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Clinical Management of Pressure Control Ventilation: An Algorithmic Method of Patient Ventilatory Management to Address "Forgotten but Important Variables"

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Clinical management of pressure control ventilation: An algorithmic method of patient ventilatory management to address "forgotten but important variables"☆

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ABSTRACT

Pressure controlled ventilation is a common mode of ventilation used to manage both adult and pediatric populations. However, there is very little evidence that distinguishes the efficacy of pressure controlled ventilation over that of volume controlled ventilation in the adult population. This gap in the literature may be due to the absence of a consistent and systematic algorithm for managing pressure controlled ventilation. This article provides a brief overview of the applications of both pressure controlled ventilation and volume controlled ventilation and proposes an algorithmic approach to the management of patients receiving pressure controlled ventilation. This algorithmic approach highlights the need for clinicians to have a comprehensive conceptual understanding of mechanical ventilation, pulmonary physiology, and interpretation of ventilator graphics in order to best care for patients receiving pressure controlled ventilation. The objective of identifying a systematic approach to managing pressure controlled ventilation is to provide a more generalizable and equitable approach to management of the ICU patient. Ideally, a consistent approach to managing pressure controlled ventilation in the adult population will glean more reliable information regarding actual patient outcomes, as well as the efficacy of pressure controlled ventilation when compared to volume controlled ventilation.

1. Introduction

Pressure control as a mode of ventilation was developed in the 1980's as an option to treat Acute Respiratory Distress Syndrome (ARDS) [1]. Pressure Control Ventilation (PCV), typically available as Pressure control–continuous mandatory ventilation (PC-CMV) or Pressure control-intermittent mandatory ventilation (PC-IMV), was designed to deliver mechanical breaths at a set inspiratory pressure—allowing clinicians to control the amount of distending pressure applied to airways and subsequently, to the alveoli. Because the amount of driving pressure applied to the airway is preset, the delivered volume is variable and dependent upon the patient's inspiratory effort, pulmonary mechanics (i.e. pulmonary compliance, airway resistance and AutoPEEP) and to a lesser extent, other ventilator settings, including rise time and inspiratory time.

The ability of the clinician to use PC-CMV to best treat a patient with variable and often poor pulmonary mechanics depends upon an in-depth understanding of the mode and how to safely apply it to the specific patient management scenario. Although nearly all ventilator manufacturers now include one, if not several, options for PC-CMV or PC-IMV, relatively little information is available to clinicians on how best to utilize the functions within these modes in a way that is most advantageous for their patients.

In reviewing the existing literature on the topic of algorithmic patient management—specifically, literature explicit to PCV, it is important to note that there was no consistency in how authors address or approach methods of PCV management between and among studies. This inconsistency may highlight a true lack of consensus among leading physicians and respiratory therapists on how best to utilize pressure control ventilation. This article does not attempt to dictate a management approach; rather, the goal of this article is to first provide a brief overview of how PC-CMV differs from modes of volume ventilation, then to highlight the detailed nature of the relationships between pulmonary mechanics and PC-CMV settings and finally, to suggest a broad, yet systematic, algorithmic approach to managing patients in the Intensive Care Unit who are ventilated using PC-CMV.

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2. Pressure and volume controlled modes of ventilation

Pressure-controlled ventilation (PCV) is a pressure-targeted, time-cycled mode of ventilation. During inspiration, the ventilator adjusts the flowrate to keep the airway pressure at the set level. The clinician sets the peak inspiratory pressure (PIP), respiratory rate (f), inspiratory time (T_I), positive end expiratory pressure (PEEP) and fraction of inspired oxygen (F_IO_2). The clinician also sets how quickly the PIP will be reached with a control usually named slope, rise time or ramp, depending upon the brand of the ventilator. The most common mode of PCV is pressure-targeted assist-control (PC-CMV), in which a minimum respiratory rate is set, but the patient is allowed to trigger additional breaths. Each breath, whether it is delivered at the set respiratory rate or an additional breath triggered by the patient, is delivered at the set PIP and the set T_I.

Volume-controlled ventilation (VCV) is a volume-targeted mode in which the tidal volume, respiratory rate (f), PEEP, inspiratory flowrate, flow waveform, inspiratory pause time and inspiratory time are controlled. The most common mode of VCV is volume-targeted assist-control (VC-CMV), in which a minimum f is set, but the patient is allowed to trigger additional breaths. Each breath, regardless of whether it is patient or machine-triggered, will be delivered at the set tidal volume; however, the airway pressure may vary as the patient's airway resistance (Raw), compliance (C) and effort change.

3. Patient-ventilator synchrony during VC-CMV and PC-CMV

Although VC-CMV guarantees tidal volume, which appears to be an ideal mode for "lung protective strategy", many clinicians prefer PC-CMV to VC-CMV. The main reason for the preference is probably the superiority in patient-ventilator synchrony and thus patient comfort during PC-CMV. To meet the respiratory demands of a patient, the ventilator's flow and pressure delivery must synchronize with the patient's respiratory demands. The fact that a patient is able to control inspiratory flowrate is the most important aspect of PC-CMV in terms of patient-ventilator synchrony.

During PC-CMV, as the patient's airway resistance, compliance or effort changes, the inspiratory flowrate and tidal volume (V_T) will potentially change. To have a constant airway pressure during PC-CMV, the ventilator varies the inspiratory flow based upon the inspiratory flowrate of the patient. In other words, the spontaneously breathing patient is able to vary the inspiratory flowrate, and thus the tidal volume as well, depending on his/her inspiratory effort, in contrast to VC-CMV where the inspiratory flow is set by the clinician [2]. When the patient's flow demand is not met in VC-CMV, it is common that the demand for tidal volume is not met. As a result, flow asynchrony is frequently accompanied by cycle asynchrony and double triggering.

4. Comparing VC-CMV to PC-CMV in the literature

Studies have been published since the early 1990's comparing VC-CMV and PC-CMV. An article by Rittayami et al., published in 2015, was a comprehensive review of published studies comparing VC-CMV to PC-CMV. According to Rittayami, there were no differences in physiologic or clinical outcomes between the two modes and that adjusting the ventilator settings based upon the patient's individual characteristics may help to reduce lung damage, minimize work of breathing, and improve patient comfort [3]. Findings from a 2015 Cochrane Review by Chacko, et al., stated that there was insufficient evidence that PC-CMV improved outcomes for people with acute lung injury when compared to VC-CMV. The authors suggested that not only more, but larger studies may provide evidence as to whether PC-CMV improves outcomes when compared to VC-CMV [4].

In reviewing the existing literature on the topic, it is important to note that there was no consistency in how a PC-CMV algorithm was applied to ventilator management between studies. The lack of a consistently applied algorithm across studies that investigate the use of PC-CMV may account for some of the variability in identifying the key differences between outcomes of patients ventilated using either VC-CMV or PC-CMV. For example, when using VC-CMV in a patient who has a respiratory acidosis, the options for ventilator changes to enhance CO_2 removal generally include increasing the tidal volume, increasing the respiratory rate, or both. When ventilating a similar patient with PC-CMV, although the options for enhancing CO_2 removal are mainly considered to be increasing the inspiratory pressure and f, these options may have little effect and could be harmful due to increased asynchrony under certain conditions. There are a number of adjustments that should be considered even before changing the two easy and attractive variables to help with CO_2 removal if clinicians fully understand the lung mechanics and ventilator graphics, which may potentially reduce patient ventilator asynchrony, ventilator days, and hopefully even mortality. The algorithm we suggest in this article provides clinicians with a systematic approach to adjust PC-CMV settings.

5. Prerequisite physiological knowledge regarding inspiratory time, expiratory time and inspiratory pressure before using PC-CMV

5.1. Time constant and autoPEEP

The time constant (TC) is a mathematical relationship between the airway resistance and static compliance, and is related to the time it takes to get gas into and out of the lung.

$$\text{Inspiratory Raw} = (\text{PIP} - P_{plat})/\text{Flowrate}(\text{l}/\text{ sec})$$

$$C_{st} = V_{TE}/(P_{plat} - \text{PEEP})$$

$$C_{dyn} = V_{TE}/(\text{PIP} - \text{PEEP})$$

$$\text{TC} = (\text{Raw})(C_{st})$$

Where: Raw = airway resistance (cm H_2O/l/s); C_{st} = static compliance (l/cm H_2O); C_{dyn} = dynamic compliance (l/cm H_2O); V_{TE} = exhaled tidal volume (l); P_{plat} = plateau pressure, equivalent to average alveolar pressure at end inspiration (cm H_2O); PIP = peak inspiratory pressure (cm H_2O); TC = time constant (seconds).

The following two examples demonstrate a difference in the time constant for two patients. In a patient with COPD who is intubated and mechanically ventilated, the airway resistance may be 25 cm H_2O/l/s and the compliance may be 0.04 l/cm H_2O. The expiratory resistance will be higher than the inspiratory resistance in these patients, which results in a longer expiratory time constant [5]. In this case the inspiratory time constant would be 1.0 s (25 cm H_2O/l/s × 0.04 l/cm H_2O). In a patient with ARDS who is intubated and mechanically ventilated, the airway resistance may be 12 cm H_2O/l/s and the compliance may be 0.02 l/cm H_2O. In this case the time constant would be 0.24 s (12 cm H_2O/l/s × 0.02 l/cm H_2O).

The inspiratory time constant refers to the amount of inspiratory time required for the alveolar pressure to reach the set pressure during PC-CMV. The inspiratory time must be equal to at least three and as long as five time constants for the alveolar pressure to approximate the set inspiratory pressure [5,6,7]. If the airway resistance or compliance increases, the inspiratory time constant will increase, and more time will be required for the alveolar pressure to reach the set pressure. If airway resistance or pulmonary compliance decreases, the inspiratory

time constant will decrease and it will take less time for the alveolar pressure to reach the set pressure.

The expiratory time constant influences the amount of expiratory time required for the patient to passively exhale to the PEEP level and prevent AutoPEEP. The expiratory time must be equal to at least three to five expiratory time constants for the patient to exhale and minimize or prevent AutoPEEP [6,7]. If the airway resistance or compliance increases, the expiratory time constant will increase, and more time will be required for complete exhalation and to prevent AutoPEEP. If airway resistance or pulmonary compliance decreases, the expiratory time constant will decrease and it will take less time for complete exhalation to prevent AutoPEEP.

6. Inspiratory pressure on PC-CMV

During PC-CMV, the manner in which the clinician sets the inspiratory pressure (P_I) varies depending upon the specific ventilator used. When using some ventilators, such as the Servo i or Servo U (Maquet), Puritan Bennett (PB) 840 or 980, and CareFusion's Avea, P_I is set directly. In other words, changes in PEEP will affect the total pressure but not the distending pressure. In these cases, the PIP = P_I + PEEP. In other ventilators such as the Drager Evita XL and Drager V500 ventilators, P_I is set as the difference between PIP and PEEP. In other words, PIP is set directly and the inspiratory pressure setting is referenced to atmospheric pressure not PEEP. This is an important distinction - increases in PEEP will now decrease the distending pressure and vice versa.

The average alveolar pressure is estimated as the plateau pressure (P_{plat}) during a 0.5–2.0 s inspiratory hold. It is recommended to monitor and keep the P_{plat} <25–30 cm H_2O in all ventilated patients in traditional "lung protective strategy". In addition to monitoring the absolute number of P_{plat}, increasing evidence is being published emphasizing the importance of targeting a P_{plat} – PEEP (ΔP) of <16 cm H_2O, especially in patients with severe ARDS. It has been shown that if the ΔP is >16 cm H_2O in patients with severe ARDS, the relative risk of death increases [8]. Thus, permitting a low tidal volume, even <6 ml/kg, to keep ΔP <16 cm H_2O as long as pH is acceptable, seems a reasonable practice.

When a patient has an increased inspiratory effort, the pleural pressure (P_{pl}) becomes more negative. Clinically, we can estimate the pleural pressure by monitoring the esophageal pressure (P_{es}). This requires the insertion of an esophageal balloon into the distal third of the thoracic esophagus. After calibrating the system and ensuring that the balloon is properly positioned, the pleural pressure is estimated by the esophageal pressure.

A value that is sometimes used clinically is referred to as the transpulmonary pressure (P_L). The transpulmonary pressure is the average alveolar pressure minus the pleural pressure (P_{pl}), and is reflective of the amount of strain on the lung. Care should be taken to not allow the patient in PC-CMV to breathe with a strong inspiratory effort as the transpulmonary pressure will increase.

$$P_L = P_{plat} - P_{pl}$$

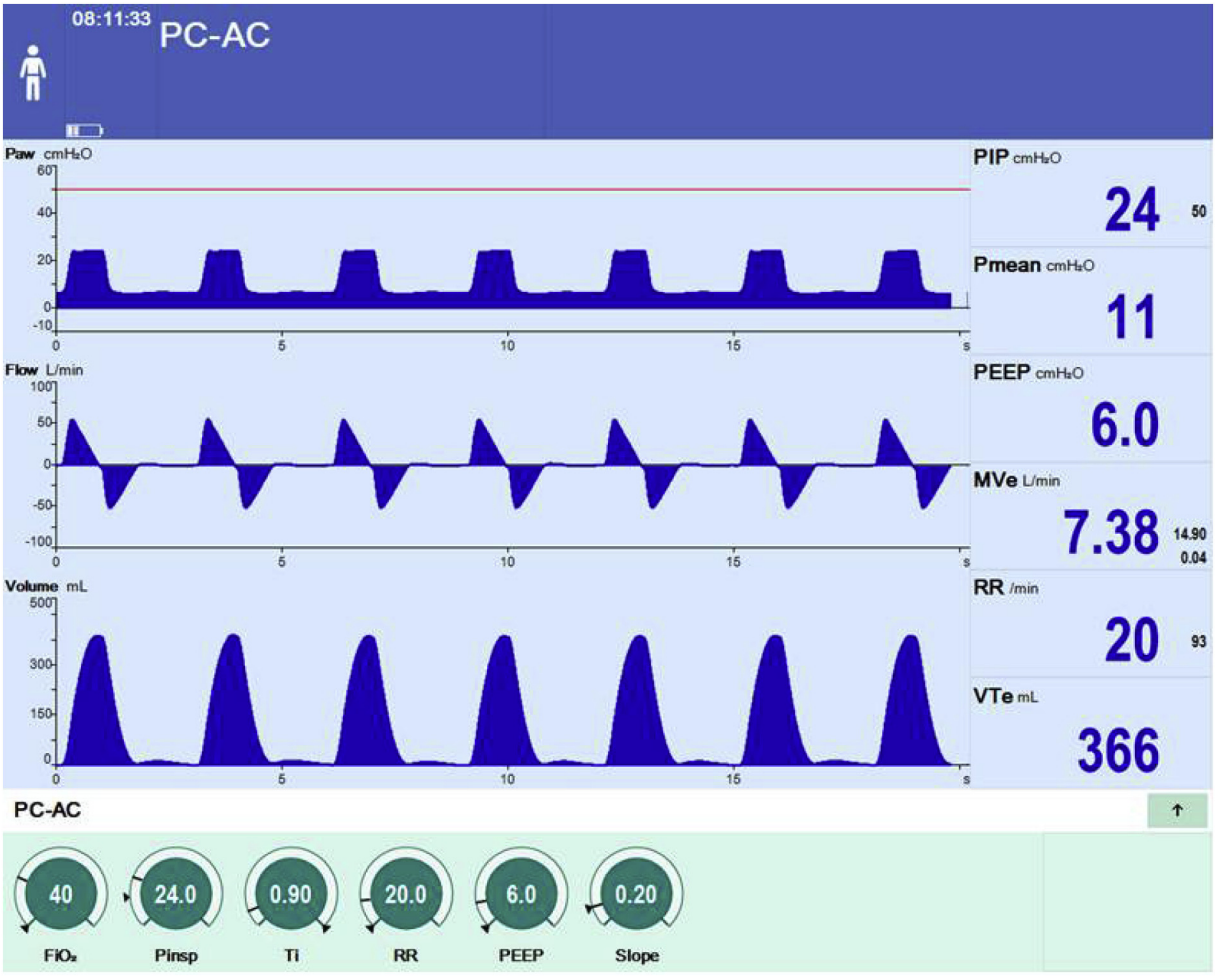

Fig. 1. Normal waveforms in PC-CMV. Fig. 1 displays normal waveforms during PC-CMV. The top waveform demonstrates pressure (Paw) versus time, the middle waveform form demonstrates flow versus time and the bottom waveform is volume versus time.

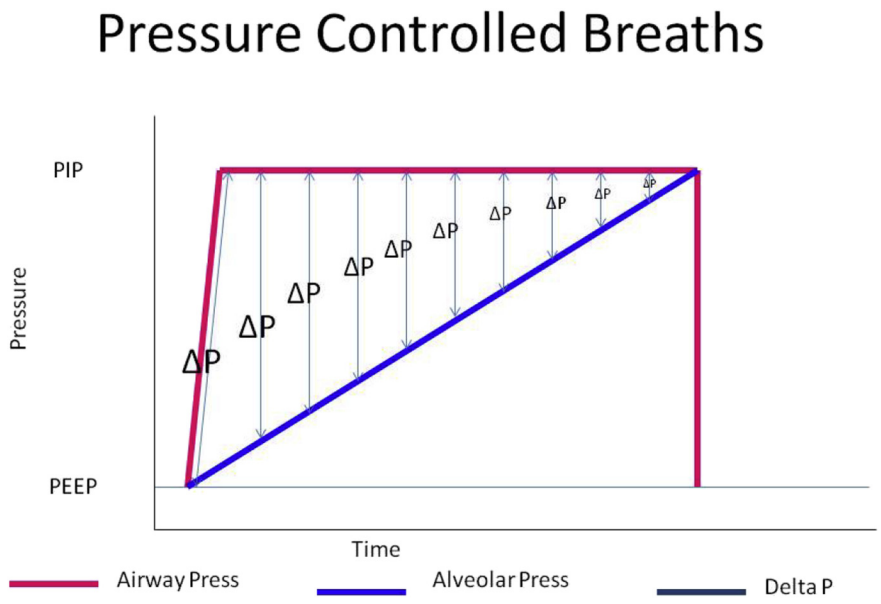

Fig. 2. Decreasing $DeltaP_{Insp}$ during inspiration. Fig. 2 demonstrates that the set airway pressure remains constant throughout inspiration, but as the alveolar pressure increases, the $DeltaP_{Insp}$ (ΔP) decreases.

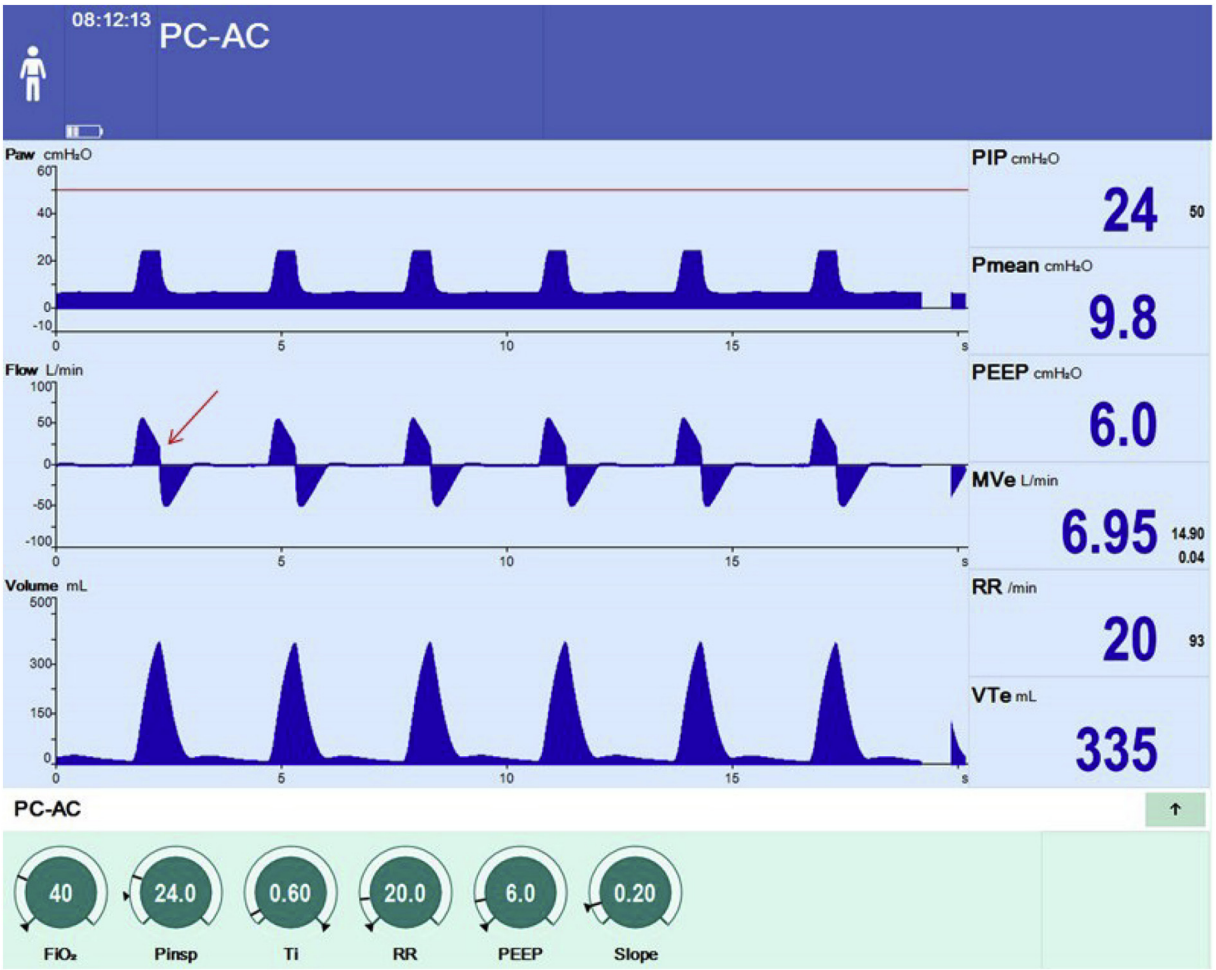

Fig. 3. Short inspiratory time. Fig. 3 demonstrates that if inspiratory time is too short, not allowing alveolar pressure to reach set airway pressure, inspiratory time ends before inspiratory flowrate returns to baseline (as indicated by the red arrow) and tidal volume is reduced. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

During PC-CMV without spontaneous breathing, if P_{plat} – PEEP (ΔP) remains constant, as compliance decreases, exhaled tidal volume will decrease. Similarly, as compliance increases, exhaled tidal volume will increase.

$$C_{st} = V_{TE}/(P_{plat} - PEEP)$$

7. Initial ventilator settings when beginning PC-CMV

When initiating PC-CMV, although the settings below are frequently used, it is very important to individualize patients by evaluating the V_{TE}, P_{plat}, SpO_2 and graphic waveforms soon after initiating PC-CMV. Even though the tidal volume is not set directly, it is important to consider the milliliters per kilogram (ml/kg) of tidal volume in relation to the predicted body weight (PBW). Current recommendations are to keep tidal volume no >6–8 ml/kg PBW, unless the patient has ARDS, in which case the recommended tidal volume should be 4–6 ml/kg PBW. Arterial blood gasses (ABGs) should be drawn and evaluated. Ventilator changes to achieve a target P_aCO_2 are described below.

Mode: PC-CMV
P_I: 5–10 cm H_2O
T_I: 0.7–1.0 s
f: 10–20 BPM
F_IO_2: 0.5
PEEP: 5–10 cm H_2O

8. Understanding the basic ventilator graphics to guide decisions

An understanding of the use of graphic analysis during mechanical ventilation is a key in managing patients receiving ventilatory support. The importance of evaluating the pressure-versus-time and the flow-versus-time waveforms will be discussed in depth below.

8.1. Pressure versus time waveform

Fig. 1 is an example of a typical waveform of a patient ventilated in PC-CMV. In this example, PIP 24 cm H_2O, T_I 0.9 s, f 20/min, PEEP 6.0 cm H_2O, Slope 0.20 s. The pressure-versus-time waveform (Fig. 1, Top Waveform) shows that at the beginning of inspiration, the ventilator increases the airway pressure from the PEEP level of 6 cm H_2O up to the set PIP of 24 cm H_2O; the time to reach this PIP is set with the slope and in this case, it is set at 0.20 s. Inspiration continues until the set inspiratory time of 0.90 s has been reached. At that time, inspiration ends and the patient is allowed to exhale back to the PEEP level of 6 cm H_2O.

8.2. Flow versus time waveform

On a typical flow-versus-time graphic display, inspiratory flow is demarcated above the horizontal baseline and expiratory flow is noted below that baseline. When looking at the flow-versus-time waveform (Fig. 1, Middle Waveform) the flowrate increases immediately at the beginning of inspiration and then gradually decreases throughout inspiration. Generally, the flow-versus-time waveform will be decelerating

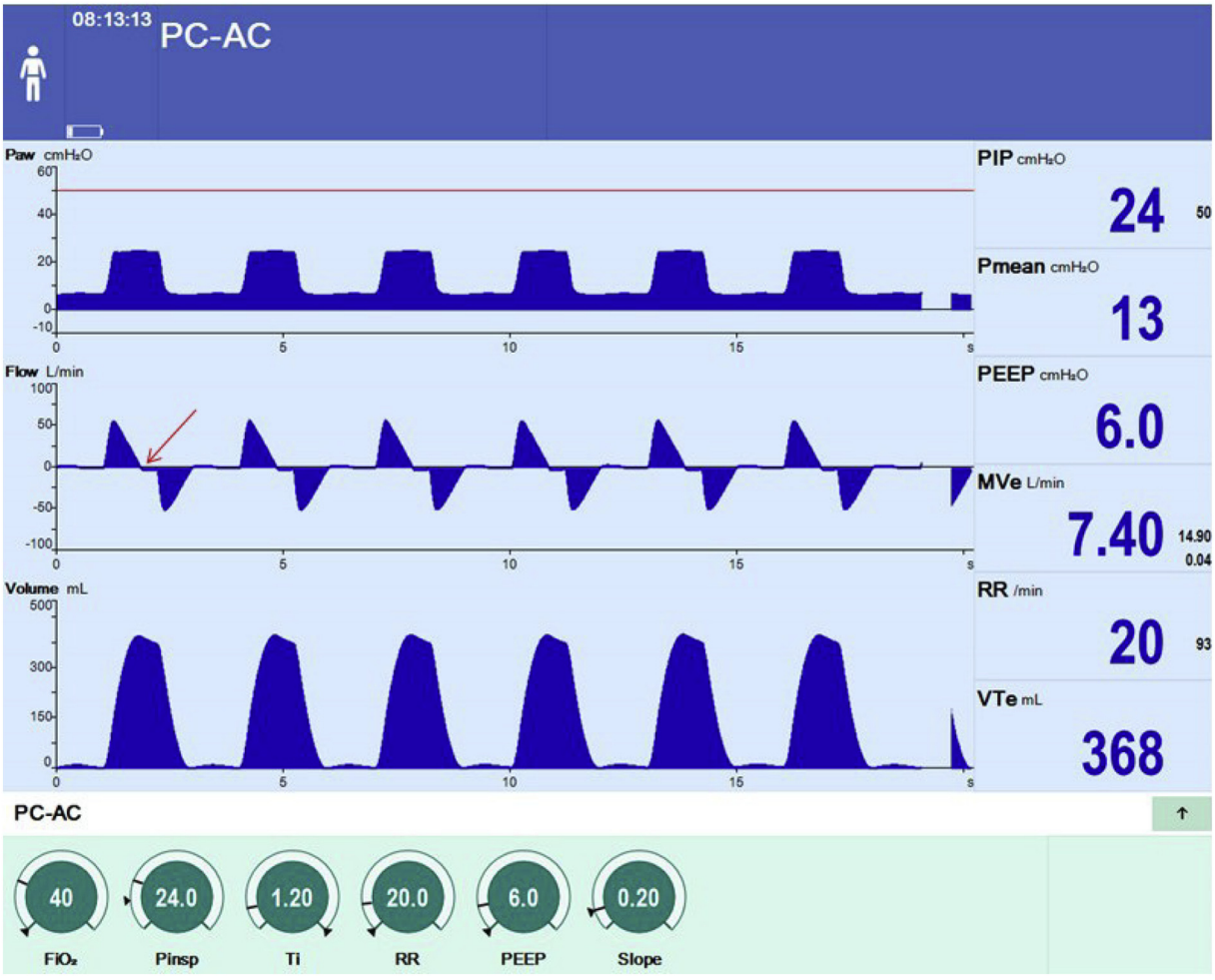

Fig. 4. Inspiratory Pause. Fig. 4 shows that if the inspiratory time is too long, the alveolar pressure will reach the set airway pressure, resulting in an inspiratory pause (as indicated by the red arrow). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

during PC-CMV. At the end of inspiration, the inspiratory valve closes and the expiratory valve opens, allowing the patient to passively exhale. If the expiratory time is long enough, the patient will be able to exhale to baseline before the next breath begins, and there will be no AutoPEEP.

8.2.1. Inspiration

When using PC-CMV, the peak flowrate is dependent upon the Total PEEP, set PIP and Slope, as well as the patient's airway resistance, pulmonary compliance, and effort. The difference between the PIP and the alveolar pressure is frequently referred to as the Delta P_{Insp} (PIP – alveolar pressure). During inspiration, as the alveolar pressure increases, the Delta P_{Insp} decreases (Fig. 2), resulting in a decreasing inspiratory flowrate. If the inspiratory time is long enough for the alveolar pressure to equilibrate with the set pressure, the inspiratory flow waveform will return to baseline (Fig. 1, Middle Waveform). However, if the inspiratory time is not long enough for the alveolar pressure to reach the set pressure, the inspiratory flow waveform will not return to baseline. This generally results in a lower alveolar pressure and a reduced tidal volume (Fig. 3, Middle Waveform). If the inspiratory time continues after the inspiratory flow has returned to the zero-flow baseline, an inspiratory pause will occur (Fig. 4, Middle Waveform).

8.2.2. Exhalation

If the expiratory time is long enough for the expiratory flowrate to return to the zero-flow baseline before the beginning of the next inspiration, there will be no AutoPEEP (Fig. 1, Middle Waveform). However, if the expiratory time is too short and there is not enough time for the expiratory flowrate to return to baseline before the next breath begins, AutoPEEP is present (Fig. 5, Middle Waveform).

When ventilating a patient in PC-CMV, the presence of AutoPEEP will reduce the actual Delta P_{Insp} by the amount of the AutoPEEP. For example, if the PIP is set at 24 cm H_2O, and the PEEP at 6 cm H_2O, and AutoPEEP is 0 cm H_2O, the Delta P_{Insp} will equal 24 cm H_2O – 6 cm H_2O = 18 cm H_2O. However, if the patient has a Total PEEP 7.8 cm H_2O, but the set PEEP is 6 cm H_2O, AutoPEEP is present and can be calculated as 7.8 cm H_2O (TotalPEEP) – 6 cm H_2O (set PEEP) = 1.8 cm H_2O (AutoPEEP). This means that the alveoli are actually starting at 7.8 cm H_2O (Total PEEP) rather than 6 cm H_2O (PEEP), which results in a reduction in the Delta P_{Insp} by 1.8 cm H_2O, resulting in an overall decrease in delivered tidal volume (Fig. 6).

During PC-CMV, if AutoPEEP exists and is subsequently reduced (e.g. a reduction in airway resistance after delivery of an inhaled bronchodilator), the Delta P_{Insp} will increase. This usually results in an increase in delivered tidal volume. Options to reduce the AutoPEEP in PC-CMV include decreasing airway resistance and/or increasing expiratory time. Expiratory time can be increased by decreasing respiratory rate and/or decreasing inspiratory time (Fig. 7). However, it is important to make sure that a decrease in respiratory rate does not result in a decreased minute ventilation, especially in a spontaneously breathing patient. Similarly, tidal volume must be monitored carefully as a decrease in inspiratory time may result in a decreased tidal volume.

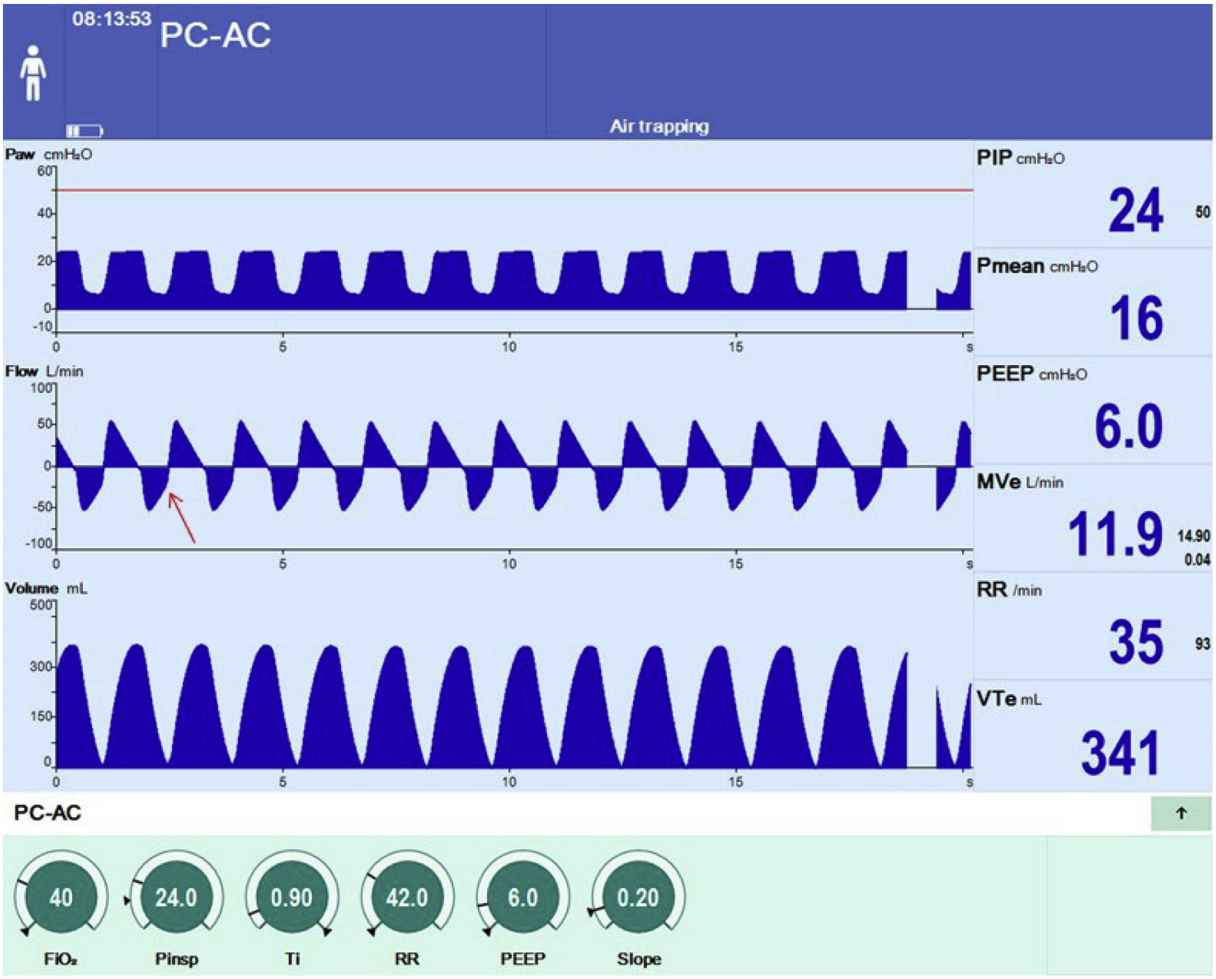

Fig. 5. Identifying AutoPEEP. Fig. 5 demonstrates that if the expiratory time is too short, AutoPEEP is likely to result. The red arrow indicates that the next breath begins before expiratory flow returns to baseline, resulting in AutoPEEP. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

9. Making changes: an algorithmic approach

9.1. Treatment of hypercapnia

9.1.1. Initial decision

When a patient has an elevated $PaCO_2$ resulting in a respiratory acidosis, and the decision is made to reduce the $PaCO_2$, one must either deliver a larger tidal volume or increase the respiratory rate. In cases where ventilator induced lung injury is a concern, clinicians may choose to not increase the tidal volume.

When evaluating acid-base status, the first decision that has to be made is whether or not the $PaCO_2$ is high enough and/or the pH is low enough to necessitate a reduction in $PaCO_2$. If the $PaCO_2$ is not >50–70 Torr and the pH is not <7.25, the decision may be made to maintain current therapy. However, if there is a need to reduce $PaCO_2$, the next decision is whether or not to increase minute ventilation by changing ventilator settings or to utilize other, non-ventilator strategies to decrease the $PaCO_2$ (Fig. 8). If the decision is made to change the ventilatory setting to increase the minute ventilation, the P_{plat} and tidal volume must first be evaluated. If the P_{plat} is <25–30 cm H_2O (or less than the desired P_{plat}), or if the tidal volume is <6–8 ml/kg PBW, *and* if the desired outcome is an increase in tidal volume, then options to increase tidal volume should be considered (Fig. 9). If the decision is made to not increase the tidal volume, then options to increase respiratory rate should be considered (Fig. 10). If the decision is made to not increase tidal volume *or* respiratory rate, then non-ventilatory strategies should be considered (Fig. 11).

9.1.2. Increasing tidal volume

When a decision is made to increase the tidal volume, there are many options to consider. As illustrated in Fig. 9, increasing the PIP should not be considered the default option. As discussed earlier, if the patient has low compliance, PC-CMV will result in a decreased tidal volume at a given pressure. Consideration should be given to try to increase the compliance by either increasing the PEEP level if it is too low (potentially causing atelectasis), or by decreasing the PEEP level if it is too high (potentially resulting in overdistension), as both of these issues can result in a low compliance.

As previously described, AutoPEEP will reduce the effective Delta P_{Insp}. Evaluating the patient for AutoPEEP should be part of the ongoing patient assessment. If the patient has AutoPEEP, methods to decrease the AutoPEEP should be considered. Such considerations include decreasing the airway resistance, increasing expiratory time by decreasing inspiratory time, prolonging the expiratory time by changing the I:E, and/or decreasing the respiratory rate.

The inspiratory flow waveform should be a major part of both routine and continual patient assessments. Throughout inspiration, as the alveolar pressure increases, the inspiratory flow will return closer to baseline. If the inspiratory flow does not return to baseline, an increase in inspiratory time will generally result in an increased tidal volume and should be considered as long as increasing inspiratory time does not result in shortening expiratory time, causing AutoPEEP, or result in patient-ventilator asynchrony. When the inspiratory flow waveform does not return to baseline, the P_{plat} will be less than the set PIP. When adjusting the inspiratory time, it is important to re-assess the

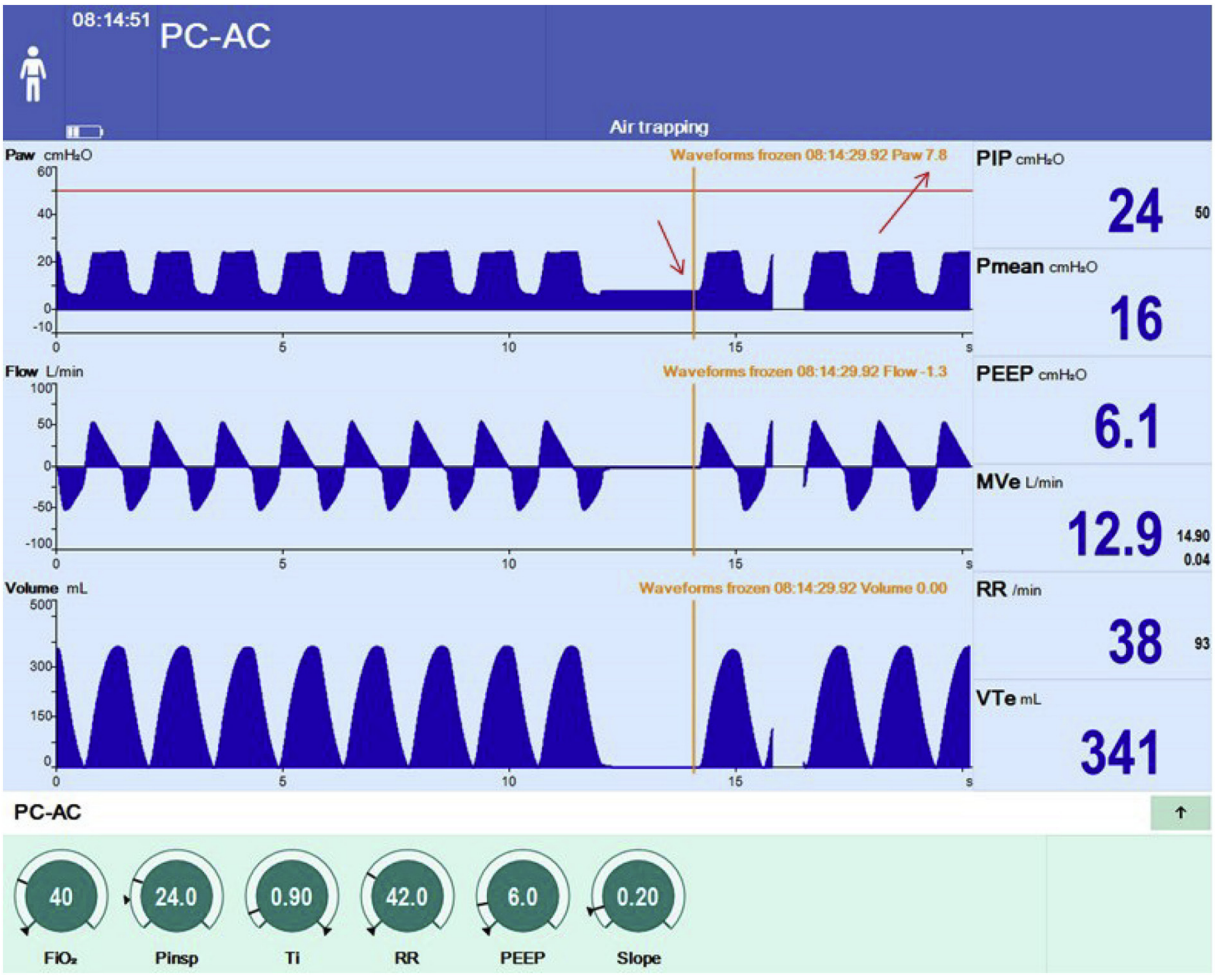

Fig. 6. Measurement of AutoPEEP. Fig. 6 demonstrates how to measure AutoPEEP. The red arrows indicate the end of the expiratory pause and the total PEEP displayed while the screen is frozen. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

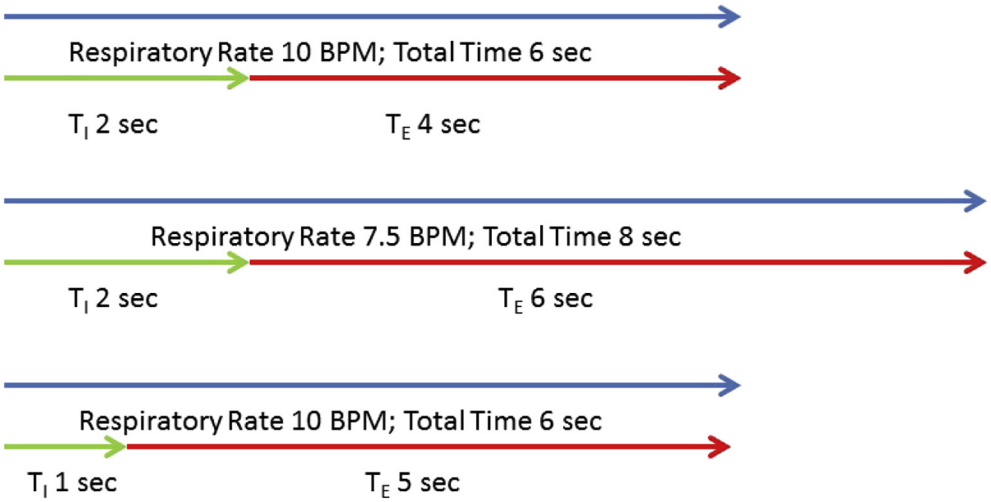

Fig. 7. Expiratory time. Fig. 7 illustrates the effect on expiratory time of changes in inspiratory time and total time.

P_{plat} and evaluate the patient-ventilator asynchrony that could be caused by the inspiratory time being too short or too long.

The next step in a complete assessment is to evaluate the P_{plat}. If the P_{plat} is <25–30 cm H_2O, or less than the desired P_{plat}, and the tidal volume is less than the desired tidal volume, PIP should be increased gradually to achieve the desired tidal volume, ensuring that the P_{plat} is <25–30 cm H_2O.

If the Total PEEP is too high, it may lead to overdistension of alveoli. This will generally result in a decrease in compliance and potentially an increase in alveolar dead space due to stretching of the alveoli and

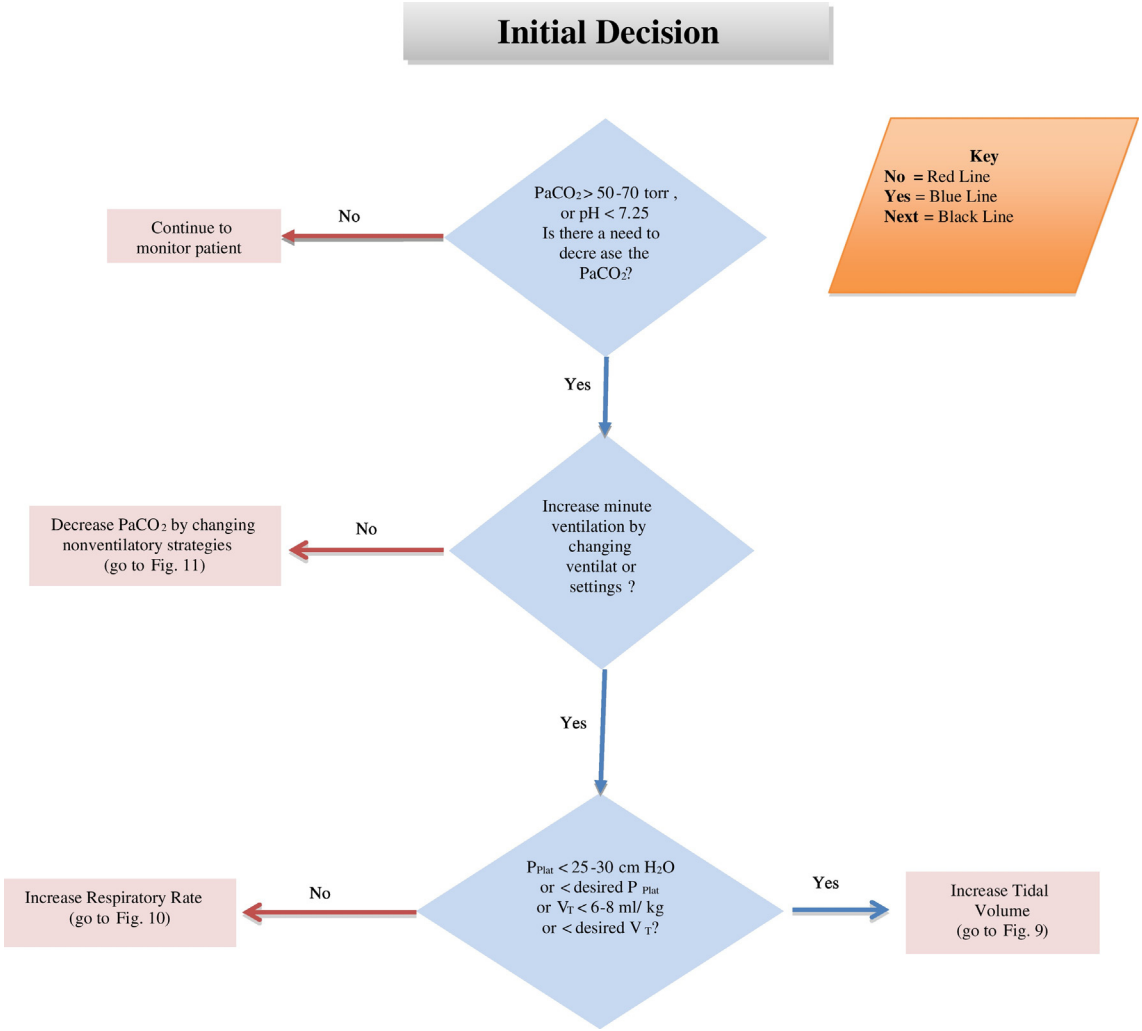

Fig. 8. Initial decision. Fig. 8 demonstrates the initial decision necessary to determine how to reduce the $PaCO_2$.

compression of the pulmonary capillaries. This causes reduced perfusion to the over-distended alveoli and an increase in the ventilation/perfusion ratio, which may increase the dead space and result in an increased $PaCO_2$. A decremental PEEP trial involves decreasing the set PEEP 1 or 2 cm H_2O every one to two minutes while monitoring the dynamic compliance (C_{dyn}), tidal volume, and SpO_2. If the Total PEEP was too high, as the set PEEP is decreased, the C_{dyn} will increase. The optimal PEEP level can be identified as the point at which the highest C_{dyn} occurred. The set PEEP level should be set 2–3 cm H_2O above this point [6,10].

If the desired increase in minute ventilation is achieved, ABG's should be repeated after 30 min and the patient continually re-evaluated. If the desired increase in minute is not achieved, see the section entitled 'the Initial Decision' (Fig. 8).

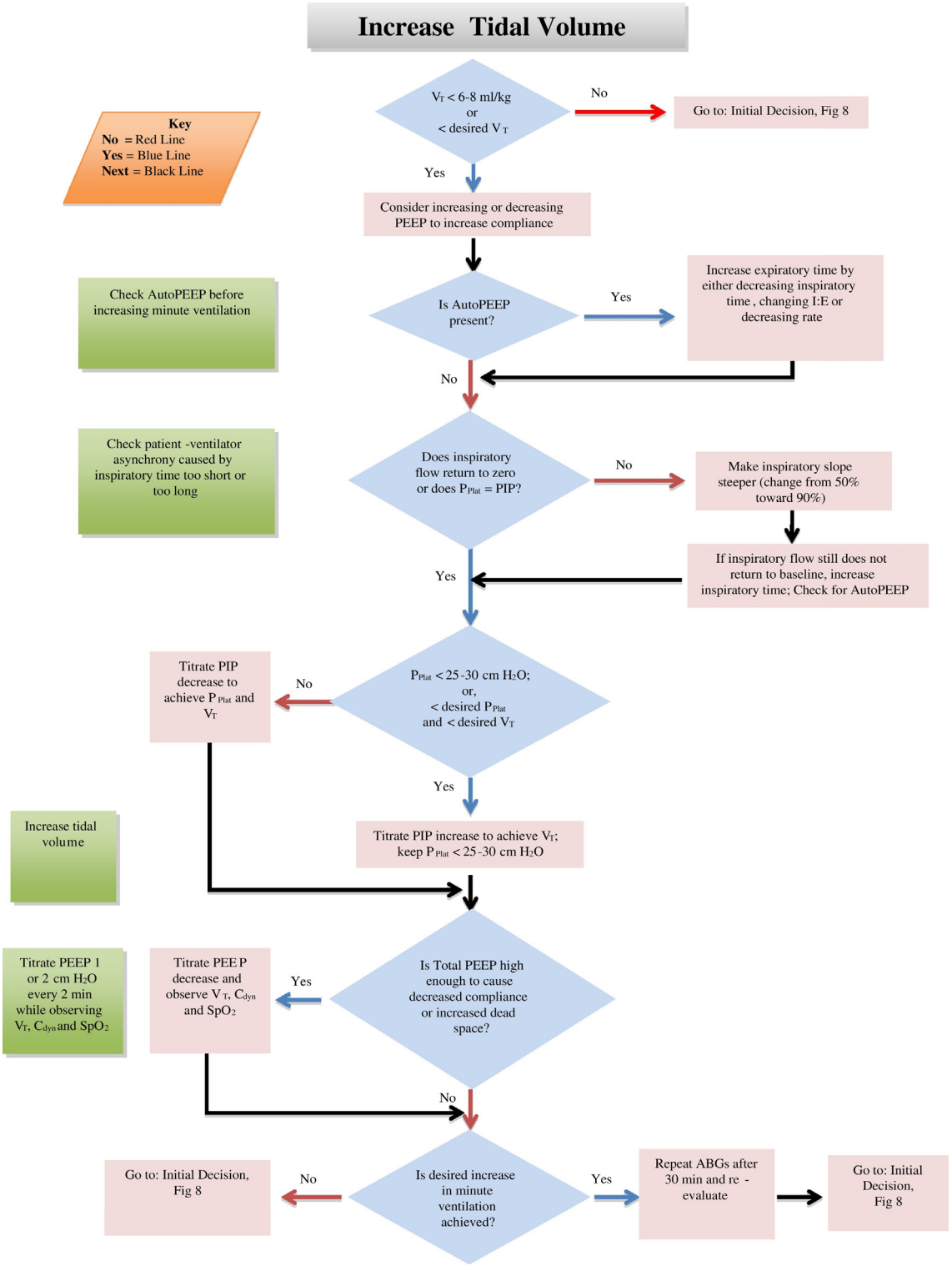

Fig. 9. Increase tidal volume. Fig. 9 demonstrates the options that are available during PC-CMV to increase the tidal volume.

9.1.3. Increasing respiratory rate

The total time in one respiratory cycle is the amount of time from the beginning of one breath (inspiration) to the beginning of the next breath. When the decision is made to increase the respiratory rate, the total time will be decreased.

$$\text{Total Time (sec)} = 60\ \text{s}/\ \text{min}/\text{f (BPM)}$$

$$\text{Total Time} = \text{Inspiratory time} + \text{Expiratory Time}$$

Because total time equals inspiratory time plus expiratory time, the total time can be decreased by shortening inspiratory time, shortening expiratory time, or shortening inspiratory and expiratory time. The guide as to whether the inspiratory time or the expiratory time should be shortened is based upon the flow-versus-time waveform (Fig. 10). If the inspiratory flow returns to baseline and an inspiratory pause is present, the inspiratory time can be decreased without producing any change in tidal volume. However, care must be taken to not reduce inspiratory time to the extent that inspiratory flow no longer returns to baseline, as this may result in a decrease in delivered tidal volume.

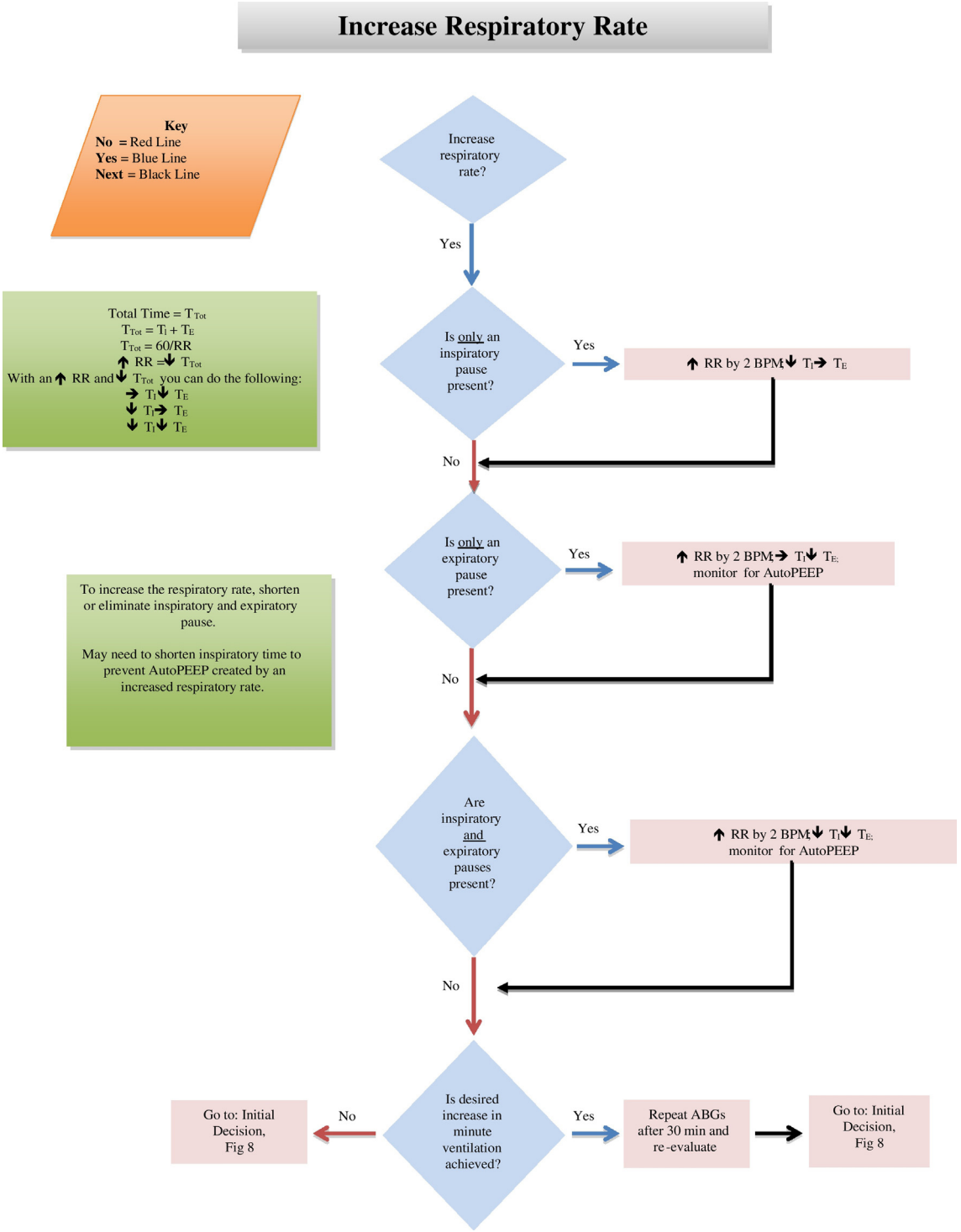

Fig. 10. Increase respiratory rate. Fig. 10 demonstrates the options that are available during PC-CMV to increase the set respiratory rate.

If the expiratory flow returns to baseline and is long enough to cause an expiratory pause (no AutoPEEP), the expiratory time can be reduced by increasing the respiratory rate by 2 BPM ensuring to carefully monitor for AutoPEEP. If both an inspiratory pause and an expiratory pause are present, inspiratory time can be decreased along with increasing respiratory rate by 2 BPM, again making sure that tidal volume is not decreased and AutoPEEP does not occur.

If the ventilator is set up to maintain a constant I:E ratio, it is important to note that increasing the set rate will result in a proportional decrease in inspiratory time and expiratory time. The opposite is also true, that decreasing the set respiratory rate will lengthen inspiratory time and expiratory time, proportionally.

If the desired increase in minute ventilation is achieved, ABG's should be obtained after 30 min and the patient continually re-evaluated. If the desired increase in minute ventilation is not achieved, see the section entitled 'the Initial Decision' (Fig. 8).

9.1.4. Nonventilatory change strategies for reducing $PaCO_2$

An increase in airway resistance increases the time constant, increases the amount of time it takes for the alveolar pressure to reach the set pressure, and increases the likelihood of AutoPEEP. Therefore, if the patient has an increased airway resistance that can be reduced, doing so will result in an increase in delivered tidal volume and the minute ventilation should increase. Options to decrease the airway resistance include administration of a bronchodilator, removal of secretions, and possibly replacing an endotracheal or tracheostomy tube which is obstructed with dry sputum or secretions. However, the use of intravenous beta agonists has been shown to increase the

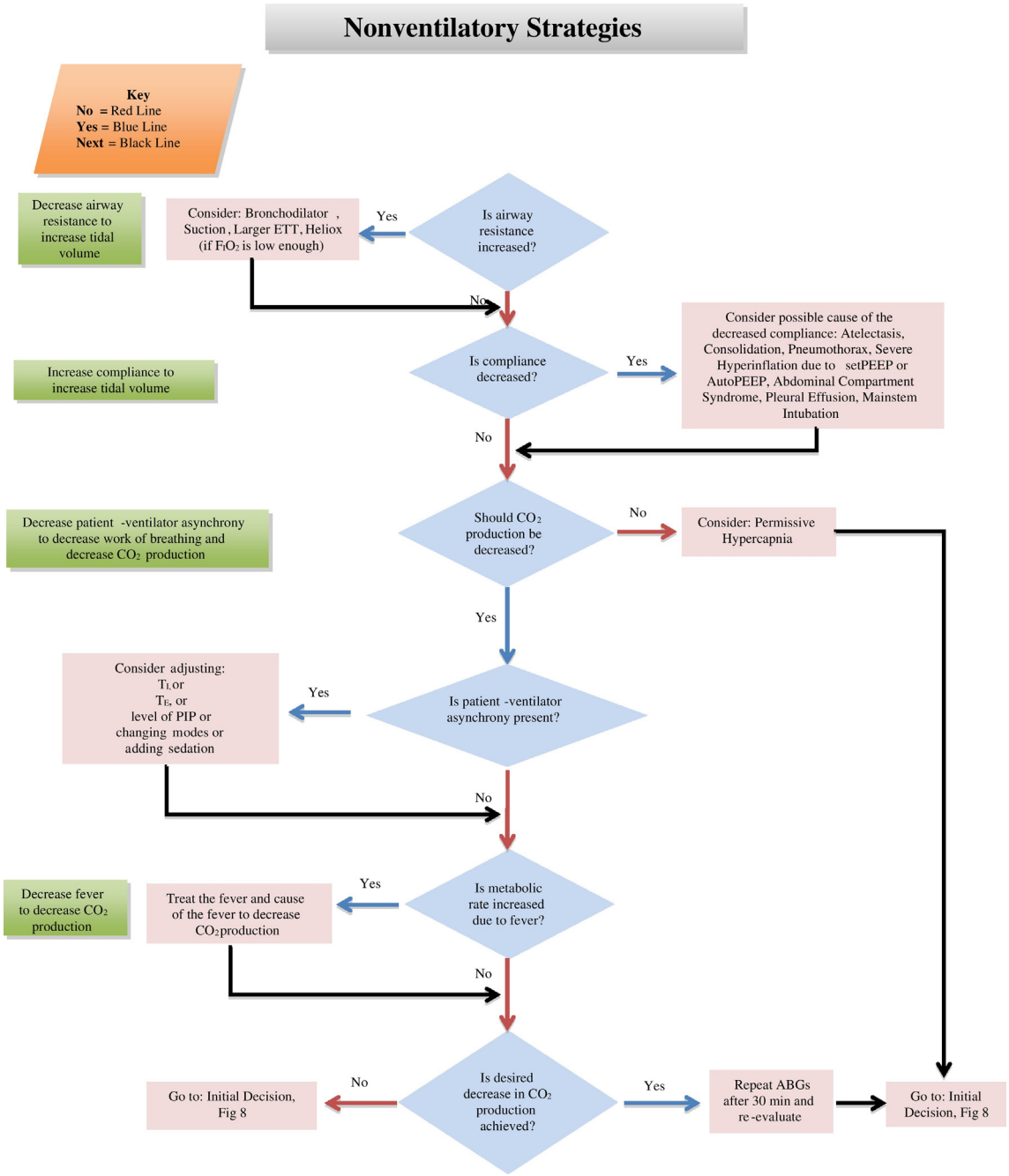

Fig. 11. Nonventilatory strategies. Fig. 11 demonstrates the non-ventilatory strategies to consider when a patient has an increased $PaCO_2$.

mortality in patients with ARDS [11]. The use of Heliox may also be considered, as long as the F_IO_2 is low enough to allow for an 80/20 or 70/30 mixture of Helium/Oxygen, and the ventilator is calibrated for this mixture. Fig. 11 outlines a strategic approach to decreasing $PaCO_2$ using nonventilatory strategies.

If the patient's CO_2 production is increased, consider methods of reducing CO_2 production. Improved patient-ventilator synchrony may reduce CO_2 production and may require altering the inspiratory time, expiratory time, I:E, Delta P_{Insp}, or changing modes of ventilation. Sedation, anesthesia, and neuromuscular blockade may be necessary in some situations. If the patient has a fever, reducing the temperature is likely to reduce both CO_2 production and the $PaCO_2$. Other methods of reducing the metabolic rate and reducing CO_2 production include a nutritional analysis to check for over feeding.

Permissive hypercapnia, as previously discussed, refers to using a limited minute ventilation and allowing the $PaCO_2$ to gradually increase. Generally, as long as the increase in $PaCO_2$ is gradual, and the pH > 7.25, the respiratory acidosis is well-tolerated. However, some sedation is usually required [5,6,9].

If the desired decrease in CO_2 production is achieved, ABGs should be obtained within 30 min and the patient continually re-evaluated. If the

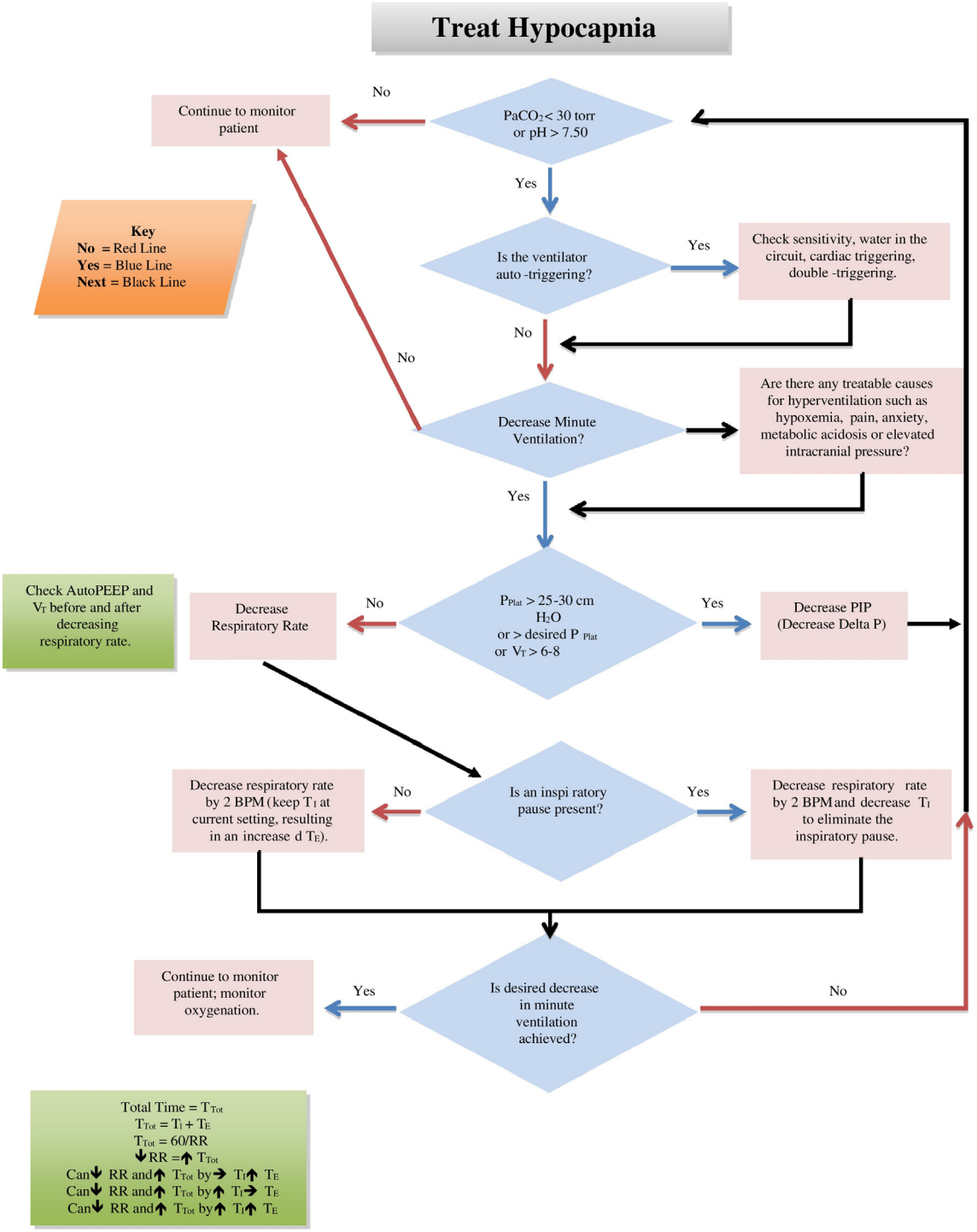

Fig. 12. Treat hypocapnia. Fig. 12 demonstrates options to consider when a patient has hypocapnia.

desired decrease in CO_2 production is not achieved, refer to the section entitled, 'Initial Decision' (Fig. 8).

9.2. Treating hypocapnia

Auto-triggering refers to an additional breath being delivered that was not triggered by the patient's inspiratory effort. Auto-triggering may occur if the ventilator sensitivity is set too high (too sensitive). Generally, a pressure trigger of −1 cm H_2O is sufficient to allow the patient to trigger a breath, yet not so sensitive as to result in auto-triggering. A flow trigger of 2 or 3 LPM is generally sufficient and not too sensitive. Auto-triggering may also occur if there is a leak in the system, such as that of an endotracheal cuff leak or a leak in a chest tube (bronchopleural fistula). When condensation collects in the circuit, the tidal motion of the water during inspiration and expiration can create enough of a change in pressure or flow to trigger a breath. Always make sure that condensation is not allowed to collect in the circuit. Another cause of auto-triggering is referred to as cardiac triggering. Patients who have hyper-dynamic cardiac pulsations may experience enough movement of the ventricle to trigger a breath. This is sometimes seen in patients who are in a high cardiac output state of sepsis. Auto-triggering may also occur from the inflation and deflation of an intra-aortic balloon bump. If this occurs, it may be necessary to make the ventilator slightly less sensitive to the patient's effort to eliminate the Auto-triggering. Double-triggering refers to the patient continuing to inhale, even though the inspiratory time has terminated; this results in two breaths without an exhalation, and an increased tidal volume. Inspiratory time should be checked to make sure that it is not inappropriately too short.

When evaluating acid-base status, if the $PaCO_2$ is <30 Torr or the pH is >7.50, it is important to determine whether or not there are treatable causes of an increased minute ventilation such as pain and anxiety. If there are no treatable causes and the decision is made to decrease the minute ventilation, the ventilator should first be checked for auto-triggering and for double-triggering.

The next step in reducing the minute ventilation is to evaluate the plateau pressure and tidal volume. If the plateau pressure is >25–30 cm H_2O or greater than the desired plateau pressure, or if the tidal volume is >6–8 ml/kg PBW or greater than the desired tidal volume, the Delta P_{Insp} can be reduced in steps of 1 or 2 cm H_2O.

If the plateau pressure is not >25–30 cm H_2O and is not greater than the desired plateau pressure and the tidal volume is not >6–8 ml/kg PBW and is not greater than the desired tidal volume, the respiratory rate can be decreased. If the inspiratory flow returns to baseline, then the respiratory rate can be reduced by 2 breaths per minute, without changing the inspiratory time. This will increase the expiratory time and result in a reduced minute ventilation. If an inspiratory pause is present, inspiratory time can be reduced, eliminating the inspiratory pause, and the respiratory rate can be reduced. If the inspiratory flowrate does not return to baseline, increase inspiratory time by 0.1–0.2 s and reduce the respiratory rate by 2 breaths per minute. Always assess the patient to ensure that the patient does not become asynchronous with the ventilator when changing inspiratory time. Usually, an inspiratory time of 0.6–1.2 s is appropriate. Rarely is an inspiratory time >1.2 s well tolerated by patients. The suggested method of treating hypocapnia while in PC-CMV is illustrated in Fig. 12.

If the desired decrease in minute ventilation is achieved, the patient should be continually monitored, including oxygenation. However, if the desired decrease in minute ventilation is not achieved, the $PaCO_2$ and pH should be re-evaluated, as listed at the top of this algorithm.

10. Discussion

Pressure-targeted ventilation allows the clinician to control the airway pressure and allows the patient to influence the inspiratory flowrate and tidal volume. In some cases, this improves patient-ventilator synchrony and reduces the work of breathing. Even though multiple articles have been published on PC-CMV, there is little evidence that PC-CMV improves outcomes when compared to VC-CMV. However, this may be due to inconsistencies in ventilator management strategies during PC-CMV.

Table 1
Summary of options to increase minute ventilation.
Table 1 is a summary of the available options to increase the minute ventilation during PC-CMV.

Options to increase minute ventilation in PCV This table summarizes options available in PC-CMV that should be considered when an increase in minute ventilation is desired.	
Increase tidal volume (V_t) Goal V_t: <6–8 ml/kg PBW	Increase respiratory rate (RR) $T_{Tot} = 60/\text{rate}$ $T_{Tot} = TI + T_E$
• Increase Delta P (Keep PPlat <25–30 cm H_2O) ○ Decrease AutoPEEP ▪ Decrease airway resistance ▪ Increase T_E • Decrease T_I • Decrease Rate	• Decrease T_{Tot} ○ Decrease T_I ○ Decrease T_E ○ Decrease TI and T_E
○ Increase Ti (if PPlat < PIP) ○ Increase PIP ○ Decrease Set PEEP (If over-distended) ▪ Monitor Oxygenation	

The algorithms and descriptions included in this article are intended to provide a standardized approach to the management of PC-CMV. Every patient is unique and needs to be evaluated individually; however, these algorithms and descriptions are intended to provide the clinician with a systematic method of evaluating the patient's physiology, clinical status, ventilating pressures, and ventilator graphics, resulting in a logical progression through which to recommend appropriate changes in ventilator settings.

As summarized in Table 1, when a clinician wants to increase the minute ventilation, either the tidal volume can be increased or the respiratory rate can be increased. However, there are multiple options available that will result in an increased tidal volume and several options available that will result in an increased respiratory rate. Selecting which option is appropriate for any given patient requires the clinician to progress through a systematic analysis of each option, after a thorough evaluation of the patient.

11. Summary

Pressure-controlled ventilation is a method of ventilating patients that may be beneficial for some patients. However, successful utilization of the mode requires a thorough understanding of PC-CMV, physiology, pathophysiology, graphic analysis, and the mechanical aspects of each specific ventilator. If a standardized and systematic approach is used to manage patients being ventilated in PC-CMV, it is possible that future studies will be performed that use more comparable treatment algorithms between studies. The goals of identifying a consistent approach to the management of PC-CMV are to glean comparable data in an effort to try to determine whether or not there is a significant difference in outcomes when ventilating patients with PC-CMV versus VC-CMV, and to improve management of patients ventilated with PC-CMV.

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