cmH_2O/L/s. In other words, an R_{pulse} value of 10 cmH_2O/L/s might equate to a resistance between 17.9 cmH_2O/L/s, which would be significantly elevated, to 5.9 cmH_2O/L/s, which would be close to the lower end of normal. Despite a limited number of patients with high inspiratory resistance values, we suggest that the limits of agreement are unacceptable for clinical decision making.

An important assumption underlying our study design is that respiratory system compliance and resistance were stable over the period of the study. Although concurrent measurement of mechanics using an oesophageal balloon to allow an independent measure of mechanics during patient triggered ventilatory support would have avoided any potential temporal change in mechanics between the two techniques we used, this was not used in our study due to changes in atelectasis and lung water following cardiac surgery. Placement of an oesophageal balloon would have added to the complexity of the study, and separation of respiratory system compliance into lung and chest wall components was unnecessary as only respiratory compliance is estimated using PAV+. However, the strong relationship between the average compliance and its difference argues for a systematic difference between the two measures rather than the differences between the two measures being due to changes in mechanics during the hours after surgery. If inspiratory P_{mus} had been significant, there would be a tendency to overestimate supported compliance, as found in our study, and the presence of expiratory P_{mus} during the pause manoeuvre would tend to reduce the gradient between peak and plateau pressure leading to a lower supported resistance, as also found in our study. However, without contemporaneously measured data, it is not possible to be completely certain regarding this issue. Systematic overestimation of compliance and underestimation of resistance using the pulse technique may also lead to less volume support and more flow support during PAV than intended. In turn, this may lead to less effective PAV than expected.

An additional assumption is the use of interrupter mechanics as a "gold standard", as this requires a relaxed patient and accurately measured pressure, flow and volume data. We specifically chose to measure mechanics using flow interruption in post-cardiac surgery patients soon after transfer to the ICU, as they would likely be relaxed due to residual anaesthesia and paralysis, avoiding the confounding effects of chest wall activation. No respiratory effort was noticed during these measures, supporting this assumption. Although the Puritan–Bennett 840 ventilator performs a self-calibration manoeuvre before patient connection, we did not independently confirm the accuracy of the flow and pressure signals, and the calculated volume signal used to derive compliance and resistance. However, as the same calibration error would have been inherent in the pulse-derived mechanics data, assuming no change in calibration over this period, we argue that the two measures should have been comparable, and that independently measured interrupter mechanics may have introduced a further confounder. Finally, interrupter mechanics were calculated independently and accounting for any intrinsic PEEP present as this is not taken into account in the automated measure displayed by the ventilator and can lead to considerable inaccuracy.[13]

The systematic differences between interrupter mechanics and pulse mechanics suggest residual inspiratory P_{mus} (see above) despite intermittent increases in ventilatory support. If this were confirmed by monitoring diaphragmatic and intercostal electromyography, and by concurrent monitoring of oesophageal pressure, it would be of interest to see whether greater increases in ventilatory support minimised the increase in P_{mus} leading to a more accurate estimate of mechanics when using the pulse technique. In the meantime, based on our observations, any interpretation of mechanics derived when ventilatory assistance is provided with PAV+ would need to be cautious.

Competing interests

None declared.

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