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Patient ventilator asynchrony in critically ill adults: Frequency and types

Karen G. Mellott, PhD, RN^{a,*}, Mary Jo Grap, PhD, RN, FAAN^b, Cindy L. Munro, PhD, RN, ANP-C, FAAN^c, Curtis N. Sessler, MD, FCCM, FCCP^d, Paul A. Wetzel, PhD^e, Jon O. Nilsestuen, PhD, RRT, FAARC^f, and Jessica M. Ketchum, PhD^g

^aDepartment of Acute and Continuing Care, School of Nursing, University of Texas Health, Health Science Center at Houston, 6901 Bertner Avenue, Houston, TX 77030, USA

^bDepartment of Adult Health and Nursing Systems, School of Nursing, Virginia Commonwealth University, 1100 East Leigh St., P.O. Box 980567, Richmond, VA 23298-0567, USA

^cResearch and Innovation, College of Nursing, University of Southern Florida, 12901 Bruce B. Downs Blvd. MDC Box 22, Tampa, FL 33612, USA

^dDivision of Pulmonary Disease and Critical Care Medicine, School of Medicine, Virginia Commonwealth University, P.O. Box 980050, Richmond, VA 23298-0050, USA

^eDepartment of Biomedical Engineering, School of Engineering, Virginia Commonwealth University, P.O. Box 843067, Richmond, VA 23284-3067, USA

^fDepartment of Respiratory Therapy, School of Allied Health Sciences, University of Texas Medical Branch, 301 University Boulevard, Galveston, TX 77555-1146, USA

^gDepartment of Biostatistics, School of Medicine, Virginia Commonwealth University, P.O. Box 980032, Richmond, VA 23298-0032, USA

Abstract

Background—Patient ventilator asynchrony (PVA) occurs frequently, but little is known about the types and frequency of PVA. Asynchrony is associated with significant patient discomfort, distress and poor clinical outcomes (duration of mechanical ventilation, intensive care unit and hospital stay).

Methods—Pressure–time and flow–time waveform data were collected on 27 ICU patients using the Noninvasive Cardiac Output monitor for up to 90 min per subject and blinded waveform analysis was performed.

Results—PVA occurred during all phases of ventilated breaths and all modes of ventilation. The most common type of PVA was Ineffective Trigger. Ineffective trigger occurs when the patient's own breath effort will not trigger a ventilator breath. The overall frequency of asynchronous breaths in the sample was 23%, however 93% of the sample experienced at least one incident of

*Corresponding author. Tel.: +1 713 248 1825, +1 713 500 2144; fax: +1 713 500 2171., Karen.G.Mellott@uth.tmc.edu, mellottkg@gmail.com (K.G. Mellott).

PVA during their observation period. Seventy-seven percent of subjects experienced multiple types of PVA.

Conclusions—PVA occurs frequently in a variety of types although the majority of PVA is ineffective trigger. The study uncovered previously unidentified waveforms that may indicate that there is a greater range of PVAs than previously reported. Newly described PVA, in particular, PVA combined in one breath, may signify substantial patient distress or poor physiological circumstance that clinicians should investigate.

Keywords

Patient ventilator interaction; Patient ventilator asynchrony; Patient ventilator dyssynchrony; Ventilators; Mechanical; Respiration; Artificial

Patient ventilator asynchrony (PVA) is a mismatch between patient and ventilator assisted breaths and the ventilator's ability to meet the patient's flow demand.¹ PVA is common in the intensive care unit (ICU) with up to 25% ventilated patients exhibiting asynchronous ventilator interaction²⁻⁴ PVA may occur with inadequate or excessive sedation⁴⁻⁶ as well as poor optimization of ventilator settings.⁷⁻¹¹ Other risk factors associated with PVA are related to the patient (decreased or increased respiratory drive, prolonged or shortened inspiratory/expiratory times, disease states/conditions) or the ventilator itself (trigger, cycling off, ventilator causes of patient agitation and dead space). PVA can result in adverse clinical consequences including hypoxemia,¹² cardiovascular compromise,¹² patient discomfort,¹³⁻¹⁷ anxiety/fear,¹² impairment of sleep quality,¹⁸ prolonged mechanical ventilation,²⁻⁴ and possible diaphragmatic injury.^{1,19} However there are few data regarding the types and frequency of PVA.

Complicating the recognition, documentation and reporting of PVA is the fact that the best measurement is invasive and possibly uncomfortable for long term use in patients. The gold standard PVA measures are phrenic neurogram and esophageal balloon catheter. The phrenic neurogram senses diaphragmatic muscle contraction (patient inspiration) through invasive sensory probes.^{17,20} The second measure is closely correlated with pleural pressure and obtained from an esophageal balloon catheter.²¹ However, both measures are infrequently or rarely used for monitoring in ICU as they are reserved for special in-depth cases (e.g. identifying diaphragm paralysis) or use in clinical research.²¹ However, ventilator graphic waveforms are typically displayed on the ventilator's graphic panel and have been used to detect PVA.^{11,22} Various waveform curves are available for monitoring, such as volume, pressure and flow on the *y* axis and time on the *x* axis. Pressure, flow and volume are detected through sensors that are present in the ventilator circuit near the airway. Waveform analysis is conducted by visually detecting particular morphological changes or changes in mathematical measures of inspiratory and expiratory times.^{2,11,22,23} Currently, waveform analysis is the most available and least invasive measure for PVA interpretation at the bedside.

Little information is available about the types and frequency of PVA identified or evaluated beyond the 30 min time frame. Therefore, the specific aim of this study was to identify the types and frequency of PVA in critically ill adults.

Methods

Design and sample

This prospective descriptive study was conducted in a 983 bed academic medical center in a Surgical Trauma ICU (STICU), Cardiac Surgery ICU (CSICU) and Medical Respiratory ICU (MRICU). The study was approved by the university institutional review board where the study was conducted. Informed written consent was obtained from the patient or if unable to provide consent, from their legally authorized representative (LAR).

Exclusion criteria were: (a) presence of a tracheostomy (rather than endotracheal intubation [ETT]) since an acutely ill mechanically ventilated subject was the focus of this study; (b) administration of neuromuscular blocking agents or presence of chronic, persistent neuromuscular disorders (such as cerebral palsy and Parkinson's disease) since these may affect the PVA phenomenon; and (c) presence of head trauma or stroke as these may affect respiratory dynamics and influence PVA. Ventilator setting exclusion criteria include use of (a) the augmented pressure ventilation mode, (b) increased pressure during inspiration (e.g. Bi-level), and (c) tube compensation (provides additional pressure support to overcome airway resistance from the endotracheal tube) since these features were found to increase the complexity of asynchrony interpretation in a pilot study prior to study implementation²⁴ and may decrease the incidence of asynchrony for evaluation in the study.^{25–28} Subjects were enrolled for up to a 1.5 h observation period, at any time of the day based on the primary investigator's (PI) schedule.

Variables and measures

Patient ventilator asynchrony—PVA is a mismatch between patient initiated and ventilator assisted breaths and the ventilator's ability to meet the patient's flow demand.¹ To identify PVA types, airway pressure-time and flow-time waveform analysis was conducted. During mechanical ventilation airflow through the endotracheal tube includes both airflow and pressure and these patterns can be visualized as waveforms (flow and pressure). The pressure and flow waveforms were obtained using the Non-invasive Cardiac Output Cardiopulmonary Management system (NICO) (Respironics®, Model 7300, Wallingford, CT) that integrates a non-invasive flow and pressure sensor between the end of the ETT and connection of the ventilator circuit. Flow and pressure measurements in the NICO monitor are made by a fixed orifice differential pressure pneumotachometer. A pneumotachometer is a transducer that measures exhaled gas flow. Inspired gas passing through the flow sensor causes a small pressure drop that is transmitted to a transducer located inside the NICO, and is correlated to flow according to the factory stored calibration.²⁹ The pressure transducer is automatically "zeroed" to correct for changes in ambient temperature and electronics.²⁹ The flow range for the device in adults is 2–180 L/min with accuracy greater of $\pm 3\%$ reading or 0.5 L/min.²⁹ The airway pressure range is ± 120 with accuracy greater of $\pm 2\%$ reading or 0.5 cm H₂O.²⁹ User calibration is not required due to the ability of the plastic injection mold to repeatedly produce precision flow sensors.²⁹ The pressure and flow signals collected from the NICO were sent to a data acquisition system (MP 150 Data Acquisition System®, Biopac Systems Inc, Goleta, CA). The MP 150 sampled, synchronized, amplified, time stamped and stored data until downloaded for later analysis.

PVA types—Detection, identification and classification of airway pressure and flow was based on expert classification of PVA by Nilsestuen and Hargett, 2005.¹¹ A coding scheme was developed with operational definitions and criteria for evaluation based on ventilator modes. A software package, The Observer XT 8.0® (Noldus, Inc), that integrates coding, analysis and presentation of video and physiological data, was used to code and document each breath as normal or asynchronous (specifically by type). A breath by breath interpretation was completed during each subject's observed time period by the PI (KGM). These breaths were then independently validated with expert consultation (JON, CNS). An a priori coding scheme with breath descriptive label and operational definitions was devised. The 5 types of asynchrony defined in the a priori coding scheme were Ineffective Trigger [Type 1 and Type 2], Premature Termination, Flow, Double Trigger and Delayed Termination [DelTerm].³⁰

PVA frequency—Frequency of PVA was documented using percentages based on the total number of asynchronous breaths in the entire sample as well as the frequency of each asynchronous type within each breath category.

Subject descriptive data—Subject demographic data (age, gender, ethnicity, race, admission diagnosis, reason for intubation, duration of MV, hospital and ICU stay) were collected, along with ventilator information (ventilator settings, presence of fluid in the ventilator circuit and presence of jet nebulizer treatment during data collection), subject medical history (chronic obstructive pulmonary disease [COPD] history was gathered by history/physical/progress notes), and severity of illness. Severity of illness was determined using scores on the Acute Physiology, Age, Chronic Health Evaluation (APACHE) III.³¹ The APACHE scoring system has demonstrated validity in the ICU setting.³² Level of sedation using RASS has demonstrated high reliability in medical-surgical, ventilated–nonventilated and sedated–nonsedated adult patients in ICU.³³

Procedure

Once the subject was enrolled, demographics and ICU admission information were obtained. Information for the APACHE III was recorded for the 24 h prior to study enrollment.

Data collection procedure

Subjects were enrolled for up to a 1.5 h observation period. The use of an extended observation period was important to fully describe PVA since the only data available to date includes observations of 15–30 min duration. Prior to the actual start of the electronic data collection, the NICO was time synchronized and time stamped with respect to the computer's real-time clock. The NICO carbon dioxide sensor was zeroed and calibrated, the airway circuit was assessed for excessive humidification and all fluid removed from the circuit to avoid measurement error in PVA interpretation. In addition, the patient's breath sounds were assessed and the need for suctioning determined. If suctioning was required, it occurred before data collection since this may cause measurement error in PVA interpretation.³⁴ The respiratory therapist working with the patient or the PI connected the NICO sensor to the ventilator circuit to ensure a stable connection.

Data analysis

Descriptive statistics were used to summarize the characteristics of the sample, counts and proportion for discrete variables and mean, range, standard deviation and median, interquartile range (IQR) for continuous variables through JMP 8.0 (SAS Institute, Inc.) statistical software.

Waveform analysis was conducted by using an a priori coding scheme based on ventilator mode algorithm that was developed with an expert consultant. Waveform coding was completed by the PI in consultation with two clinical experts. To avoid waveform interpretation and measurement bias two methods were used, (a) subject selection for waveform coding was randomized using a random number table, and (b) an assistant blinded the PI from the subject's identification number on the waveform file before waveform coding ensued.

During coding of waveforms for PVA, new asynchronous breath types emerged from the data. Each new breath that was not on the a priori coding scheme was added to the scheme, given a descriptive label and operational definition for complete and thorough documentation longitudinally.

At the time of data analysis, all types of PVA were reviewed and the coding categories and PVA types were altered to more accurately represent the data and included two additional categories (Newly Described [New] and Unknown) (Fig. 1).^{11,22,35} The New PVA type was added to describe PVA that has not been previously identified in the literature and includes combinations of asynchrony within the same breath cycle occurred (e.g. Premature Termination [PreTerm], and Double Trigger [DblTrig] occur together). Unknown breath types were unable to be categorized by either the PI or expert consultants. This modified classification system enabled a mutually exclusive representation of the data for analysis and resulted in three overall breath categories (Normal, Asynchronous and Unknown). The final adjusted coding schemes for PVA types including operational definitions are described in Fig. 1.

Results

Characteristics of the sample

Forty-nine patients were approached for consent. Of these, 30 were consented and enrolled (LAR refused = 17; ventilator setting changed after enrollment = 2), with 27 subjects available for data analysis (3 had equipment malfunction). The sample had more males than females with whites slightly more predominant than blacks and mean age of 55 years (see Table 1). Subjects were almost equally distributed among medical and surgical ICU's and were primarily intubated for hypoxemic respiratory failure. The most common admitting diagnosis was metastatic cancer, sepsis followed by surgery (Table 1). They had varying levels of sedation, but most were awake and calm or deeply sedated (Table 1). Most were on a spontaneous ventilator mode with a mean PEEP level of 6 cm H₂O (Table 1). The total observation time for the entire sample was 2221 min (35 h) with a mean of 79 min (range 53–92) per subject which consisted of 43,758 individual breaths (Table 2)

Patient ventilator asynchrony

Patient ventilator asynchrony was found in both medical and surgical subjects and during each mechanical ventilation (MV) mode (Spontaneous, Synchronized Intermittent Mandatory Ventilation [SIMV], Assist Control, Pressure Control Ventilation [PCV]) included in this study.

PVA types

Seventy-six percent of the sample's breaths were normal during the observed time period (Table 2). A patient-initiated, normal breath on volume-cycled ventilation begins when the patient or ventilator triggers a breath (phase 1, see Fig. 1A). When the patient initiates a breath, there is a negative dip on the pressure-time waveform. However, when the ventilator, based on the rate setting, initiates a breath, this negative deflection will not be present. Fig. 1B demonstrates a ventilator initiated breath on volume-cycled ventilation (a negative deflection is not present on the pressure-time waveform). After breath initiation, phase 2 begins with flow of air being delivered that generates a positive upstroke in the flow and pressure-time waveforms. Once the patient meets the pre-set ventilator termination criteria (phase 3), there is a deceleration of the pressure-time waveform toward zero and flow-time waveform below zero as inspiration ends. Phase 4 of a normal ventilated breath is expiration, the flow-time waveform moves from a negative value toward zero prior to the next breath. Fig. 1 represents the phases of ventilation on pressure-cycled ventilation.

The most common PVA type in the sample was Ineffective Trigger (IneffTrig) (63% of all asynchronous breaths), with Type 2 being more prominent than Type 1. The second most common category was Newly Described PVA; however, this contains a variety of asynchronous types. Premature Termination occurred separately, but also combined with other types of PVA in one breath, such as Flow, Active Double Trigger, Double Trigger, Active Multiple Trigger, Multiple Trigger and Patient Gasp PVA. One of the Newly described-Combined Phase breath types, PreTerm-Flow, was by far the most frequent combination, although only experienced by one subject. Whereas, isolated PreTerm ($n = 937$ breaths) was observed in 19 subjects (70% of sample).

Newly Described PVA types

A variety of unexpected PVA types were detected during waveform analysis and categorized as New (Fig. 1 and Table 2). The Newly Described types were further sub-categorized based on the phase of a ventilated breath where they occurred (flow, trigger or termination phase) or whether combinations of PVA occurred within the same breath, but during different phases of that ventilated breath (Combined Phase PVA). Patient Gasp PVA (PtGasp) occurred in only one subject with COPD. This subject was on SIMV-Volume targeted; pressure support ventilation (PSV)/positive end expiratory pressure (PEEP); and experienced three other PVA types (IneffTrig, PreTerm, Flow). Patient Gasp PVA occurs when the subject starts to breathe, then gasps once the ventilator begins inspiratory gas flow. In Fig. 1, notice that the initial pressure begins to increase at a normal rate, but then indents or "scoops" out because the patient suddenly changes inspiratory effort. The patient is not relaxed and tries to breathe ahead of the ventilator, but the ventilator cannot synchronize to this gasping pattern.

During the trigger phase Unusual Double Trigger (UnDbITrig) occurred having two positive flow inflections, but no associated second rise in pressure for the second positive flow inflection. There is a spike in the expiratory flow trace that occurs after the first breath in the DbITrig cycle, but it is unusual in that there is no second increase in the pressure waveform associated with the second breath and there is exhalation in the flow trace. Only one subject had UnDbITrig but it occurred consistently over an 11 min time period. Another unusual appearance was the Multiple Trigger (MultTrig) which had more than two triggered breaths with minimal exhalation between triggers. In some of these triggers an exceptionally negative pull on the pressure traced was termed “active” because the patient was trying so hard to inhale.

An unexpected PVA type occurred during the termination phase and was labeled Resisting Ventilation (ResistVent). ResistVent appeared similar to the morphology of Delayed Termination; however, this PVA type demonstrated a very sharp pressure spike that frequently resulted in the ventilator reaching the peak pressure limit or “pop off,” while other DelTerm PVAs had a smaller spike that more closely followed the 2 cm H₂O pressure above target pressure rule for Pressure Support termination.

Variability in PVA types

Twenty-one of the 27 subjects (77%) experienced more than one category of PVA. Two subjects had no PVA, four had 1 PVA type, seven had 2 PVA types, seven had 3 PVA types, six had 4 PVA types, and one had 6 PVA types. IneffTrigg was present in 20 (74%) patients, isolated PreTerm in 19 (70%), Multiple Trigger (MultTrig) in 17 (63%), Newly Described in 7 (26%), DelTerm in 6 (22%) and Flow in 2 (7%).

Discussion

PVA is a common event for mechanically ventilated ICU patients, however it is not frequently recognized by all clinicians. PVA can lead to unstable physiological states, patient discomfort, poor sleep quality and is associated with prolonged MV.^{2-4,12-16,18} There are few studies that have documented the types and frequency of PVA greater than 30 min. By increasing the observed time frame, we were able to detect different types of PVA that have not been described in the literature, therefore providing evidence that other forms exist and can be identified.

PVA types

Patient ventilator asynchrony occurs frequently in critically ill, mechanically ventilated adults. This study found PVA types similar to those in published reports (IneffTrigg, DbITrig, Flow, PreTerm and DelTerm). However, the operational definitions for PreTerm and DelTerm differ between our study and others in that we use morphological definitions that are not bound by mathematical measures for Double Trigger, Premature Termination and Delayed Termination. In addition, we evaluated for literature-supported variation of Ineffective Trigger, specifically Type 2,²² which other studies have not recently evaluated.

The scope of asynchrony types in this study vary from other cited works^{2,3,23,36} since this was an evaluation of all breaths during a longer study period than has been previously

reported and a function of our coding scheme. Similar to other reports that looked at more than one type of PVA,^{2,23} Ineffective Trigger was the most common asynchrony in this study. We included a second, “non-classic” type of Ineffective Trigger (Type 2)²² that has been less studied, but we found that it was more frequent in this sample than Type 1. Inappropriately high levels of sedation have been associated with ineffective trigger. de Wit and others²³ found medical ICU patients who were ranked as awake versus those who were not awake (measured by the Richmond Agitation Sedation Scale) had higher ineffective trigger index scores ($p = 0.04$). Ineffective trigger was also significantly higher in those who were comatose (measured by the Confusion Assessment Method-ICU).²⁰ Thille and colleagues (2006) found that ineffective trigger occurred in patients who had a less sensitive inspiratory trigger, which may be associated with over-sedation or extensive levels of ventilator support.⁶ Clinicians should include ventilator graphic analysis when conducting sedation assessment. If ineffective trigger is noted on waveform analysis and associated with a patient’s uncoupling of accessory respiratory muscle movement during onset of machine breaths, then clinicians should consider the dose of sedation and whether downward titration should occur.

Premature Termination was a common type of PVA in isolation and combined; this level of frequency has not been previously documented. Identifying this degree of frequency is important to note because patients with this type of PVA may experience increased levels of discomfort. PreTerm causes the patient to exhale before they are ready, which may translate to feelings of air hunger or frustration in not being able to get enough air with attempts to inhale when there is no mechanism to do so. If aware, nurses can more readily detect the problem and limit possible patient distress.

The prevalence of PreTerm in this study may be due to shorter duration of observation in prior works, our definition or, more likely from the individually pre-set ventilator termination criteria on our subjects. In addition, previous studies have not described a combination of phase asynchrony types, such as Premature Termination and Flow asynchrony during the same breath cycle. However, the combination of two asynchronies occurring within the same breath cycle is theoretically possible. In the case of a PreTerm-Flow asynchronous breath, two phases of a mechanically ventilated breath are influenced: gas flow and cycling off.

Furthermore, Premature Termination occurred with the phenomenon of Patient Gasp PVA during gas delivery. This combination may occur in a patient whose flow demand is greater than what is pre-set on the ventilator flow setting. He/she may be experiencing anxiety trying to adjust to the ventilator’s gas flow causing a gasp during the inspiratory phase, thereby causing a longer neural inspiratory time to which the ventilator does not respond because of its predetermined cycle-off criteria. Additionally, PreTerm PVA was also combined with active multiple triggers in the same patient who experienced almost every breath as PreTerm-Flow. Theoretically, it is possible that more patient effort was generated to trigger a breath (reflected by the active trigger – a deeper negatively pronounced Paw trace), and this caused neural inspiratory time to be longer, thereby influencing the development of Premature Termination after the active trigger.

Although Double Trigger has been identified in other studies as a common type of PVA,^{2,4,36} they were not prominent in this study (perhaps due to coding definition), and were complicated by a variety of features. First, they were observed in subjects who had other underlying problems such as PreTerm-Flow PVA. It is probable that an increased respiratory drive is the common feature involved in Double Triggers, Premature Termination and Flow PVA and this is why they were observed. This has not been documented in the literature to our knowledge. Unusual Double Trigger, a newly described breath pattern, may have been related to a ventilator malfunction or a problem with the flow sensor, since the same subject had high flows that did not return to zero during exhalation at times.

Other newly described PVA includes Active Multiple Triggers and Combined Phase PVA. Active Multiple Triggers are observed when there is a deeper negative pull on the Paw trace during phase I of a ventilated breath. This negative deflection may indicate air hunger, an aggressive manifestation of increased patient demand, changing clinical status or discomfort. The underlying cause of the active triggered breath may be the presence of intrinsic PEEP from dynamic hyperinflation, influencing the patient to work harder to inhale. Perhaps early identification of MultTrig PVA could alert clinicians to perform a focused assessment of the patient-ventilator interaction. Last, we observed more than two breaths in succession without full exhalation after inhalation, such as three or four breaths in a row (Multiple Trigger [MultTrig]). Patients who manifest this type of PVA may be at risk for physiological consequences (e.g. significant over-inflation, pressure induced lung injury, pneumothorax, interference with hemodynamics), and clinicians should monitor subjects closely for respiratory dynamics, patient factors that could promote stress and result in more PVA.

Combined phase PVA breaths are newly described in our study. Clinicians who vigorously monitor ventilator graphics may have already observed these in practice, however, this is the first time they have been documented. Interestingly, we found these breaths to occur during two of the first three phases of a ventilated breath: trigger, flow and termination. These types of breaths may lead to autoPEEP since exhalation is decreased during excessive patient triggering efforts and dyspnea may occur during poor flow ("flow starvation state"). Studies have shown that adjusting trigger thresholds and other ventilator settings can reduce patient dyspnea during asynchrony.³⁷ Therefore, clinicians should be observant for combined type PVA and be prepared to adjust ventilator settings to optimize these phases.

Clinical implications

Pressure/time and flow/time waveform analysis can detect PVA, yet requires a trained eye. Since the frequency of PVA is common, varied and complex, clinicians need to be knowledgeable regarding waveform analysis to detect ineffective patient ventilator interaction. Nurse educators and clinical experts should collaborate with respiratory therapists and pulmonary physicians to educate bedside nurses about waveform analysis for use in clinical care.

While physicians and respiratory therapists may be more adept at recognizing PVAs, nurses typically spend many more hours at the bedside which provides more opportunity to detect asynchrony. Being familiar with alterations during each phase of a ventilated breath will inform discussions with the collaborative team and enhance therapeutic interventions.

Collaborative interventions such as teaching/coaching patients during asynchrony, providing “on-target” sedation, identifying high risk factors and adjusting ventilator triggering, flow delivery, cycling off or expiratory timing can be provided by the team.³⁰ Chanques et al³⁸ found that adapting ventilator settings to the patient with breath stacking reduced the phenomena significantly and dramatically compared to increasing sedation-analgesia. Additionally, interventions such as appropriate sedation titration, changing ventilator settings that meet the patient’s current dynamic physiological demand and administering bronchodilators may also be effective for PVA.³⁰

Newer ventilation modes (e.g. neurally adjusted ventilatory assist [NAVA] and proportional assist ventilation [PAV]) have been developed to reduce PVA. There are no studies that report on the frequency and types of PVA that subjects experience in these modes. One study cites that the number of subjects with significant asynchrony was reduced by 50% with NAVA.³⁹ A pilot study ($n = 14$) revealed that PAV mode correlated with better patient ventilator synchrony, however did not improve sleep outcome measures.⁴⁰ At this time it is uncertain if these modes have any outcome benefit.

Future technology may provide continuous monitoring of PVA at the bedside, however, until sedation, PVA-related discomfort and PVA-related mechanical ventilation is optimized, associated poor outcomes may continue. Equipping ventilators to generate a standard ventilator pattern based on particular ventilator mode for nurse comparison to the current patient’s ventilator graphic display would be beneficial. Development of measures to recognize PVA pattern similar to ST segment elevation recognition software has been discussed in the literature, although it is unclear whether these features will be incorporated into future ventilator generations.^{41,42} Last, the capacity to print paper strips of ventilator waveforms for nurses to interpret PVA like cardiac monitor strips would be particularly helpful for nurses.

Future research should include examining the patterns of PVA and their relationships to patient behaviors, investigating how the use of waveform analysis may improve the use of sedative therapy, determining how nurses interpret and use ventilator graphics in practice, investigating PVA prevalence and outcome benefit in newer ventilation modes designed to reduce PVA. In addition, once available, evaluation of nurses use of continuous computerized PVA recognition software to recognize PVA to determine if this practice improves patient outcomes and patient–ventilator interaction. Last, future research should identify the effect of different types of PVA on patient outcomes.

Limitations

Study duration of 90 min may be a limitation, because not all factors could be controlled in the subject’s environment that may have contributed to PVA including need for suctioning or alterations in the ventilator circuit. Notes were taken during the observation period and events that could influence waveform morphology were coded and considered during waveform analysis. However, these conditions may have resulted in a greater incidence of Unknown breaths in the form of artifact or other morphologies.

The use of three operational definitions (Double Trigger, Pre-Term and DelTerm) in our coding scheme, are somewhat different than those published in two other studies at this time.^{2,23} Careful comparison of these 3 PVA types in this study with those published in other reports should be considered. While authors^{2,23} have used mathematical definitions averaging over 30 breaths and calculating mean inspiratory and expiratory times to define PreTerm and DelTerm, the advantage of using a morphological coding scheme as done in our study is that it may be more clinically realistic for bedside assessment and onsite intervention.

We did not monitor for automatic positive end expiratory pressure (autoPEEP) or include Volume–time waveform interpretation in coding PVA. AutoPEEP has a large influence on the frequency of trigger asynchronies. Therefore, in the face of not using esophageal balloon pressure monitoring, surveillance of autoPEEP would have helped to corroborate the presence of ineffective trigger. Volume–time waveform reviews in collaboration with pressure and flow–time waveform detection would have also assisted in providing insight into the coding of PVA. It is possible that esophageal or phrenic neurogram would have provided more quantifiable information, however as mentioned these are rarely used in the ICU and not as readily available as ventilator graphics. While PI blinding was generally effective, some subjects were difficult to blind since their respiratory behaviors were dramatic and unique, potentially adding to coder bias. Finally, the use of a convenience sample may reduce generalizability to other ICU populations.

Conclusions

This study contributes new knowledge about the phenomena of PVA. While we found prior documented PVA types, the investigation also uncovered multiple previously unidentified waveforms that may indicate there is a greater range of PVAs than previously reported. There is no accepted taxonomy to consistently label the types of asynchrony^{38,43} and until a general consensus has been reached, clinicians and scientists should consider the previously unidentified PVA found in this study and add them to the repertoire of knowledge in this area.

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Abbreviations

ActDbITrig	Active Double Trigger
ActDbITrig-PreTerm	Active Double Trigger-Premature Termination
ActMultTrig-PreTerm	Active Multiple Trigger-Premature Termination
AI	Asynchrony Index

APACHE	Acute Physiology, Age, Chronic Health Evaluation
COPD	Chronic Obstructive Pulmonary Disease
CSICU	Cardiac Surgery ICU
DelTerm	Delayed Termination
DblTrig	Double Trigger
DblTrig-Flow	Double Trigger-Flow
DblTrig-PreTerm	Double Trigger-Premature Termination
ETT	Endotracheal intubation
ICU	intensive care unit
IneffTrig	Ineffective Trigger
IQR	interquartile range
MV	mechanical ventilation
MRICU	Medical Respiratory ICU
MultTrig	Multiple Trigger
MultTrig-PreTerm	Multiple Trigger-Premature Termination
New	Newly Described
NICO	Non-invasive Cardiac Output
LAR	legally authorized representative
PCV	pressure control ventilation
PI	Primary investigator
PEEP	positive end expiratory pressure
Pre-Term	Premature Termination
PreTerm-Flow	Premature Termination-Flow
PSV	pressure support ventilation
PtGasp	Patient Gasp PVA. PtGasp-PreTerm
Patient Gasp	PVA–Premature Termination
PVA	patient ventilator asynchrony
ResistVent	Resisting Ventilation
SIMV	Synchronized Intermittent Mandatory Ventilation

STICU

Surgical Trauma ICU

UnDbITrig

Unusual Double Trigger.

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A. Identify Phases of a Volume-Cycled Ventilated Breath

Phase 1: Trigger (Breath initiated. No negative dip will occur on Pressure-time wave if ventilator triggered based on rate setting. However, negative dip will occur if patient pulls enough negative pressure to overcome trigger threshold setting on ventilator)

Phase 2: Flow (Air enters airway)

Phase 3: Cycling off (Breath terminated)

Phase 4: Exhalation (Exhalation of gases)

B. Identify Phases of a Pressure-Cycled Ventilated Breath

Phase 1: Trigger (Breath initiated, negative dip present on Pressure-time wave)

Phase 2: Flow (Air enters airway)

Phase 3: Cycling off (Breath terminated)

Phase 4: Exhalation (Exhalation of gases)

Identify Ineffective Trigger (IneffTrig)

1. Ineffective Trigger, Type 1 (IneffTrig, Type 1)

(Same in all modes)

Flow: Positive inflection not followed by (f/b) mechanically ventilated (MV) breath

AND

Paw: Negative deflection, not f/b MV breath.

2. Ineffective Trigger, Type 2 (IneffTrig, Type 2)

(Same in all modes)

Flow: Positive inflection, not f/b MV breath

AND ASSOCIATED with,

Paw: Presence of flat line or no negative deflection simultaneous with change in Flow wave.

1. Ineffective Trigger, Type 1 (IneffTrig, Type 1)

2. Ineffective Trigger, Type 2 in a Volume breath

(IneffTrig, Type 2)¹¹ Nilsestuen JO, Hargett KD. Using ventilator graphics to identify patient-ventilator asynchrony. *Respir Care* 2005;50:202-234.

Causes of Ineffective**Trigger:**

Those with low respiratory drive do not reach trigger pressure in correct time.³² Other factors: low PCO₂, high tidal volume and pH,²⁰ sedation,²⁰ high levels of assist (pressure support or assist control),^{1,33,34}

Identify Premature**Termination (PreTerm):**

(Same in all modes)

Flow: Positive inflection at the end of expiration "black arrow, AND, ASSOCIATED with,

Paw: Negative deflection at the end of expiration. "black arrow

Causes of Premature**Termination:**

During pressure-support ventilation: Caused by low levels of support, short time constant (rate of flow decay influenced by resistance and compliance factors of respiratory system),¹⁷ and dynamic hyperinflation.³⁵
During assist volume control: Caused by settings that yield short inspiratory time.³⁵

Identify Flow Asynchrony

(Flow)

(Same in all modes)

Flow: Normal wave, AND,

Paw: Concave Dip (negative), "scooped out" on accelerating wave.

Causes of Flow Asynchrony:

An increased patient respiratory effort causes ventilator to not match the patient's demand.¹¹

In volume-controlled ventilation: Incorrect peak flow setting for patient.¹¹

In pressure-controlled ventilation:

A patient's flow demand and the rate of flow delivery.¹¹

2. Ineffective Trigger, Type 2 in a PSV breath

(IneffTrig.Type 2)²¹ Georgopoulos D, Primianakis G, Kondili E. Bedside waveforms interpretation as a tool to identify patient-ventilator asynchronies. *Intensive Care Med* 2006;32:34-47.

2. Ineffective Trigger, Type 2 in Pressure targeted

breath (IneffTrig.Type 2)³⁶ Bonetto C, Calo M, Delgado MO, Mancebo, J. Modes of pressure delivery and patient-ventilator interaction. *Respir Care Clin N Am* 2005;11:247-263.

Premature Termination (PreTerm) **Flow Asynchrony (Flow)**

Identify Double Trigger

(DbITrig)

(Same in all modes)

Flow: Initial triggered breath quickly I/b by 2nd increased Flow in same breath cycle. No significant drop in expiratory flow after first triggered breath (barely exhales below "0" *black arrow) AND

Paw: Negative deflection for each breath taken during Double Trigger. Second breath of DbITrig drops to trigger threshold thereby generating a MV breath causing 2nd positive inflection on Flow waveform.

Causes of Double Triggering:

Patient effort is greater than volume/flow delivery (inappropriate settings or sudden onset of increased patient demand).^{2,11} shortened ventilator inspiratory time and low ratio of PaO₂ to fraction of inspired oxygen.²

Identify Delayed**Termination (DelTerm)**

(Same in all modes)

Flow: Normal wave, AND

Paw: Pressure spike just before exhalation. Spike goes higher than expected maximum inspiratory pressure. *black arrow.

Causes of Delayed**Termination:**

May be more prevalent in patients with COPD³⁵, Pressure-support ventilation settings that result in long time constant (COPD, high pressure support level and low flow threshold for cycling off variable).³⁵ Assist-control ventilation settings that result in long inflation time (high tidal volumes, low inspiratory flow).³⁵

Double Trigger (DbITrig) **Delayed Termination (DelTerm)**

Identify Newly Described**PVA****1. Flow Phase -****A. Patient Gasp PVA***(PiGasp)**(Seen in SIMV- Volume Targeted mode)***Paw:** Initial Paw begins to ramp up at normal rate, but quickly dishes out, then returns to normal pressure pattern.**B. Variant Flow***(Seen in SIMV-Pressure Targeted mode)***Flow:** Flow negative or unproportional to Paw response. *black arrows**Identify Newly Described PVA- cont.****1. Flow Phase -****C. Variant Inspiratory Effort***(Seen in SIMV-Pressure Targeted and Spontaneous modes)***Flow:** Flow reveals variable patient effort during inhalation in proportion to Paw response.**2. Trigger Phase -****A. Unusual Double Trigger***(UnDbITrig)**(Seen in Spontaneous mode)***Flow:** Same as in DbITrig, Except flow goes deeper than usual, AND,**Paw:** second breath in cycle exhibits a small positive Paw *black arrow.**B. Multiple Trigger***(MultTrig)**(Same in all modes)***Paw:** Same as in DbITrig, but now has more than 2 triggers AND,**Flow:** Same as in DbITrig, but more than 2 flow inflections without exhalation**1. Flow Phase-****A. Patient Gasp PVA (PiGasp)**

Legend: PG=Patient Gasp PVA; NL= Normal breath

B. Variant Flow **C. Variant Inspiratory Effort** **2. Trigger Phase -****A. Unusual Double Trigger (UnDbITrig)** **B. Multiple Trigger (MultTrig)**

Identify Newly Described PVA- cont

2. Trigger Phase -

C. Active Double Trigger (ActDbITrig)

(ActDbITrig)

(Same in all modes)

Flow: Same as in DbITrig *black arrows.

AND

Paw: Same as in DbITrig, except that one pressure dip is much more negative than subject's other Paw trigger pressures. *black arrow

C. Active Double Trigger (ActDbITrig)

Some subjects, although not common, used excessive negative pressure to generate Double and Multiple Triggers. The phrase "Active" describes the subject's obvious effort used during some triggered breaths. The associated Paw wave has a much larger negative pressure compared to the subject's other initiated breaths.

3. Termination Phase -

A. Resisting Ventilation (ResistVent)

(ResistVent)

(Seen in SIMV-Pressure Targeted mode)

Paw: Paw spikes upward past maximum pressure expected *straight gray line for patient with a possible pressure "pop-off" (see second circle)

3. Termination Phase -

A. Resisting Ventilation (ResistVent)

Identify Newly Described PVA- cont

4. Combined Phase -

A. Premature Termination-

Flow (PreTerm-Flow)

(Seen in AC-Pressure Targeted)

Flow: PreTerm PVA is seen as positive inflections at end of expiration. *long black arrows, AND ASSOCIATED with:

Paw: PreTerm PVA is usually seen as a negative deflection at end of expiration- here this may be hidden in the decelerating wave. Flow PVA is demonstrated by concavity seen on the accelerating Paw trace. *short black arrow

4. Combined Phase -

A. Premature Termination-Flow (PreTerm-Flow)

B. Active Double Trigger – Premature Termination
(ActDbITrigg-PreTerm)

(Seen in Assist Control– Pressure Targeted)

Flow: ActDbITrig breath has flow between 2 breaths that barely dips below “0”. On second breath of ActDbITrig, PreTerm PVA is demonstrated by a positive inflection. *third long black arrow

AND, ASSOCIATED with,

Paw: Active DbITrig breath with more negative Paw than triggered breaths *first lateral arrow. PreTerm noted in negative deflection after exhalation. *third long black arrow

Identify Newly Described PVA- cont

4. Combined Phase- cont.

C. Double Trigger-Flow
(DbITrig-Flow)

(Seen in AC- Pressure Targeted mode)

Flow: 2 positive inflections without full exhalation, *black arrows

AND,

Paw: Same as DbITrig *first two black arrows, & Flow PVA with concavity in accelerating wave of Paw. *short black arrow

D. Double Trigger- Premature Termination
(DbITrig-PreTerm)

(Seen in AC-PressureTargeted and Spontaneous mode)

Flow: Same as DbITrig *first 2 black arrows, and PreTerm *third black arrow,

AND,

Paw: Same as DbITrig (negative deflections) and PreTerm (negative deflection) *third black arrow.

B. Active Double Trigger – Premature Termination
(ActDbITrigg-PreTerm)

4. Combined Phase- cont.

C. Double Trigger-Flow (DbITrig-Flow)

D. Double Trigger - Premature Termination
(DbITrig-PreTerm)

Fig. 1.
 Waveform categories used for coding and data Analysis. Paw, airway pressure waveform; PSV, pressure support ventilation; AC, Assist Control mode; SIMV, Synchronized Intermittent Mandatory Ventilation mode; cm H₂O, centimeters water pressure.

Table 1Characteristics of sample and major variables ($n = 27$).

Variable	Frequency	%
Gender		
Male	15	56
Female	12	44
Ethnicity		
White, Non Hispanic	15	56
Black, Non Hispanic	11	41
Pacific Islander, Non Hispanic	1	3
ICU type		
Medical Respiratory ICU	14	52
Surgical Trauma ICU	10	37
Cardiac Surgical ICU	3	11
Admitting diagnosis		
Sepsis	8	30
Surgery	7	25
Pneumonia	3	11
Cardiac surgery	3	11
Trauma	3	11
GI bleed	1	4
Liver failure	1	4
Metastatic cancer	1	4
History of COPD	9	33
Reason for intubation		
Hypoxemic respiratory failure	12	44
Airway control	7	26
Both hypoxemic and ventilatory failure	4	15
Respiratory distress	4	15
Ventilatory failure	0	0
Mechanical ventilation mode		
Spontaneous-PSV	15	55
Assist Control-Pressure Targeted	2	7
Assist Control-Volume Targeted	0	0
SIMV-Pressure Targeted-PSV	5	19
SIMV-Volume Targeted-PSV	5	19
Sedation level (RASS)		
Restless (+1)	1	4
Awake and Calm (0)	8	30
Drowsy (-1)	1	4
Light sedation (-2)	3	11
Moderate sedation (-3)	4	15

Variable	Frequency	%	
Deep sedation (−4)	7	26	
Unarousable (−5)	3	11	
Variable	Mean	Range	SD
Age (years)	55	32–83	13.3
APACHE III	75	30–173	31.6
PSV (cm H ₂ O)	11	0–18	3.9
Positive end expiratory pressure (cm H ₂ O)	6	5–10	1.6
MV duration (days)	13	2–56	10.6
ICU length of stay (days)	19	3–72	16.5
Hospital length of stay (days)	31	5–86	19.8
Observation time (minutes)	79	53–92	13.0

GI, gastrointestinal; COPD, chronic obstructive pulmonary disease; SD, standard deviation; PSV, pressure support ventilation; SIMV, Synchronized Intermittent Mandatory Ventilation; PEEP, positive end expiratory pressure; APACHE III, Acute Physiology, Age, Chronic Health Evaluation Physiological; RASS, Richmond Agitation Sedation Score.

Table 2Breath types (Total ventilated breaths of sample, $n = 43,758$).

Breath Category	Frequency	% of total breaths	% of PVA
Normal	33,403	76.34	–
Identified asynchrony	10,195	23.30	100
Ineffective Trigger (IneffTrig)	6411	14.65	62.88
IneffTrig, Type 2	4035	9.22	39.58
IneffTrig, Type 1	2376	5.43	23.30
Premature Termination (PreTerm)	937	2.14	9.19
Flow	89	0.20	0.87
Double Trigger (DblTrig)	75	0.17	0.74
Delayed Termination (DelTerm)	9	0.02	0.09
Newly Described (New)	2674	6.10	26.20
Flow phase	904	2.10	8.87
PtGasp	898	2.05	8.81
Variant Flow	4	<0.01	0.04
Variant Inspiratory Effort	2	<0.01	0.02
Trigger Phase	28	0.06	0.27
UnDblTrig	24	0.05	0.23
MultTrig	3	<0.01	0.03
ActDblTrig	1	<0.01	0.01
Termination phase – ResistVent	16	0.04	0.16
Combined Phase PVA	1726	3.94	16.90
PreTerm-Flow	1712	3.91	16.79
ActDblTrig-PreTerm	7	0.02	0.07
DblTrig-Flow	2	<0.01	0.02
DblTrig-PreTerm	2	<0.01	0.02
ActMultTrig-PreTerm	1	<0.01	0.01
MultTrig-PreTerm	1	<0.01	0.01
PtGasp-PreTerm	1	<0.01	0.01
Unknown	160	0.37	1.57