Continuous use of an adaptive lung ventilation controller in critically ill patients in a multi-disciplinary intensive care unit

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Study objective. To evaluate an adaptive lung ventilation (ALV) controller in critically ill patients with various causes of respiratory failure during their entire period of mechanical ventilatory support in an intensive care unit (ICU).

Study design. Prospective, selected case study.

Setting. The 13-bed, multidisciplinary respiratory ICU (RICU) at Groote Schuur Hospital, a teaching unit of the University of Cape Town.

Patients. Six patients with respiratory failure due to various causes who required prolonged mechanical ventilation were included. Our institutional committee for ethical research approved the study and informed consent was obtained.

Interventions. A closed-loop control algorithm providing ALV was implemented on a modified Hamilton AMADEUS ventilator with a PC-based lung function analyser. After calculating a target gross alveolar ventilation of 70 ml/kg/min, the patients were placed in the computer-controlled ALV mode and ventilatory and haemodynamic measurements were taken after 30 minutes and at 6-hourly intervals. Pertinent measurements included airway pressures, pressure support levels, mechanical and spontaneous respiratory rates, airway resistance and system compliance indices. Severity of illness, serial arterial blood gas analysis and progress of respiratory function recovery as evidenced by standard weaning criteria were documented.

Measurements and results. In all 6 patients the ALV controller selected an appropriate synchronised pressure support ventilatory pattern within minutes of initiation of the computer-controlled mechanical ventilation. All patients appeared comfortable on the mode of ventilation provided and arterial blood gases remained within the normal range at all times. The patients were ventilated for a mean of 51,6 hours (range 21 - 82 hours). The pressure support was maintained by the ALV controller at a mean level of 14,8 cm H_2O (range 6 - 20 cm H_2O). In some patients who had good ventilatory effort the ALV controller allowed and encouraged spontaneous effort early on, further reducing the level of pressure support. In others the ALV controller did not allow weaning until the target alveolar ventilation was reduced by the investigator. All patients were successfully weaned with a target alveolar ventilation of 45 ml/kg/min. All were successfully extubated and discharged from the RICU after a mean time of 5,6 days (range 5 - 8 days), having recovered from their critical illnesses.

Conclusions. The ALV controller will provide a clinically acceptable, safe and effective form of ventilatory support at the outset of respiratory failure when a target alveolar ventilation of 70 ml/kg/min is selected. It will wean the patient off mechanical ventilation when the disease resolves sufficiently, provided a target alveolar ventilation no greater than 45 ml/kg/min is selected.

S Afr Med J 1995; **85:** 430-433.

Adaptive lung ventilation (ALV) refers to closed-loop mechanical ventilation designed to work in paralysed as well as spontaneously breathing patients, enabling variable ventilatory support as required, breath by breath, in each individual patient.[1,2]

The ALV controller utilises pressure-controlled synchronised intermittent ventilation as its basic ventilatory mode. The attending clinician chooses a target gross alveolar ventilation (V'gA, in ml/kg/min) and the ALV controller partitions the alveolar ventilation into a target volume and a target rate and then adjusts inspired pressure support, mandatory rate and inspired/expired time ratio to achieve the desired V'gA. The adjustments are based on measurements of the patient's lung mechanics and series dead space (Vds), and are designed to achieve minimal work of breathing and avoid intrinsic positive end-expiratory pressure (PEEP). The adjustments occur gradually without significant overshoot. The ALV controller starts with a sequence of 5 test breaths to evaluate the effective compliance, airway resistance, expiratory time constant (RC) and the patient's series dead space (similar to anatomical dead space). The controller then starts to adjust rate and inspired pressure support to meet the prescribed goals using a conventional program interface controller. To optimise the controller performance, the volume controller gain is continuously adapted to the patient's susceptibility to inspiratory pressure (effective lung compliance and resistance). The RC and Vds are also updated breath by breath, but for safety reasons the controller continues to utilise the initial Vds data calculated with the 5 test breaths.

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The ALV controller with its input/output relationships are depicted in Fig. 1. The ALV controller will facilitate weaning from mechanical ventilation because the mandatory rate and inspired pressure support will continue to be reduced if the measured V'gA exceeds the target value, indicating that the patient can sustain adequate independent ventilation.

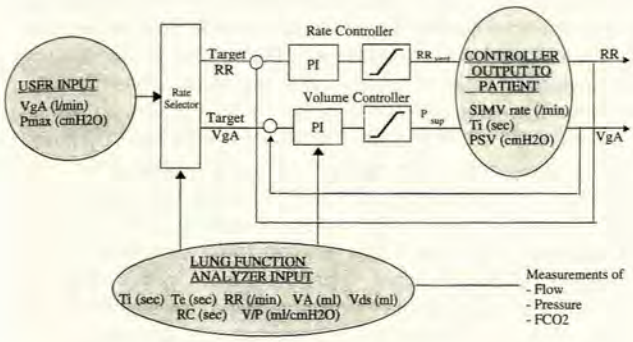

Fig. 1. Diagram of the ALV controller showing the input and output relationships. User input is V'gA (l/min) and Pmax (cm H_2O). Lung function analyser input is Ti (s), Te (s), RR (/min), VA (ml), Vds (ml), RC (s) and V/P ratio (ml/cm H_2O). Controller output is mandatory rate (/min), Ti (s) and Pinsp (cm H_2O). (From *Chest*.[3])

The efficiency of the ALV controller has been demonstrated in lung models, in patients with normal lungs undergoing general anaesthesia, and in patients with pulmonary disease during weaning from mechanical ventilatory support.[1-3] This study was therefore performed to evaluate the ALV controller continuously for the first time in patients with various pathological lung conditions when they were admitted to our multidisciplinary respiratory intensive care unit (RICU). We wished to determine whether the ALV controller would select a clinically acceptable form of mechanical ventilation at the outset of a patient's respiratory failure when a target alveolar ventilation of 70 ml/kg/min was selected, to assess the practical implications of utilising the ALV controller over an extended period of ventilatory support, and, finally, to confirm that the ALV controller would wean the patient from mechanical ventilatory support as soon as the disease resolved sufficiently for weaning at a target V'gA of 70 ml/kg/min or whether this had to be reduced in all cases.

Patients and methods

Six patients in our RICU who required mechanical ventilatory support for respiratory failure due to various causes — blunt chest trauma, pneumonia, acute-on-chronic obstructive pulmonary disease (COPD), adult respiratory distress syndrome (ARDS) or restrictive pulmonary parenchymal disease — were entered into a prospective selected case study to evaluate the ALV controller.

Our institutional ethical research committee approval and informed consent from each patient were obtained before the study commenced. The patients were initially ventilated at a target gross alveolar ventilation (V'gA in l/min) of 70 ml/kg/min.

Recordings of ventilatory and haemodynamic measurements and arterial blood gases were made after 30 minutes and then at 6-hourly intervals. A patient was considered to be weaned and could be extubated if he or she required no more than 5 cm H_2O of pressure support and no more than 4 mechanical ventilatory breaths and met our standard weaning criteria. Weaning was documented as successful if the patient required no further ventilatory support and continued to meet the standard weaning criteria after 24 hours.

A modified computer-controllable Hamilton AMADEUS ventilator, a PC-based lung function analyser and a Macintosh SE computer were used to test the ALV control algorithm. Airway flow, airway pressure and instantaneous CO_2 concentration were measured between the Y-piece and endotracheal tube. For this purpose a Hamilton variable orifice pneumotachograph and a Novametrix 1260 CO_2 analyser were used. All signals were low-pass filtered through a second-order bessel filter with a 3 dB cut-off frequency of 25 Hz. The filtered signals were read into an IBM-PC/AT-compatible microcomputer at a sampling rate of 60 Hz using an AD converter DT2801 (Data Translation Inc., Marlboro, Mass., USA). The signals were corrected for gas viscosity changes and CO_2 analyser delay. An algorithm based on the CO_2 and flow signals detected the start of inspiration and expiration.[5] This allowed for automatic calculation of breath-by-breath lung function indices. Inspiratory time (T_I), expiratory time (T_E) and total respiratory rate (f) were measured. Integration of the flow signal yielded the inspired volume (V_I) and the expired volume (V_E). Tidal volume (V_T) was calculated as the arithmetical mean of both. An estimate of the expiratory time constant (RC) was obtained by dividing V_E by the maximal expiratory flow V_{Emax}. The quotient of V_T and maximal airway pressure (P_{awmax}) minus PEEP, the V/P ratio, was calculated to give a measure of the pressure support needed to obtain a given V_T. It is influenced by lung compliance and the patient's co-operation — the better the compliance and co-operation, the higher the V/P ratio becomes. From the flow and CO_2 signal a CO_2 v. volume curve was constructed to determine the Vds.[5] All breath-by-breath data were sent via an RS 232 link (9 600 baud) to an Apple Macintosh SE computer, which served as the user interface and on which the ALV controller was implemented. A second RS 232 link was used to control the ventilator. Calibration of the sensors was done before each measurement. Arterial blood gases, mechanical and spontaneous respiratory rates (f_{mech}, f_{spont}), V_T, minute volume (V'm), maximum and end-expiratory airway pressure (P_{awmax}, PawEE), vital capacity (VC), an index of airway resistance relative to muscular effort (Rtot), an index for respiratory drive (P0.1), imposed work of breathing (IPD), pressure time product (PE), end-tidal CO_2 and slope of the alveolar plateau (FCO_2-et, slopeCO_2) were measured at baseline.[6-11] We also measured the level of pressure support (ΔPinsp) subsequent to placing the patients on the ALV controller.

Results

The 6 patients studied ranged in age from 38 to 61 years and were admitted to the RICU with respiratory failure for 5 - 8 days (mean 5,6 days). The mean APACHE II score on admission was 10 (range 1 - 16) and the injury severity

scores of 2 patients admitted following trauma were 17 and 29 respectively.

Patient data and primary diagnoses are given in Table I. In all 6 patients the ALV controller selected an appropriate synchronised pressure support ventilatory pattern within minutes of initiation of the computer-controlled mechanical ventilation. All patients appeared comfortable on the mode of ventilation provided and arterial blood gases remained within the normal range at all times. The patients were ventilated for a mean of 51,6 hours (range 21 - 82 hours). The pressure support was maintained by the ALV controller at a mean level of 14,8 cm H_2O (range 6 - 20 cm H_2O). In some patients who had good ventilatory effort the ALV controller allowed and encouraged spontaneous effort early on, further reducing the level of pressure support.

During mechanical ventilation it was notable that individual patients' ventilatory requirements varied considerably from time to time during the day and night in relation to activities such as suctioning, turning, bed washing and sleeping. This variability of spontaneous breathing patterns resulted in adaptation of the ALV controller to the patients' respiratory activity and impedance.

Figs 2 and 3 show the trend of pressure support in 2 patients together with the trends of the mechanical ventilatory breaths supplied and the patients' spontaneous ventilatory breaths.

It was remarkable how comfortable the patients appeared on the ALV controller and how they were adaptively supported during periods of increased requirements due to increased activity and during periods of rest and sleep.

In some patients the ALV controller did not allow weaning until the target alveolar ventilation was reduced by the investigator. All patients were successfully weaned with a target alveolar ventilation of 45 ml/kg/min, and all were successfully extubated and discharged from the RICU, in a mean time of 5,6 days (range 5 - 8 days), having recovered from their critical illnesses.

Discussion

ALV is a revolutionary new method of providing closed-loop controlled ventilation utilising synchronised pressure support ventilation. It enables mixed modes of ventilation while providing immediate responses to spontaneous breathing activity and constant vigilance to patient fatigue.[1-3]

The basic concept of the ALV controller is to maintain a preset gross alveolar ventilation irrespective of the respiratory activities of the patient. If the patient is able to perform more ventilation in relation to the preset value, the ALV controller will gradually reduce pressure support down to a minimum of 5 cm H_2O above PEEP and the mandatory rate to a minimum of 4 breaths per minute. The former is to compensate for the resistance of the endotracheal tube and the imposed work of breathing of the circuit, while the latter is a safety measure to prevent inadvertent periods of apnoea of longer than 15 seconds. The ALV controller will increase or decrease respiratory support in an attempt to guide the patient into a breathing pattern that theoretically requires the least amount of work. The model is based on the work of Otis *et al.*[12] and Mead[13] and requires the measurement of the respiratory time constant. A pertinent input to this model is a measure of dead space incorporating patient size (lung size) rather than the nature of the patient's lung disease. Therefore, series dead space[5] and not, as originally proposed by Otis *et al.*,[12] total respiratory dead space was chosen for the ALV controller algorithm.

The ALV controller *per se* does not initiate or push the weaning process. This is done by the preset V'gA, which is entered by the operator. It is therefore the operator who directs the weaning of the patient, and the correct setting and adjustment of the V'gA must be understood by the operator.

In a previous study, we found that a simple fixed value of 30% of the baseline V'gA turned out to be sufficient for the ALV controller to initiate the final weaning process.[3] It remains unclear how the V'gA needs to be set throughout the time course of mechanical ventilation, from the onset until standard weaning criteria are met. This study suggests that it might be appropriate to set it to 100% of the patient's needs (usually 70 ml/kg/min) until he is ready to be weaned, at which time the target value of 30% of the measured value can be introduced. Although further work is necessary to confirm a strategy of V'gA setting which is appropriate for all patients, it is clear that the target V'gA is a relatively gross setting — 2 of our patients were able to breathe spontaneously from the outset of their mechanical ventilatory support.

Table I. Patient details, primary diagnosis, severity of illness, time on ALV, outcome and mean values of indices of total compliance (Ctot), airway resistance (Rtot) and pressure support (Pinsp)

Patient No.	Age (yrs)	Diagnosis	APACHE II score	Injury severity score	Time on ALV	Time in ICU	Outcome	Ctot (ml/cm H_2O)	Rtot (cm H_2O/l/s)	Pinsp (cm H_2O)
1	60	Post-pleural biopsy and COPD	16	N/A	48 h	5 d	Successful	30,2	21,7	18,2
2	59	Pneumonia and COPD	14	N/A	53 h	5 d	Successful	46,3	13,5	12,7
3	40	Chest trauma with lung contusion	9	17	54 h	8 d	Successful	43,8	14,3	16,4
4	38	Multiple trauma including blunt chest trauma	1	29	21 h	6 d	Successful	88,0	3,1	6,6
5	61	ARDS post-cholecystectomy	10	N/A	52 h	5 d	Successful	41,6	22,5	19,7
6	46	ARDS and renal failure due to septicaemia	10	N/A	82 h	5 d	Successful	58,7	10,5	15,6

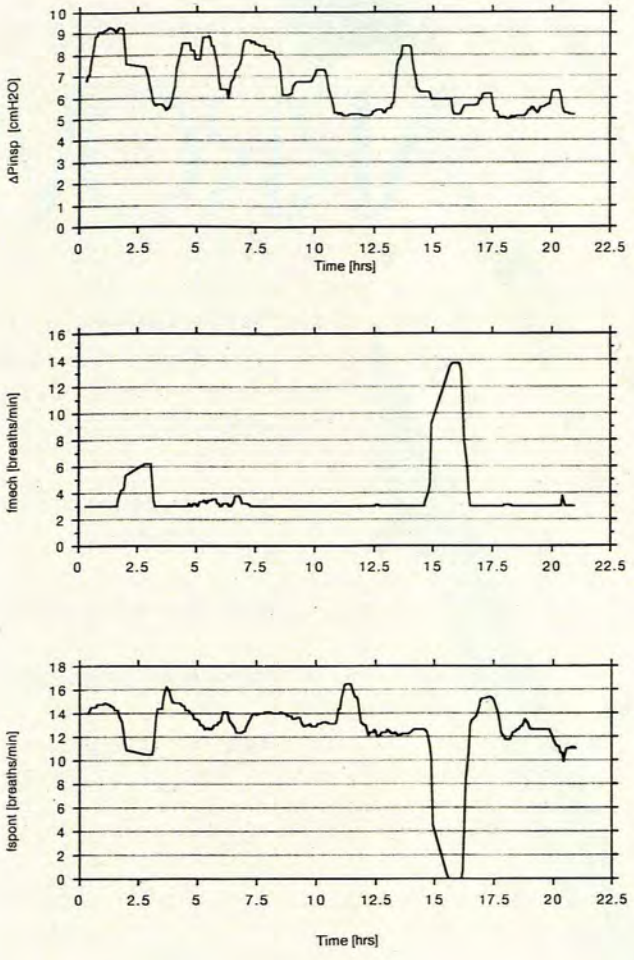

Fig. 2. Trend of level of inspired pressure support in patient 2 together with the trend of the patient's mechanical ventilatory breaths and spontaneous ventilatory breaths.

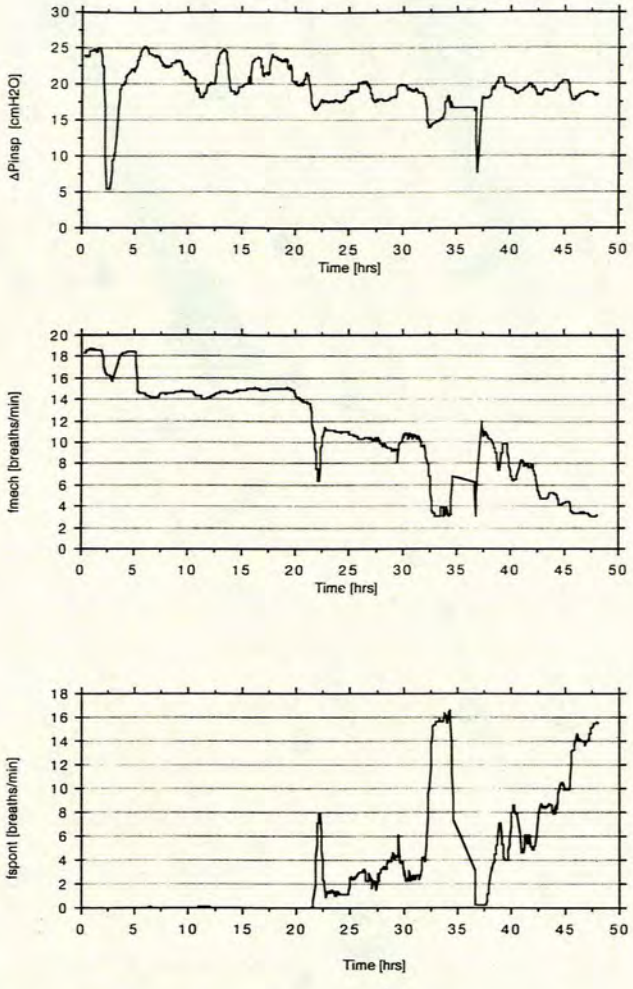

Fig. 3. Trend of level of inspired pressure support in patient 5 together with the trend of the patient's mechanical ventilatory breaths and spontaneous ventilatory breaths.

In summary, this study describes 6 patients who were successfully and appropriately ventilated by and then weaned from an ALV controller. The ALV controller responded adequately and appropriately to increased ventilatory needs by increasing the pressure support level as required, and the patients were safely ventilated by the controller at all times.

The ALV controller has the potential to provide a safe and effective pattern and depth of mechanical ventilation in all forms of lung disease and will continually test the patient's weaning capability while ensuring adequate optimal alveolar ventilation in the most suitable form.

No patient in our study was placed at any risk during their mechanical ventilation and weaning by the ALV controller. Further studies are required to confirm that the target alveolar ventilation setting chosen in this study is appropriate as a setpoint for initial ventilation.

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Accepted 8 Feb 1995.