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Advanced Modes of Mechanical Ventilation

Carmen Silvia Valente Barbas and Sergio Nogueira Nemer

Abstract

Advanced modes of mechanical ventilation emerged from the need for better control of the ventilator by the patient, the possibility of respiratory mechanics and respiratory drive monitoring in assisted modes and a better patient-ventilator synchrony. Volume-assured pressure support ventilation (VAPSV) has the advantage of the variable of flow pressure support ventilation (PSV) assuring tidal volume in each respiratory cycle. Proportional assist ventilation plus (PAV+) delivers assistance in proportion of inspiratory efforts while monitoring work of breathing, respiratory compliance, resistance and auto-PEEP, improving patient-ventilator asynchrony. Neurally adjusted ventilatory assist ventilation (NAVA) provides diaphragmatic electroactivity information and a better inspiratory and expiratory patient-ventilator synchrony. Adaptative support ventilation (ASV) assures a pre-set minute ventilation adjusting Pressure Support according to respiratory rate. Intellivent-ASV adds SpO₂ and PETCO₂ monitoring to adjust minute ventilation and PEEP/FIO₂ according to lung pathology. Smart-Care ventilation provides an algorithm that decreases PSV according to patients tidal volume, respiratory rate and ETCO₂ according to lung pathology and performs a spontaneous breathing trial indicating the readiness for extubation. Clinical indications of advanced modes are to improve patient-ventilator synchrony and provide better respiratory monitoring in the assisted modes of mechanical ventilation.

Keywords: new modes of mechanical ventilation, VAPSV, PAV+, NAVA, ASV, Smart Care®

1. Introduction

When patients with acute respiratory failure recovery from the respiratory insufficiency, they are transitioned to assisted modes of ventilation to start the weaning process. The most common assisted modes are volume assisted ventilation in which the ventilator delivers the same tidal volume during every inspiration, and Pressure support ventilation (PSV) in which the ventilator delivers the same delta pressure assistance during every inspiration. The fixed deliver tidal volume or pressure assistance are the main reason for the occurrence of patient-ventilator asynchrony in these modes of ventilation. In PSV, the inspiratory flow is variable resulting in less asynchrony than in volume assisted ventilation, however asynchrony can still be present in cases of patients with obstructive lung disease and ineffective efforts or under assistance with insufficient tidal volume, can also occur especially in patients with low respiratory system compliance or high respiratory resistance. In these cases, the patients' tidal volume cannot be guaranteed and the patient can generate a huge inspiratory effort that is often under detected. During PSV, the same assistance is independent of the

patient's demand, allowing under or over-assistance and the occurrence of patient-ventilator asynchrony [1]. The advanced modes of mechanical ventilation emerged from the need of greater control of the ventilator by the patient, the possibility of better synchrony and monitoring of the respiratory mechanics during the assisted modes of mechanical ventilation [1].

2. Volume assured pressure support ventilation

Volume assured pressure support ventilation (VAPSV) is a dual mode of mechanical ventilation that associates pressure support ventilation to volume assisted ventilation. This combination optimizes the inspiratory flow, decreasing the patient's work of breathing while assuring the set tidal volume. Compared to volume assisted ventilation, VAPSV can decrease the patient's respiratory drive (a lower measure P0.1), the pressure -time product and the patient's work of breathing. This advanced mode of ventilation extends the benefits of PSV to unstable patients with acute respiratory failure, assuring a pre-set tidal volume (Figure 1) [1].

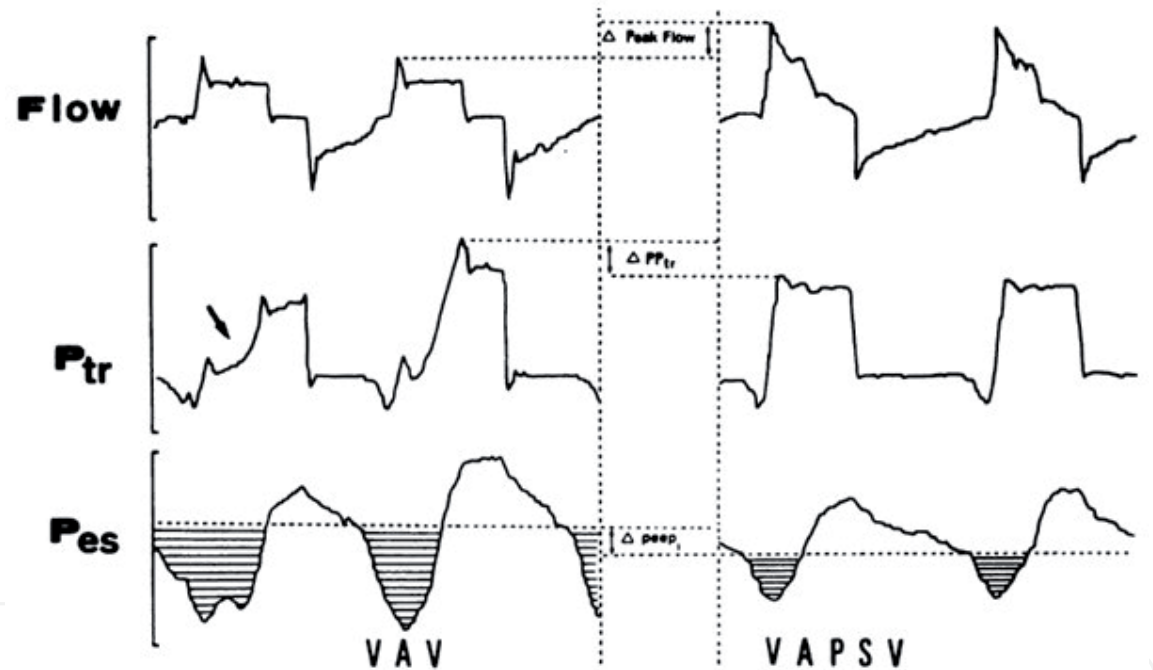


Figure 1. Volume assisted ventilation (VAV) compared to volume assured pressure support ventilation (VAPSV): note the decrease of the esophageal pressure and the better inspiratory flow synchrony during VAPSV [1].

3. Proportional assist ventilation (PAV)

Proportional modes deliver assistance in proportion to the patient's demand, allowing variation of inspiratory pressure and avoiding diaphragm excessive loading and atrophy by disuse. Proportional assist ventilation (PAV) is a form of synchronized ventilator support in which the ventilator generates pressure in proportion to the instantaneous patient effort, or in proportion to flow and volume generated by the same [2–4]. Therefore, the ventilator allows at any time during inspiration, airway pressure in proportion to the pressure generated by inspiratory muscles (Pmus) and respiratory mechanics [4].

Initially described by Magdy Younes in 1992, PAV amplifies inspiratory efforts with the goal of the patient comfortably attain whatever ventilation and breathing pattern that the control system desires [2].

There is no target tidal volume, mandatory rate and airway pressure preset [5]. The ventilator is able to automatically adapt to changes in ventilatory demand of the patient. The pressure delivered by the ventilator follows the P_{mus} profile, usually with a progressive increase from the beginning of inspiration, with gradual pressurization, to the end of inspiration [4]. Maximal assistance is achieved until the end of inspiration [4].

Unlike PSV, in which a constant preset level of pressure assists each inspiration, regardless of the patient's inspiratory effort, PAV allows assistance proportional to the patient's demand, avoiding under-assistance or over-assistance [4], frequently observed during PSV. Under-assistance can induce respiratory distress and over-assistance can cause overdistension, and both may generate patient-ventilator asynchrony, that are associated with poor outcomes [5].

Therefore, PAV is designated for patients with stable respiratory drive, and can be used in any patient who is being ventilated under pressure support ventilation (PSV) or during weaning from mechanical ventilation [2, 6]. PAV is also designated to improve synchronism, while generating proportional assistance [2, 6].

3.1 How PAV works

PAV plus (PAV+) or Proportional Pressure Support (PPS) represent an upgrade to PAV [4] and are the clinically available versions of PAV.

During assisted ventilation, both the patient and ventilator contribute to the pressure required to overcome the elastic and resistive load during tidal breathing, according to the equation of motion [6]:

$$P_{\text{mus}} + P_{\text{vent}} = V' \times R + V \times E + P_{\text{EE}} \quad (1)$$

where P_{mus} is the pressure generated by respiratory muscles, P_{vent} is the pressure provided by the ventilator, V' is the instantaneous flow, V is the volume, R and E are the resistance and elastance of the respiratory system respectively, and finally, P_{EE}, is the elastic recoil pressure at end-expiration [7].

During PAV+, the ventilator software calculates elastance or compliance of the respiratory system and airway resistance using a brief end-inspiratory occlusion performed randomly every four to ten breaths [7, 8]. During each end-inspiratory occlusion, a 300 ms pause allows the ventilator to measure compliance (C_{rs}) or elastance of the respiratory system (E_{rs}) [9] and airway resistance (R_{aw}). Based on inspiratory effort and respiratory mechanics, the ventilator adjusts inspiratory pressure, according to the equation of motion. As patient demand changes, PAV can also change proportionally inspiratory pressure above positive end-expiratory pressure (PEEP) level.

During Proportional Pressure Support (PPS), a combination of two parameters, generate inspiratory pressure: flow assist (FA) and volume assist (VA).

Airway occlusion pressure (P_{0.1}) can be monitored during PPS and PAV+, but the work of breathing (WOB) cannot be monitored during PPS.

The transition from inspiration to expiration, or the cycling off criteria occurs when inspiratory flow decreases to a pre-set level between 1 to 10 liters per minute. Cycling of criteria in PAV+ should be adjusted around 10 liters per minute in

obstructive patients, while around 1 liter per minute in restrictive and around 3–5 liters per minute in those without respiratory abnormalities.

If apnea occurs, the apnea ventilation is automatically activated as in other spontaneous modes.

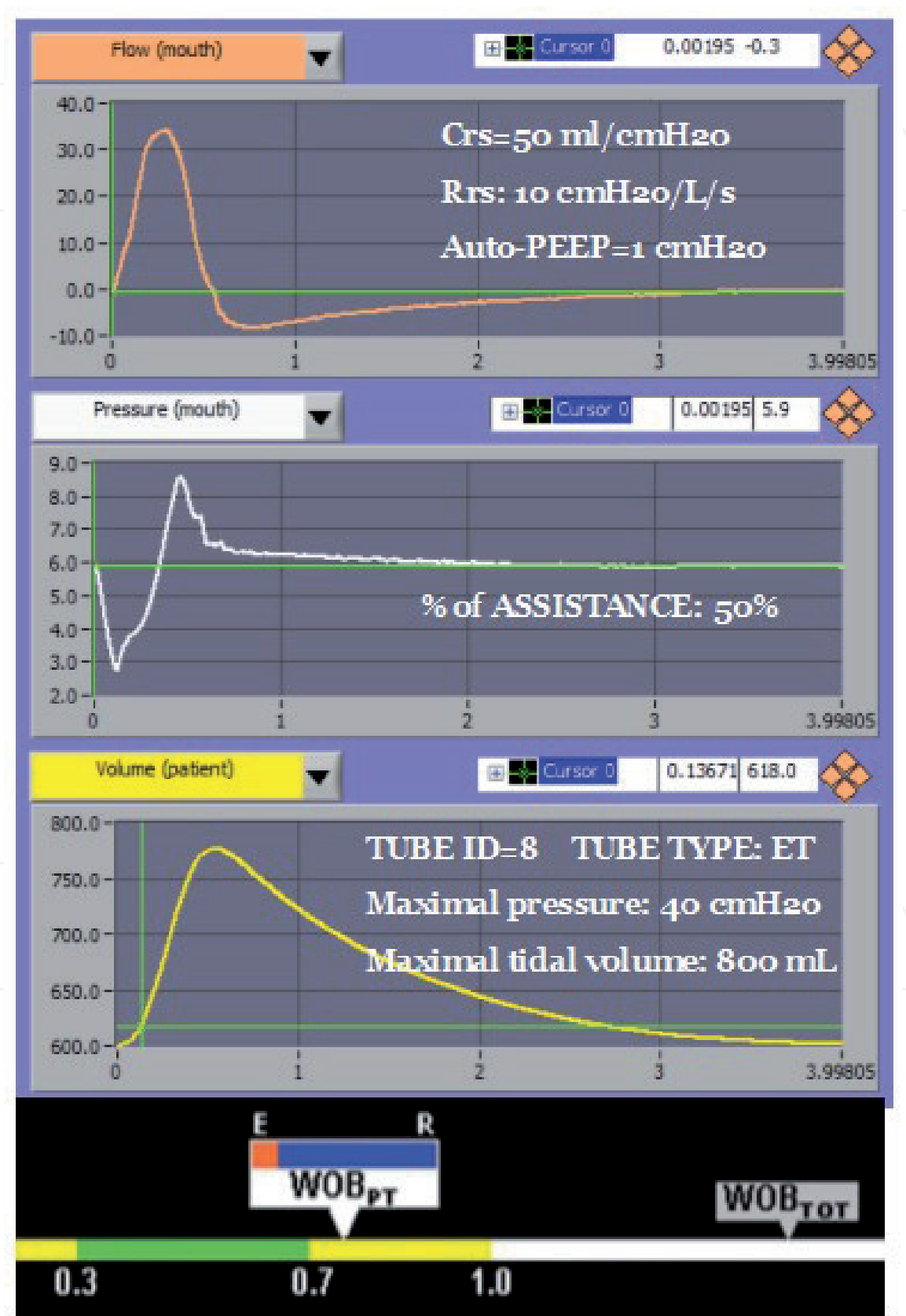


Figure 2. PAV+ adjustments in clinical practice: parameters to set: % of assistance, tube ID, tube type, maximal pressure, maximal spontaneous tidal volume. Monitored parameters: compliance, resistance, auto-PEEP, work of breathing (J/liters). (Obtained from a simulator of the authors laboratory).

3.2 How to adjust parameters in PAV

In PAV+, the percentage support can be adjusted between 5 to 95%, usually between 10 and 20 to 70–80%. When percentage support is 50%, ventilator amplifies P_{mus} by two times, while when in 90%, P_{mus} is amplified by ten times. When the percentage support is set, patient and ventilator are sharing WOB, as defined by the operator. If the percentage support is 60%, the patient will be responsible by 40% of total WOB. The percentage support can be adjusted according to WOB, that can be kept between 0.3 to 0.7 joules/liter. However, WOB is considered normal between 0.2 to 1.0 J/L [10], and eventually, if others criteria are normal, like respiratory rate and $P_{0.1}$, percentage support not necessarily should be changed in case of WOB between 0.7 to 1.0 J/L (**Figure 2**). As the patient improves the percentage support is decreased to 20–30%; if the tidal volume remains 5–6 ml/kg/predicted body weight, respiratory rate less than 28, FiO_2 less than 40%, PEEP less than 10 cmH₂O and WOB less than 1.0 J/L, the patient can be extubated.

During Proportional Pressure Support (PPS), initially, the flow assistance (FA) should be set around 80% of airway resistance and volume assistance (VA), around 80% of elastance of the respiratory system, and then, changed according to the respective variations in these criteria. As higher FA and VA values, highest will be airway pressure and probably, tidal volume. PEEP and fraction of inspired oxygen (FiO_2) should preferably be set in less than or equal to 10 cmH₂O and 50% respectively.

3.3 Limitations, advantages and current evidences of PAV

PAV can also be used during noninvasive ventilation (NIV). As PAV requires clinical estimation of resistance and elastance, and measurements of these criteria with short end-inspiratory occlusions cannot be accurately performed in presence of leaks, it can, however, be of limited reliability [5]. Therefore, PAV as NIV did not present any evidence for daily routine.

Synchronism, proportional assistance and WOB monitoring seem to be the main advantages of PAV as well as to improve the patient-ventilator synchrony. Several studies and reviews evaluated PAV in comparison to PSV [7, 11–14] showing results favorable to PAV regarding synchronism, weaning success, sleep quality, duration of mechanical ventilation, lung and diaphragm protection and lower proportion of patients requiring reintubation [7, 11–14]. Although mortality seems to be generally favorable with PAV [11], this hypothesis has not been confirmed and more studies are necessary for this issue. One systematic review and meta-analysis that evaluated 14 randomized controlled studies, involving 931 patients [15] showed no difference on intubation risk (as noninvasive PAV), weaning time, hospital mortality, reintubation, or tracheostomy.

4. Neurally adjusted ventilatory assist (NAVA)

Neurally adjusted ventilatory assist (NAVA) is a mode of mechanical ventilation delivering pressure in response to the patient's respiratory drive, measured by the electrical activity of the diaphragm (EAdi) [16–18]. Initially described in 1999, by Christer Sinderby et al. [16], NAVA introduced a new dimension to mechanical ventilation, in which the patient's respiratory center can assume full control of the magnitude and timing of the mechanical support provided, regardless of changes in respiratory drive. This technology helps to decrease the risk of hyperinflation, respiratory alkalosis and hemodynamic impairment [16].

NAVA captures the EAdi, and uses it to assist the patient's breathing in synchrony with, and in proportion to respiratory drive [17–19]. Normal EAdi generally ranges between a few and 10 μV , while patients with chronic respiratory insufficiency may demonstrate signals 5–7 times stronger [17]. Although there is no cutoff for weaning outcome, EAdi above 26 μV can be related to failure [20].

Like PAV, there are no target tidal volume, mandatory rate and airway pressure preset. Ventilator support is proportional to a combination of EAdi, and NAVA level, which defines the magnitude of pressure delivered for a given EAdi [18]. NAVA depends of the captured signal of EAdi via sensing electrodes on a nasogastric tube [17] so, in case of damage on phrenic nerve or alterations on its activity, NAVA cannot be used.

Therefore, NAVA, like PAV, is also designated for patients with stable respiratory drive, and can be used in patients who are ventilated on PSV (as long as EAdi is detected), or during weaning from mechanical ventilation. NAVA is also designated to improve synchronism, while generating proportional assistance to EAdi.

4.1 How NAVA works

A specialized nasogastric feeding catheter with electrodes should be inserted until the electrical activity of the crural diaphragm is observed [17, 21]. Correct positioning of the catheter is checked using the transesophageal electrocardiographies signal recorded by the electrodes as a guide [4], observed on the screen of the ventilator at second and third tracings. The absence of detectable EAdi is a contraindication of NAVA [17].

Ventilator support begins when EAdi starts [18]. As EAdi increases, assistance increases proportionally, and pressure delivered is cycled-off when EAdi is ended by the respiratory center (**Figure 3**) [17]. Application of a respiratory load, agitation, pain, respiratory distress or other causes that increase respiratory drive, can result in an increased EAdi, while over assistance should reduce EAdi [17].

NAVA trigger is not pneumatic as other ventilatory modes, but utilizes EAdi, a reflection of neural respiratory output to the diaphragm, as its primary source to trigger [17]. Pneumatic trigger is available, but electrical trigger of NAVA allows faster response to inspiratory effort than traditional pneumatic trigger.

When NAVA level is changed, the resulting pressure depends on how respiratory afferents modulate neural output to diaphragm [18]. If the response to an increase in NAVA level is not a reduction in EAdi, delivered pressure increases [17, 18]. In the presence of high inspiratory efforts (inspiratory pressures higher than 7 cmH_2O), when EAdi is at its highest, pressure delivered could reach extreme levels and may cause lung injury [18]. In this situation, NAVA and other spontaneous modes should be avoided.

Inspiratory pressure above PEEP level is adjusted automatically multiplying the EAdi by a proportionality factor, called NAVA level, expressed as $\text{cmH}_2\text{O}/\mu\text{V}$ [17, 22].

$$\text{Inspiratory pressure (above PEEP)} = \text{EAdi} \times \text{NAVA level} \quad (2)$$

$$\text{Peak pressure} = \text{EAdi} \times \text{NAVA level} + \text{PEEP} \quad (3)$$

For example: a NAVA level of 1 $\text{cmH}_2\text{O}/\mu\text{V}$ will give an inspiratory pressure (above PEEP level) of 7 cmH_2O when EAdi is 7 μV . Increasing NAVA level to 2 $\text{cmH}_2\text{O}/\mu\text{V}$ with the same EAdi will give an inspiratory pressure of 14 cmH_2O .

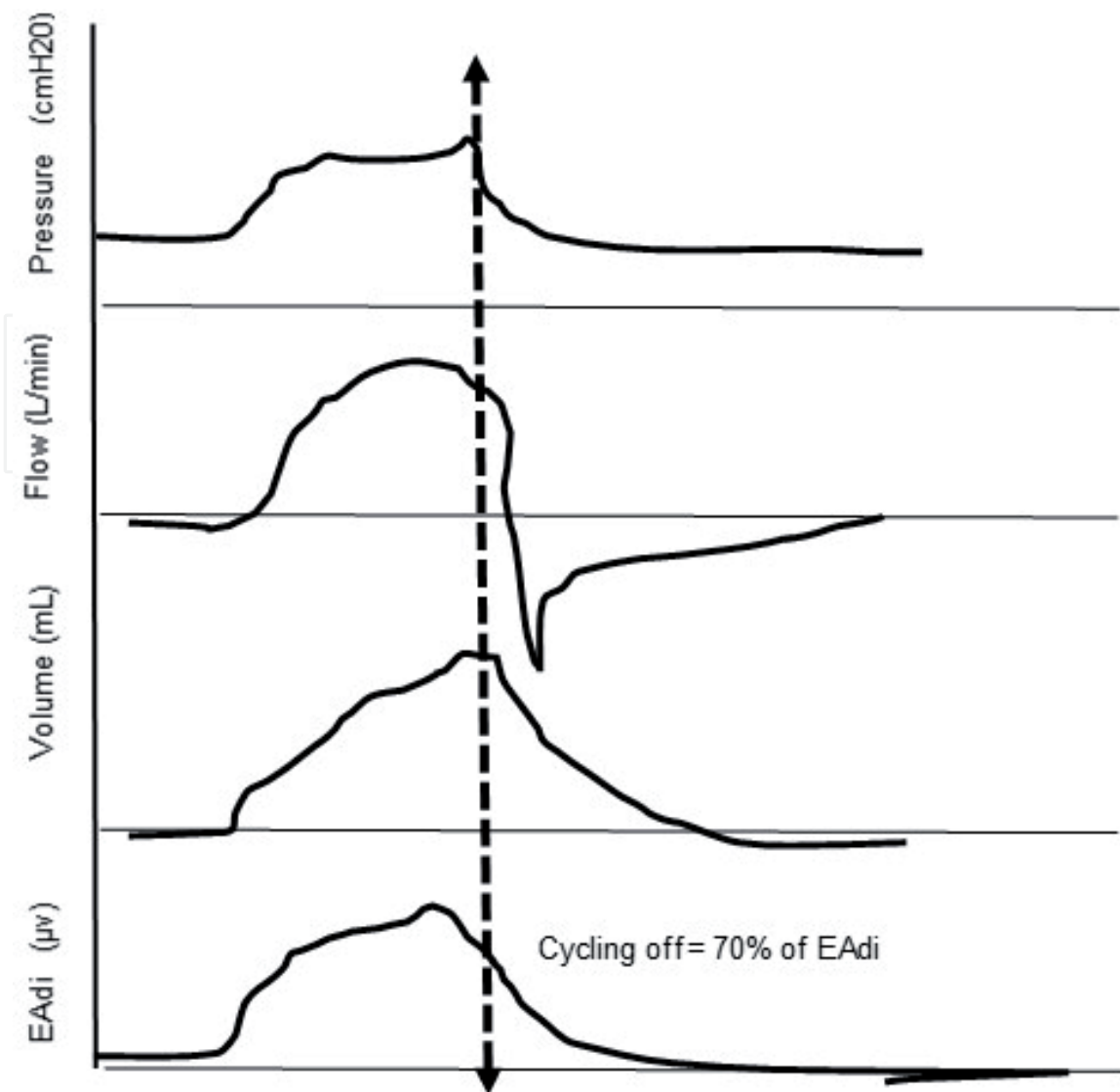


Figure 3.
 NAVA curves in the clinical practice: pressure, flow, volume & EAdi (drawn by the author Carmen Barbas).

The transition from inspiration to expiration, or the cycling off criteria occurs when EAdi decreases automatically to 70–40% of the peak inspiratory flow value observed at the same breath, and cannot be modified by the operator [4, 17]. If apnea occurs, the apnea ventilation is automatically activated as in other spontaneous modes.

4.2 How to adjust parameters in NAVA

During NAVA, minimal and maximum EAdi are monitored constantly. The NAVA trigger detects increases in EAdi and should be set to a level where random variation in the background noise does exceed the trigger level. The neural inspiratory trigger default of 0.5 μV , or 0.5 μV above the minimal EAdi is adequate in most cases [4]. Auto-triggering is possible due to a too sensitive trigger setting and /or leak. In case of auto-triggering, neural inspiratory trigger can be slightly increased, until this asynchrony disappears.

Frequently, NAVA level is used between 0.5 to 2.0 $\mu\text{V}/\text{cmH}_2\text{O}$ [4, 19]. Initial value can be around 1.0 $\mu\text{V}/\text{cmH}_2\text{O}$ in most cases. There is no consensus as to best approach and no definitive recommendations are available how to set NAVA level.” [4, 22]. Even so, some proposals deserve to be highlighted:

1. Pressure support that obtains 6 to 8 ml/kg predicted body weight during PSV, on ventilator function “NAVA preview” estimates the NAVA level that would achieve the same peak inspiratory pressure [4, 22].
2. To use NAVA level that generates 60 to 75% of maximal EAdi, observed during minimal inspiratory pressure of 3 to 7 cmH₂O [22].
3. To use the minimal NAVA level associated with the absence of respiratory distress [4].

When inspiratory pressure reaches around 5 cmH₂O, either by decreasing EAdi or decreasing NAVA level, weaning should be considered. PEEP and fraction of inspired oxygen (FiO₂) should preferably be set in less than or equal to 10 cmH₂O and 50% respectively.

4.3 Limitations, advantages and current evidence of NAVA

A limitation of NAVA mode is that it requires a specialized nasogastric feeding catheter with electrodes located in the esophagus for its functioning which adds additional costs. The advantages of NAVA mode are that it can monitor the EAdi (electroactivity of diaphragm), it improves the inspiratory and expiratory synchrony and it can be used as a non-invasive ventilation (NIV) mode too [17]. Since EAdi is a pneumatically independent signal and not affected by leaks, NAVA can deliver assist synchrony during NIV even with leaks [17]. Only a few larger studies [23, 24] compare NIV-NAVA with NIV-PS. No improved clinical outcomes were observed except a decreased incidence of asynchronies in NIV-NAVA.

In a large, multicenter, randomized, controlled clinical trial that included patients with acute respiratory failure (ARF) from several etiologies [19], NAVA was used in 153 patients, while another 153 enrolled in the control group used volume control ventilation, pressure control ventilation, PSV, or pressure-regulated volume control. NAVA decreased duration of mechanical ventilation, although it did not improve survival in ventilated patients with ARF.

5. Adaptive support ventilation (ASV)

Adaptive Support ventilation (ASV) is a closed-loop controlled ventilatory mode, which is designed to ensure optimization of the patient work of breathing, automatically adjusted according to the patient's requirements. ASV combines passive ventilation with pressure-controlled ventilation with adaptive pressure support if the patient's respiratory effort is present.

ASV delivers pressure-controlled breaths according to the set minute ventilation, resulting in the best combination of tidal volume and respiratory rate. As the patient's inspiratory efforts start, ASV delivers pressure-supported breaths according to the set minute ventilation resulting in the best combination of tidal volume, respiratory rate and the patient's inspiratory effort. In ASV mode FIO₂ and PEEP are set manually [25].

6. Intellivent-ASV

Intellivent ASV is also a closed-loop ventilation that adds the monitoring of SpO₂ and Pressure End-tidal CO₂ to best manage ventilation and oxygenation.

In Intellivent ASV mode the clinician sets patients' sex, height and choice the following respiratory mechanics situations: normal, ARDS, chronic hypercapnia and brain injury. Intellivent ASV determines the target PETCO₂ and SPO₂ according to the patient's condition. The ventilator controller adjusts the best tidal volume and respiratory rate to achieve the minute ventilation and PETCO₂ set by the clinician combining pressure-control and or pressure support ventilation according to the patient's inspiratory effort. In Intellivent ASV, FIO₂ and PEEP are adjusted according to the patient's SpO₂ following a PEEP-FIO₂ table [25].

7. Smart-care ventilation

Smart Care ® is an automatic weaning protocol, designed to stabilize the patient's spontaneous breathing in a comfort zone of a preset defined ventilation and to automatically reduce the ventilatory support. Smart Care ® ventilates the patient with pressure support which levels are adjusted according to respiratory rate, tidal volume and End tidal CO₂ to meet the patient's demand. Smart Care ® classifies the patient a minimum of every 5 minutes into one of 8 categories and decreases or increases the pressure support levels accordingly. Smart Care® assesses and indicates the readiness for extubation after a successful automatic spontaneous breathing trial [26].

8. Conclusions

1. Volume assured pressure support ventilation can guarantee tidal volume with the advantages of pressure support variable inspiratory flow.
2. PAV+ can monitor the patient's respiratory compliance, respiratory resistance, auto-PEEP and work of breathing decreasing patient-ventilator asynchrony in comparison to PSV and other ventilatory modes. PAV plus allow lung and diaphragm protection, avoiding under and over-assistance.
3. NAVA allows the measurement of the patient's diaphragmatic eletroactivity and NAVA mode decreases patient-ventilator inspiratory and expiratory asynchrony.
4. ASV adjust pressure support, according to the respiratory rate to maintain the pre-set minute ventilation.
5. Intellivent-ASV adds the monitoring of PTCO₂ and SpO₂ and adjusts of pressure support according to respiratory rate to maintain the minute ventilation according to lung pathology.
6. Smart-care ventilation can automatically wean the patients, according to distinct patients classifications of lung pathology and indicates readiness for extubation.

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