Intelligent ventilation in the intensive care unit

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Objectives. Automated, microprocessor-controlled, closed-loop mechanical ventilation has been used in our Medical Intensive Care Unit (MICU) at the Hadassah Hebrew-University Medical Center for the past 15 years; for 10 years it has been the primary (preferred) ventilator modality.

Design and setting. We describe our clinical experience with adaptive support ventilation (ASV) over a 6-year period, during which time ASV-enabled ventilators became more readily available and were used as the primary (preferred) ventilators for all patients admitted to the MICU.

Results. During the study period, 1 220 patients were ventilated in the MICU. Most patients (84%) were ventilated with ASV on admission. The median duration of ventilation with ASV was 6 days. The weaning success rate was 81%, and tracheostomy was required in 13%. Sixty-eight patients (6%) with severe hypoxia and high inspiratory pressures were placed on pressure-controlled ventilation, in most cases to satisfy a technical requirement for precise and conservative administration of inhaled nitric oxide. The overall pneumothorax rate was less than 3%, and less than 1% of patients who were ventilated using only ASV developed pneumothorax.

Conclusions. ASV is a safe and acceptable mode of ventilation for complicated medical patients, with a lower than usual ventilation complication rate.

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Adaptive support ventilation (ASV), first described in 1994 by Laubscher and colleagues, is a microprocessor-controlled closed-loop method of intelligent automatic establishment and breath-by-breath adjustment of mechanical ventilation.[1,2] It is based on a combination of ventilation modes including pressure-controlled (PCV) synchronised, pressure-support (PSV) ventilation.[3,4] ASV intelligently allows the patient to initiate weaning and then moves to progressively reduce the pressure support levels until the patient is breathing spontaneously, while continuously monitoring respiratory sufficiency and if necessary again increasing the level of pressure support. ASV intelligently and automatically adapts the respiratory rate and level of ventilatory pressure to the patient's passive and active respiratory mechanics.[5-7] It ensures that the predetermined target minute ventilation, based on ideal body weight and per cent minute volume settings, is delivered to the patient. Using on-line, breath-by-breath analysis of lung function, the ventilator is driven by a programmed computer to provide optimal alveolar ventilation, according to the patient's changing requirements (Fig. 1).[8,9]

The programming is based on a concept of maximal energetic benefit: for any single breath, the ventilator selects the optimal respiratory rate target, and the optimal tidal volume target that corresponds to the minimal work of breathing of the patient-ventilator unit. The automatic selection of these targets is based on algorithms for minimal dead space and optimal expiratory time constant provided by the lung function analyser that is communicating continuously with the ventilator's controller. The lung function analyser calculates compliance, resistance and air trapping (residual end-expiratory flow), to optimise respiratory flow patterns and inspiration/expiration ratio. Target volume and rate are calculated specifically for each patient to achieve the set target minute volume according to the patient's lung mechanics (compliance, resistance, air trapping, dead space and expiratory time constant) and peak airway pressures. At any breath, the controller compares target and actual data for tidal volume and respiratory rate, and programmes the mandatory rate and the inspiratory pressure to be applied in the next breath, to approach the desired targets.[1,10,11]

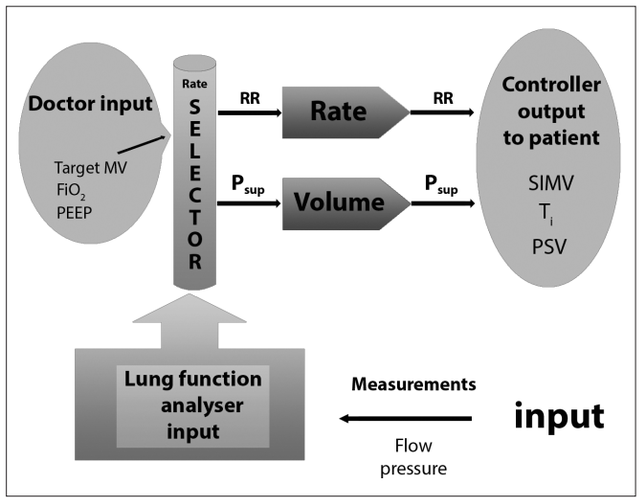

Fig. 1. ASV technology – target minute volume (MV), FiO_2 and PEEP are set and the lung function analyser measures lung mechanics to optimise respiratory flow patterns and inspiration/expiration ratio. Target volume and rate are calculated to achieve the set target minute volume according to the patient's lung mechanics and peak airway pressures. RR = respiratory rate; MV = minute volume; P_{sup} = pressure support level; SIMV = synchronised intermittent mandatory ventilation; T_i = inspiratory time; PSV = pressure support ventilation.

Inspired pressures are delivered using pressure control in apnoeic patients, or pressure support in spontaneously breathing patients.

The use of closed-loop ventilation has previously been advocated for intensive care units.[12,13] Wysocki and Brunner consider ASV an under-used, safe and cost-effective modality. They call for more extensive application of this ventilation mode in intensive care units.[13]

ASV has been in use as the primary mode of ventilation in the Medical Intensive Care Unit (MICU) at the Hadassah-Hebrew University Medical Center for the past 10 years. We describe our experience with this automated ventilation technology using prospective data collected over a 6-year period.

Materials and methods

The 9-bed MICU at the Hadassah-Hebrew University Medical Center, a 750-bed academic tertiary referral centre, admits critical, non-surgical cases with acute respiratory, infectious, neurological, haematological-oncological, renal, metabolic and other general medical problems. Data on all patients ventilated in the unit were collected prospectively during the period 1 April 2003 - 30 November 2009. These data included demographics, chronic diseases, diagnoses, severity of illness scoring, indication for ventilation, ventilation modes, interventions (inotropic support, haemodialysis), need for sedation, complications (respiratory, infectious, etc.), length of ventilation, unit and hospital length of stay, tracheostomy insertion, ventilation outcome and unit and hospital mortality outcomes.

Chronic diseases were defined per organ system as a previously known organ failure requiring ongoing treatment. Diagnoses were grouped into diagnostic categories related to each system; e.g. 'respiratory' included pneumonia, acute respiratory distress syndrome (ARDS), chronic obstructive pulmonary disease (COPD) exacerbation, pulmonary embolism and interstitial lung disease.

Actual ventilator settings were chosen at the attending physicians' discretion, and the primary ventilator mode recommended for all patients was ASV, delivered by either a Galileo or Raphael Model ventilator (Hamilton Medical AG). Initial settings included ideal body weight (IBW), determined using gender and height tables, and minute ventilation as a percentage of the value of 100 ml/kg of IBW/min. This was started at 100% and subsequently reduced according to arterial partial pressure of carbon dioxide ($PaCO_2$) measurements and the patient's spontaneous efforts. The fractional inspired oxygen (FiO_2) was set targeting an arterial partial pressure of oxygen (PaO_2) of 70 mmHg or more. The level of positive end-expiratory pressure (PEEP) was determined using either the inbuilt volume/pressure (V/P) tool indicating the lower inflection point as *minimal* PEEP or the *optimal* PEEP required for adequate oxygenation with FiO_2 less than 0.6 if possible. The upper pressure limit was set according to protective lung strategy guidelines, usually below 35 cmH_20. The ASV controller, according to the ventilator programmer, then automatically modified the delivered ventilator parameters. In occasional cases where a Galileo or Raphael ventilator was not available, patients were connected to other available ventilators (Puritan Bennet 7200, CA) and ventilated in conventional modes (synchronised intermittent mandatory ventilation, pressure control, pressure support).

Cases in which the physician determined that ASV was not being tolerated for any reason were documented, and a different mode of ventilation was employed. As soon as the reason for converting to another mode was no longer relevant, patients were usually placed back on ASV immediately or when weaning from mechanical ventilation was desired. Duration of ventilation and total number of ventilation days in each mode were documented. Patients who were ventilated with ASV for most of their ventilation duration (more than 50% of the time) were also documented.

Weaning was performed preferably using ASV. As the patient's spontaneous efforts and respiratory mechanics (compliance, resistance) improved, the percentage of target minute volume was gradually manually reduced to a minimum of 60%. Patients were switched to PSV if ASV failed to decrease pressure support levels below 14 cmH_20 due to impaired pulmonary mechanics. Pressure support levels were subsequently manually decreased according to patient effort and respiratory pattern. Patients were not routinely given a spontaneous breathing trial, as this is not part of our routine weaning policy. Extubation was performed at the discretion of the attending physician when pressure support levels (applied by the ASV or manually adjusted in PSV) were below 10 cmH_20 and if an adequate cough, conscious level and a patent airway were demonstrated.

Severity of illness was calculated using the Acute Physiology and Chronic Health Evaluation II (APACHE II) score in the first 24 hours of ICU admission. Documented respiratory complications included ventilator-associated pneumonia (VAP), which was defined as the need for antibiotics or an antibiotic change due to a presumed respiratory infection developing in patients ventilated for 48 hours or more.[14] Extubation success was defined as discharge after being weaned from mechanical ventilation. Weaning or extubation

failure was defined as patients discharged from the ICU with an ongoing need for mechanical ventilation.

A waiver for the requirement of informed consent for data collection was obtained from the Institutional Review Board.

Statistical analysis

Data were collected and analysed with the JMP 8.1 (SAS). Normally distributed variables are presented as means and non-normally distributed variables as means and medians. To better define the characteristics of patients who failed ASV, compared with all other ventilated cases, we performed comparative analysis of categorical variables using the Pearson chi-square test. *P*-values of 0.05 or less were considered statistically significant.

Results

During the study period 1 985 patients were admitted to the MICU; 1 220 were ventilated (61.5%). Patient characteristics and outcomes of ventilated cases are summarised in Table 1. Mean length of hospital stay before ICU admission was 8.1 days (standard deviation (SD) ±17; median 2). The mean APACHE II score was 27±10 with a calculated predicted mortality of 57%, most patients having underlying chronic disease. Overall hospital mortality was 45.7%, giving a standardised mortality ratio of 0.8. The most frequent causes of ICU death were sepsis and multi-organ failure.

Table 2 summarises the descriptive data of the application of ventilation in our patient group, including modes of ventilation, timing and indications for ventilation.

Table 3 demonstrates the duration of ventilation in the different ventilation modes. Mean length of ventilation (all modes) was more than 10 days with a median of 6 days. Sedation was required in 812 patients (67%) for a median length of 2 days. Nine hundred and forty-eight patients were ventilated with ASV for more than 50% of the time (93%).

Sixty-eight patients (6%) required transition from ASV mode to pressure control mode. The primary indication for switching from ASV to PCV was to satisfy our technical requirement for a stable tidal volume to allow administration of inhaled nitric oxide (NO), which is delivered through a continuous-flow device precisely and conservatively, to avoid excessive wastage. Patients were placed back on ASV when NO was discontinued and/or when weaning from ventilation was required. On rare occasions, patient-ventilator asynchrony (usually rapid shallow breathing); precipitated a change to more heavy sedation, and more rarely muscle relaxation and PCV was introduced to achieve the desired controlled minute ventilation.

Comparison of this patient group, who required a mode of ventilation other than ASV, with all other ventilated patients showed that 47% v. 35% (p=0.05) had sepsis or septic shock, 41% v. 35% had pneumonia (p=0.3), 28% v. 5% (p<0.0001) were diagnosed with ARDS, and 16% v. 2% (p<0.0001) had interstitial fibrosis. The mean APACHE II score in this group was 31.3, with an ICU mortality of 79% and hospital mortality of 87%. Fifteen (22%) developed pneumothorax compared with 2% in other ventilated cases (p<0.001). Patients who do not tolerate ASV therefore represent a group of sicker patients with a higher rate of ARDS and interstitial fibrosis and a poorer prognosis.

Table 1. Patient profiles and outcomes

Ventilated patients (*N*=1 220)	
Age (years), mean (SD)	63.1 (18.8)
Gender	60% male, 40% female
Source of admission, *n* (%)	
Emergency room	382 (32)
Ward	652 (53)
Other ICU	75 (6)
Other hospital	109 (9)
Chronic disease profile, *n* (%)	
Respiratory disease	410 (34)
Cardiac disease	470 (39)
Renal failure	283 (23)
Liver failure	125 (10)
Diagnostic categories, *n* (%)	
Respiratory	663 (54)
Infectious	480 (39)
Cardiac	234 (19)
Renal	238 (20)
GI and hepatic	137 (11)
Neurological	176 (14)
Haematological	96 (8)
Metabolic	47 (4)
Other	174 (14)
APACHE II score, mean (SD)	27 (10)
Predicted mortality (%)	57 (28)
GCS (median)	9
Outcomes	
Length of ICU stay (days), mean (SD)	12.8 (13.5), median 9
Total length of hospital stay (days), mean (SD)	30.4 (30.2), median 21
Died in ICU, *n* (%)	406 (33.3)
Died in hospital, *n* (%)	558 (45.7)
Cause of death in ICU (*N*=406), *n* (%)	
Sepsis and MOF	288 (71)
Respiratory	38 (9)
Cardiac	32 (8)
Anoxic brain damage	18 (4)

GI = gastrointestinal; APACHE = Acute Physiological and Chronic Health Evaluation; GCS = Glasgow Coma Scale; MOF = multi-organ failure.

Ninety-two patients (7.5%) were ventilated for more than 28 days (mean 42.8±15 days). Thirty-nine per cent in this group were admitted with pneumonia and 9% with chronic obstructive pulmonary disease (COPD). Twelve of these patients (13%) were chronically ventilated before admission, 68 (74%) required insertion of a tracheostomy in the ICU, and 55 (58%) were discharged ventilated from the ICU.

Complications and ventilation outcomes are summarised in Table 4. Respiratory complications included VAP in 288 patients (23.6%),

giving an incidence of 23.1/1 000 ventilated days. Pneumothorax developed in a total of 42 patients (3% of all ventilated patients), of whom only 10 were ventilated with ASV at the time (less than 1% of all patients ventilated with ASV). Twenty-three per cent of patients developed sepsis in the ICU, 55% required inotropic support, and 19% needed haemodialysis.

Weaning from mechanical ventilation was mostly (86%) performed with ASV. In 54 cases (4%), pressure support mode was used after ASV had failed to wean completely. The rate of extubation success for all patients was 81%, and that for patients weaned with pressure support mode was 54%. Tracheostomy was required in 159 (13%) of all ventilated patients (Table 4). Seventy-seven patients were admitted to the MICU chronically ventilated with a tracheostomy in place. Indications for tracheostomy in the ICU included facilitation of chronic ventilation (57%), as part of the weaning process (28%), and for upper airway problems (4%).

Table 2. Descriptive data of ventilation

Time of ventilation (*N*=1 220), *n* (%)	
At admission	931 (76)
After admission	289 (24)
Primary indication for ventilation (*N*=784), *n* (%)	
Respiratory failure	474 (60.5)
Shock	111 (14)
CPR	48 (6)
Neurological	100 (13)
Procedure	11 (1.5)
Chronic	14 (2)
Other	26 (3)
Modes of ventilation (*N*=1 214), *n* (%)	
ASV	1 016 (84)
SIMV	258 (21)
Pressure control	152 (13)
Assist control	34 (3)
Pressure support	141 (12)

CPR = cardiopulmonary resuscitation; ASV = adaptive support ventilation; SIMV = synchronised intermittent mandatory ventilation.

Two hundred and thirty-five patients (19%) were discharged ventilated from the ICU to the general ward or to a chronic ventilation care facility (Table 4), of whom 42 had been admitted to the MICU with a tracheostomy in place. The mean duration of ventilation in this patient group was 18.7±17.5 days, with a median of 14 days.

Discussion

We have described our experience with intelligent ASV as the preferred mode of ventilatation in the MICU. This is the first such report of a large group of complex medical patients ventilated with ASV for relatively long periods of time. The mean age of our patient population was 63.1 years and the mean APACHE II score was 27, suggesting relatively high severity of illness. The APACHE II score might have been affected by the patients' age and a median Glasgow Coma Score (GCS) of 9, attributed to impaired neurological status and/or sedation. Our complication rates were low, and weaning rates were acceptable for this complicated patient group. Most previous reports examined smaller groups of patients, mostly surgical, who needed ventilation for much shorter periods of time.[15-17]

ASV requires that an adequate and optimal target minute volume is set according to the ideal body weight.[17] Calculations of dead space, peak inspiratory pressures and respiratory function such as compliance, resistance and expiratory time constant are measured, so that optimal target volumes and rates are provided.[18-19] Target volumes are provided by increasing inspiratory pressures as necessary, and these are decreased as patient respiratory function and effort improve.[20] Few manipulations of the ventilator are therefore required,[21] and the automated controller provides rapid adaptation to changing ventilator needs of ventilated patients.[8,22] Our unit does not employ respiratory therapists trained in setting ventilators. Such changes are therefore left to the ICU medical staff, who are not always available to respond quickly to changing ventilation requirements. The ASV mode therefore reduces the need for manipulation of the ventilator settings, as it adjusts automatically to altered lung mechanics and patient effort, compensating for reduced staffing levels.

Previous studies have tested the efficiency, safety and adaptability of ASV in various lung diseases, in patients undergoing general anaesthesia, and during position changes and transition between two- and one-lung ventilation.[11,23,24] Tassaux and colleagues demonstrated improvement in patient-ventilator interaction and reduction in signs of asynchrony with ASV compared with synchronised intermittent mandatory ventilation (SIMV) and

Table 3. Length of ventilation (days)

Mode	Total ventilation	Median	Mean (SD)
All modes (*N*=1 217)*	12 467	6	10.2 (12)
ASV (*n*=1 212)	9 220	6	9.1 (10.5)
SIMV (*n*=176)	965	3	5.5 (5.9)
Pressure control (*n*=124)	628	3	5.1 (6.2)
Pressure support (*n*=131)	662	3	5.05 (6.1)
Relative ventilation days with ASV	9 220/12 467 (74%)		

*Data missing for 3 patients.

ASV = adaptive support ventilation; SIMV = synchronised intermittent mandatory ventilation.

Table 4. Complications and ventilation outcomes

Complications, *n* (%)	
Pneumothorax – all causes (*N*=42)	42 (3)
Ventilation with ASV	10 (24)
Ventilation with other modes	16 (38)
Central line	6 (14)
Intubation and procedures	10 (24)
Ventilator-associated pneumonia*	288 (24)
Sepsis in the ICU	284 (23)
Ventilation outcomes, *n* (%)	
Tracheostomy in the ICU	159 (13)
Chronic ventilation with tracheostomy	77 (6)
Failed extubation†	97/784 (12)
Ventilated on discharge	235/1 220 (19)

Data available for 784/1 220 patients.

*Defined as the need for antibiotics or an antibiotic change due to a presumed respiratory infection developing in patients ventilated for 48 hours or more.

†Extubation requiring re-intubation within 48 hours, including self-extubation.

pressure-support ventilation (PS) in patients during early weaning with partial ventilator support.[6] In their study reporting the use of ASV as the primary mode of ventilation in a mixed ICU (322 patients), Arnal and colleagues found that ASV was used in 98% of invasive ventilation days, and appropriately selected different rate/volume combinations for patients with different types of underlying lung disease, including ARDS and COPD.[25]

ASV has been shown to hasten weaning from ventilation compared with other modes.[26] It can appropriately decrease ventilator support in patients with chronic respiratory failure who tolerated a conventional weaning trial, suggesting that this mode may facilitate respiratory weaning.[20] ASV is practical as a respiratory weaning protocol in post-surgical patients, and it may accelerate tracheal extubation and simplify ventilatory management in patients after cardiac surgery.[21,27] It has also been shown to be a safe weaning modality, as patient demands are adequately met during weaning from ventilation.[20,28] In our patient population, which included complicated medical patients with chronic diseases, 6% of whom were chronically ventilated before admission to the ICU, our weaning failure rate (patients discharged ventilated form the ICU) was 19%. This may be viewed as high, but it must be stressed that usual practice in Israel does not include 'terminal weaning' and withdrawal of ventilation, so patients who are ventilator dependent usually undergo tracheostomy and remain fully or partially ventilated indefinitely. In our experience, ASV is highly suitable for patients with COPD and for weaning most patients from ventilatory support. There was only minimal need to convert any patient from ASV to other modalities during the weaning phase, with only partial success. Changes to modes other than ASV were only required in a small percentage of patients.

ASV has been shown to be safe in a model of ARDS, by limiting peak pressures and reducing tidal volumes.[29] We found that most patients in our database with ARDS tolerated ASV well throughout the required ventilation of their lung disease. However, a minority of patients (6%) required transition to PCV, due to patient-ventilator asynchrony, severe hypoxia necessitating inhaled NO or a desire by the attending clinicians to provide more inverse ratio ventilation than the ASV controller allowed. This patient group was sicker and required a more sophisticated ventilation approach, such as the administration of muscle relaxants, deeper sedation, induced hypothermia and inhaled NO. Other potential problems with ASV include that fact that ASV guarantees a minimum preset minute volume but not a constant tidal volume. However, we found that when targeting optimal ideal body weight and thus target tidal volumes, ASV will provide adequate pressures to achieve these volumes optimally.

Our overall pneumothorax rate was 3%, which is comparable to that reported in the literature.[30] Less than 1% of patients who were ventilated using only ASV developed pneumothorax. Most patients who developed a pneumothorax were either ventilated with other modes or the pneumothorax was related to procedures and central line insertion (Table 4). A subgroup of patients with severe respiratory dysfunction and hypoxaemia, requiring PCV, had a higher rate of pneumothorax compared with other ventilated patients (22% v. 2%, $p<0.001$). Although this may represent selection bias, it raises the need for comparative studies looking at the safety of PCV versus closed-loop ventilation in such high-risk patients.

ASV has been the sole mode of ventilation in some chronic care facilities in Israel for several years[31] and has been shown to be cost-effective, safe and efficient in ventilating and weaning patients with chronic respiratory failure.

Limitations to our study include the fact that we chose not to randomise patients to different modes of ventilation, but rather to describe our experience with the ASV modality of ventilation as the preferred mode in our ICU. Although we found that some patients required change to a different mode of ventilation, mostly those with difficult oxygenation and more severe disease, we did not randomise these patients to receive ASV or another mode. Our data suggest, however, that further studies are required to assess the precise limitations of ASV in patients with severe pulmonary restriction and hypoxia who require more inverse ratio ventilation and a stable tidal volume to facilitate NO inhalation. We also did not use a weaning protocol, which might have standardised our practices with different ventilation modes. ASV, however, automatically weans most patients and therefore requires less manipulation of the ventilator during the weaning process. The diagnosis of VAP was defined as the need for antibiotics or an antibiotic change due to a presumed respiratory infection developing in patients ventilated for 48 hours or more. This definition may cause an over-estimation of the actual VAP rate, as it may include patients with a false-positive diagnosis of VAP. Our patient population consists of complicated medical patients. The implications of our findings to surgical patients may require further research.

The recent introduction of automatic FiO_2 and PEEP adjustment to the ASV design, which uses feedback from on-line monitored SaO_2 and end-tidal CO_2 as well as heart-lung interaction parameters, will in theory greatly enhance the intelligent ventilation capability of these microprocessor-controlled ventilators.[32] We are currently studying this advanced S1 version of IntelliVent (Hamilton Medical AG) in our MICU during the mechanical ventilation of patients with critical ARDS who also require NO administration. Our initial

experience with this has been most positive, avoiding the need for any mode changes to the fully automated closed-loop system.

Conclusions

ASV is an acceptable mode of ventilation for complicated medical patients in the MICU, with a good weaning success rate and low complication rate. In critical ARDS and other forms of severe restrictive lung disease, e.g. pneumonitis, interstitial fibrosis and chest stiffness, the temporary use of PCV is preferred to the basic ASV mode in more heavily sedated and paralysed patients when inhaled NO is used, to optimise patient-ventilator synchrony and oxygenation.

In the future, use of the IntelliVent may avoid this need to change from ASV to PCV in critical ARDS patients.

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Conflict of interest. Drs S Sviri, A Bayya, P D Levin, R Khalaila and D M Linton have no conflicts of interest in this study. Mrs I Stav was paid from the internal unit funds for preparation of the database.

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