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Auto-positive end-expiratory pressure: Mechanisms and treatment

■ ABSTRACT

Auto-positive end-expiratory pressure (auto-PEEP) is a common problem in patients receiving full or partial ventilatory support, as well as in those ready to be weaned from the ventilator. Physicians should be alert for it and take measures to reduce it, as it can have serious consequences.

■ KEY POINTS

Auto-PEEP occurs much more frequently than was previously thought.

Auto-PEEP and dynamic hyperinflation may cause significant discomfort and precipitate patient-ventilator asynchrony through several mechanisms.

Auto-PEEP increases the work of breathing and can worsen gas exchange and decrease cardiac output.

In some patients with auto-PEEP due to airflow obstruction and dynamic hyperinflation, external PEEP may be used to decrease the work of breathing and relieve dyspnea.

AUTO-POSITIVE END-EXPIRATORY PRESSURE (auto-PEEP), a common problem in patients receiving mechanical ventilation, can have serious consequences. The clinician needs to fully understand the physiology of auto-PEEP so as to choose appropriate ventilator settings.

Why should generalists think about mechanical ventilation? A recent study showed that intensivists care for only 36.8% of critically ill patients in the United States, while general internists, surgeons, and anesthesiologists manage the rest.¹ The incidence of acute respiratory failure requiring mechanical ventilation increases nearly 10-fold between the ages of 55 and 85 years.² With the aging of the population, even more generalists will likely care for these patients in the future, and it is necessary for them to understand the important elements of managing patients on mechanical ventilation.

This review, part of a series of articles covering topics in mechanical ventilation published in this journal,³⁻⁵ provides an overview of auto-PEEP.

■ WHAT IS AUTO-PEEP?

Positive end-expiratory pressure (PEEP) is defined as pressure in the alveoli at the end of exhalation that is greater than the atmospheric pressure.

Normally, during passive exhalation, the lungs empty by elastic recoil, and at the end of exhalation the alveolar pressure is the same as the atmospheric pressure. However, for several reasons, the lungs may not deflate fully before the next breath starts, and the pressure remains elevated. PEEP can be applied inten-

TABLE 1

Physiologic mechanisms of auto-positive end-expiratory pressure

Dynamic hyperinflation plus intrinsic expiratory flow limitation
Chronic obstructive pulmonary disease

Dynamic hyperinflation without intrinsic expiratory flow limitation
Breathing pattern and ventilator settings
Rapid breaths
High tidal volume
Inspiration greater than expiration
End-inspiratory pause
Added flow resistance
Fine-bore endotracheal tube
Ventilator tubing and devices

Without dynamic hyperinflation
Recruitment of expiratory muscles

Auto-PEEP should be anticipated in exacerbations of COPD

tionally from the outside, but when it arises inadvertently it has been called *auto-PEEP*, *occult PEEP*, or *intrinsic PEEP*.^{6,7}

Mechanical causes of auto-PEEP in a passive respiratory system are:

- Increased resistance to expiration, eg, in a patient with asthma or chronic obstructive pulmonary disease (COPD)
- A large volume of air delivered per minute by the ventilator
- A short expiratory time
- A combination of these factors.

WHO DEVELOPS AUTO-PEEP?

Auto-PEEP is more common than previously thought in critically ill, mechanically ventilated patients. Unexpected auto-PEEP occurs in up to 35% of patients even when there is no significant history of wheezing or COPD.⁸

Auto-PEEP should be anticipated in patients with respiratory failure due to obstructive lung disease. Patients with an exacerbation of COPD who require intubation and mechanical ventilation frequently develop dynamic hyperinflation from impaired lung-emptying due to a limitation of expiratory flow, resulting in auto-PEEP.^{7,9}

However, auto-PEEP and dynamic hyperinflation may also occur without any intrinsic

limitation on expiratory flow,¹⁰ and auto-PEEP is not uncommon in ventilated patients with sepsis, respiratory muscle weakness,⁸ or the adult respiratory distress syndrome.¹¹

THREE TYPES OF AUTO-PEEP

Three types of auto-PEEP can occur in patients on mechanical ventilation, each with a different cause and consequences (TABLE 1).¹⁰

Dynamic hyperinflation with intrinsic expiratory flow limitation

The main cause of auto-PEEP in patients with COPD on mechanical ventilation is closure of the airways, which limits expiratory flow.¹²

In COPD, the alveolar attachments that normally keep the smaller airways open via radial traction are lost. Consequently, during exhalation, when the pleural pressure is positive, these airways can be compressed and collapse. The flow of air during expiration is therefore limited and cannot be augmented by effort, resulting in auto-PEEP and dynamic hyperinflation.¹²

This condition can be helped by applying external PEEP (FIGURE 1).

Dynamic hyperinflation without expiratory flow limitation

Auto-PEEP can also occur even if the airways are widely patent without intrinsic expiratory flow limitation. This may occur if the volume of air delivered per minute is high (usually > 20 L/minute), if the exhaled time is too short to allow exhalation to functional residual capacity, or if exhalation is impeded by a blockage external to the patient, such as a blocked endotracheal tube, exhalation valve, or PEEP valve.¹⁰

Under such circumstances, external PEEP would not be beneficial because it would impose a back pressure to expiratory airflow, causing parallel increases in lung volume and airway, alveolar, and thoracic pressures.¹⁰

Exaggerated expiratory activity without dynamic hyperinflation

Although auto-PEEP and dynamic hyperinflation are usually thought to be synonymous, auto-PEEP does not necessarily imply dynamic hyperinflation. Auto-PEEP may also occur when strong expiratory muscle activity con-

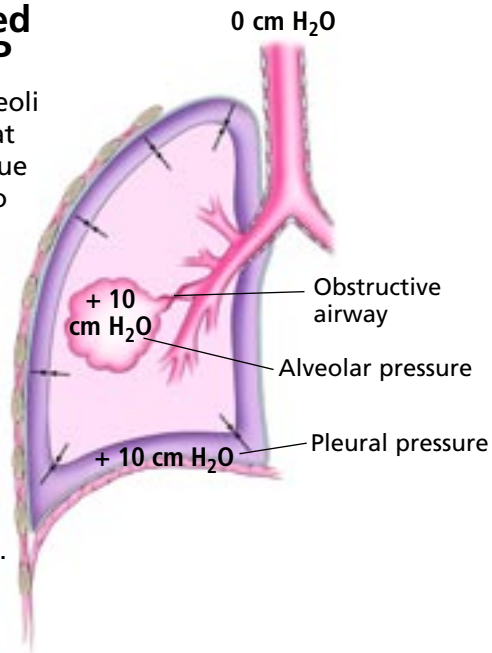


■ Auto-PEEP in chronic obstructive pulmonary disease

Auto-positive end-expiratory pressure (auto-PEEP) is common in patients with respiratory failure due to obstructive lung disease who require intubation and mechanical ventilation. Causes: obstruction (the most common cause, shown here), rapid breathing, large volumes of air, and exaggerated expiratory effort.

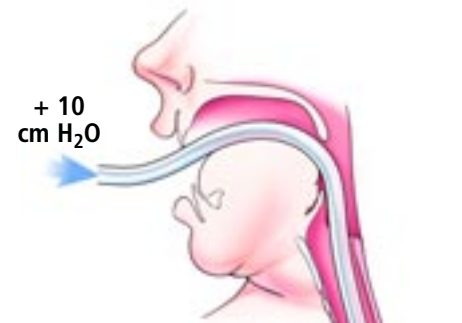
Air is trapped in auto-PEEP

In auto-PEEP, alveoli remain inflated at end-expiration due to obstruction, so alveolar pressure is greater than atmospheric pressure. In the absence of inspiratory effort, intrapleural pressure approximates alveolar pressure.



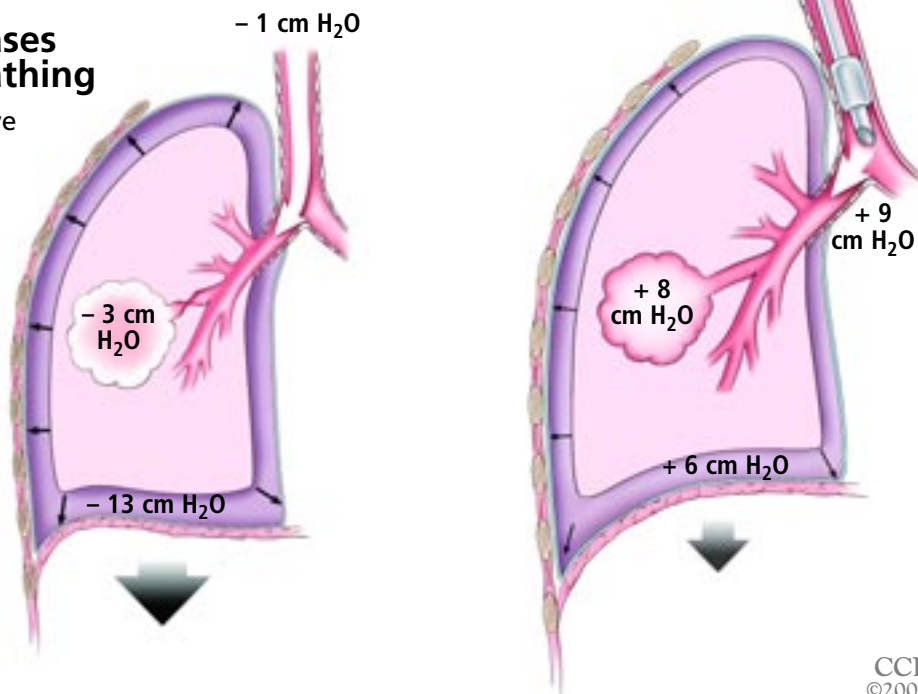
External PEEP treats auto-PEEP

The positive pressure of external PEEP eases the amount of work the diaphragm must do to draw air in, by allowing small negative deflections in intrapleural pressure to be sensed by the ventilator when the patient tries to trigger a breath.



Auto-PEEP increases the work of breathing

To overcome the positive pressure in the alveoli during inspiration, the diaphragm must generate enough negative pressure to exceed the auto-PEEP and transmit negative pressure to the central airways, generating airflow.



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FIGURE 1

Estimating auto-positive end-expiratory pressure (auto-PEEP)

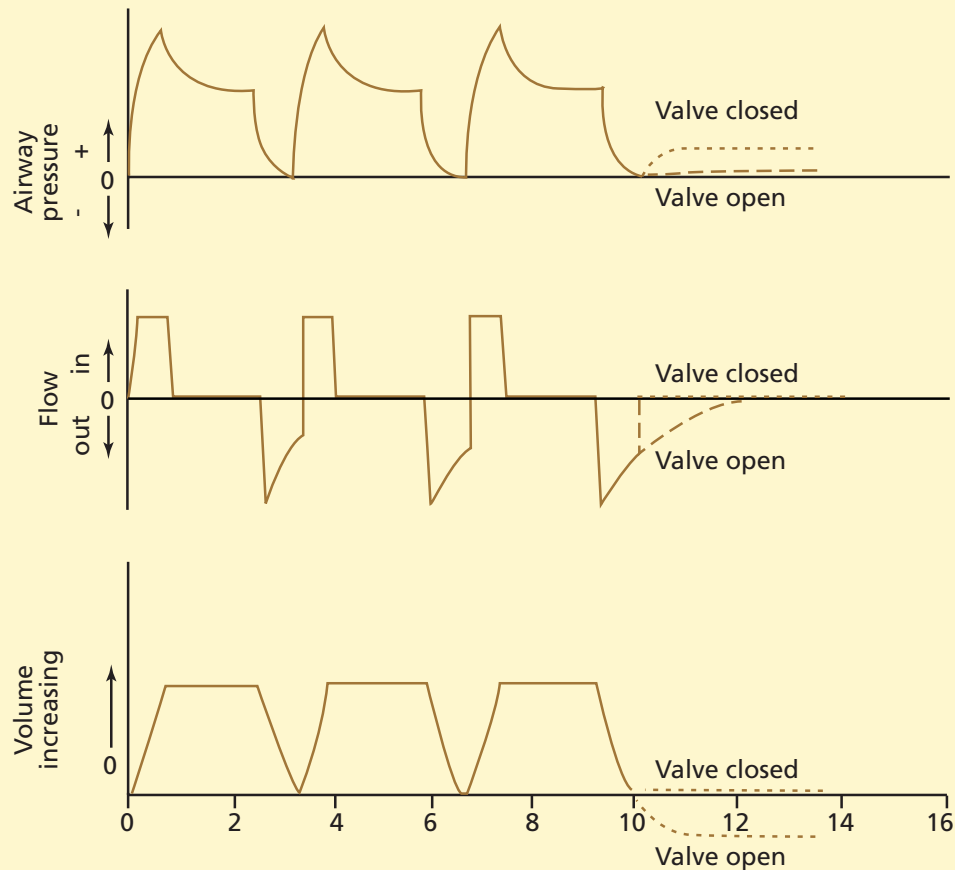


FIGURE 2. Expiratory hold techniques to estimate auto-PEEP. The exhalation valve is closed during an expiratory hold at the end of the set expiratory time. When the flow equals zero, airway pressure rises to the auto-PEEP level. With the valve open, flow continues, and the additional exhaled volume equals the volume of trapped gas.

MACINTYRE NR. INTRINSIC PEEP. PROB RESPIR CARE 1991; 4:45, WITH PERMISSION.

Auto-PEEP is measured by occluding the airway at end-expiration for several seconds

tributes to alveolar pressure, often with normal or even low lung volumes. If the flow persists to the end of the expiratory cycle, there will be an end-expiratory gradient of alveolar to central airway pressure—an auto-PEEP effect without lung distention.^{13,14} This auto-PEEP phenomenon is due to dynamic airway collapse with exaggerated expiratory activity.

Zakynthinos et al¹⁵ demonstrated that in intubated patients who are spontaneously breathing and actively exhaling, auto-PEEP due to expiratory muscle contraction can be estimated by subtracting the average expiratory rise in gastric pressure from the end-expiratory airway pressure during airway occlusion.

CONSEQUENCES OF AUTO-PEEP

Increases the work of breathing

Auto-PEEP causes a considerable increase in the resistive and elastic work of breathing,^{16,17} which may interfere with attempts at weaning from mechanical ventilation.¹⁸ This can cause significant discomfort and precipitate patient-ventilator asynchrony.

Worsens gas exchange

Brandolese et al compared the impact of auto-PEEP and external PEEP on pulmonary gas exchange in mechanically ventilated patients.¹⁹ Arterial oxygen tension was lower in patients



with auto-PEEP than in patients with a comparable level of external PEEP, an effect the authors attributed to a less homogenous distribution of auto-PEEP among lung units.

Can cause hemodynamic compromise

Auto-PEEP also has hemodynamic consequences. Elevated intrathoracic pressure reduces the preload of the right and left ventricles, decreases left ventricular compliance, and can increase right ventricular afterload by increasing pulmonary vascular resistance. This can lead to hemodynamic compromise.^{12,20}

In a dog model described by Marini et al,²¹ selective hyperinflation of the lower lobes (particularly the right lower lobe) or any distention of lung tissue adjacent to the right side of the heart was associated with decreased stroke volume. The decrease in stroke volume was more closely related to an increase in right atrial pressure than in left atrial pressure, implying that impaired venous return was the dominant cause of reduced cardiac output. This mechanism is likely the cause of hypotension in patients with inadvertent PEEP.

Hemodynamic effects of auto-PEEP should be considered as a possible reversible cause of pulseless electrical activity. In one report,²² auto-PEEP may have played a part in up to 13 (38%) of 34 patients with electromechanical dissociation.

During cardiopulmonary resuscitation, dynamic hyperinflation can develop in patients with obstructive airway disease, owing to rapid manual ventilation with inadequate time for exhalation. This elevated end-expiratory pressure (auto-PEEP) decreases venous return and may depress cardiac output even after a cardiac rhythm has been established. Transient withdrawal of ventilation allows the dynamic hyperinflation to diminish, reducing intrathoracic pressure and permitting the return of spontaneous circulation.

Can lead to inappropriate treatment

Failure to recognize auto-PEEP and adjust for it can lead to inappropriate treatment in several ways:

- Misinterpretation of central venous and pulmonary artery catheter pressure measurements¹²: the auto-PEEP-induced

increase in intrathoracic pressure may falsely increase the pulmonary capillary wedge pressure and right atrial pressure, which can lead to mistakes in hemodynamic management.

- Erroneous calculations of static respiratory compliance: the true value of static compliance will be underestimated in the presence of auto-PEEP.¹⁹
- Inappropriate fluid administration or unnecessary vasopressor therapy.

■ RECOGNIZING AUTO-PEEP

Four practical clues may suggest the diagnosis of auto-PEEP:

- Exhalation that continues until the next breath starts, as determined on physical examination²³ or on graphic display of expiratory flow vs time in a patient on a ventilator that is set to deliver a certain number of breaths per minute
- A delay between the start of inspiratory effort and the drop in airway pressure or the start of machine-delivered flow in a patient on a ventilator that is set to deliver breaths on demand
- Failure of peak airway pressure to change when external PEEP is applied
- In paralyzed or heavily sedated patients, reduction of plateau pressure after prolonged exhalation.

■ HOW TO MEASURE AUTO-PEEP

Static auto-PEEP. Auto-PEEP can be accurately measured only in patients without active respiratory effort. It is routinely determined under static conditions by occluding the airway at end-exhalation. During controlled mechanical ventilation, reliable quantification of auto-PEEP requires an end-expiratory hold maneuver, terminating expiratory flow and allowing equilibration of alveolar pressure and the airway pressure (FIGURE 2). The resulting airway pressure represents the average total PEEP present within a nonhomogeneous lung, and auto-PEEP is calculated by subtracting external PEEP from total PEEP.

Dynamic auto-PEEP. There is no accepted, reliable method to measure auto-PEEP in spontaneously breathing patients. However,

Suspect auto-PEEP if exhalation continues until the next breath starts

Auto-positive end-expiratory pressure: measured value can underestimate true value

End-expiratory airway occlusion pressure (cm H₂O)

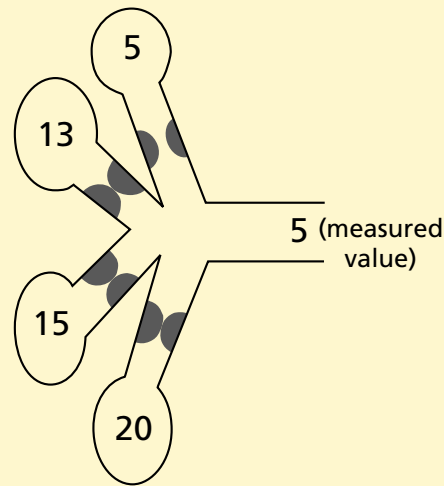


FIGURE 3. Hypothetical model showing low measured auto-positive end-expiratory pressure despite high average end-expiratory alveolar pressure as a consequence of widespread airway closure.

FROM LEATHERMAN JW, RAVENSCRAFT SA: LOW MEASURED INTRINSIC POSITIVE END-EXPIRATORY PRESSURE IN MECHANICALLY VENTILATED PATIENTS WITH SEVERE ASTHMA: HIDDEN AUTO-PEEP. CRIT CARE MED 1996; 24:541–546, WITH PERMISSION.

an esophageal balloon catheter can be used to measure the auto-PEEP during unoccluded breathing in such patients, as the esophageal pressure is assumed to be about the same as the pleural pressure. This is achieved by calculating the negative deflection in esophageal pressure from the start of inspiratory effort to the onset of inspiratory flow.

This method is based on the assumption that the change in esophageal pressure reflects the inspiratory muscle pressure required to counterbalance the end-expiratory elastic recoil of the respiratory system (ie, auto-PEEP). To obtain valid measurements, the inspiratory and expiratory muscles need to be relaxed at end-expiration.^{13,14}

It has been suggested that dynamic auto-

TABLE 2

Treatment of auto-positive end-expiratory pressure

Change ventilator settings

- Increase expiratory time
- Decrease respiratory rate
- Decrease tidal volume

Reduce ventilatory demand

- Reduce anxiety, pain, fever, shivering
- Reduce dead space
- Give sedatives and paralytics

Reduce flow resistance

- Use large-bore endotracheal tube
- Suction frequently
- Give bronchodilators

Counterbalance expiratory flow limitation

- External positive end-expiratory pressure

PEEP reflects the lowest regional auto-PEEP and therefore underestimates static auto-PEEP in the presence of heterogenous mechanical properties,²⁰ ie, if some airways are blocked and some not, or some parts of the lung are stiff and others are compliant. Maltias et al²⁴ demonstrated that dynamic auto-PEEP considerably underestimates static auto-PEEP in patients with significant airway obstruction. In such patients two major problems must be solved, therefore, to obtain a correct measure of auto-PEEP: airway occlusion must be synchronized to the end of the expiratory cycle, and respiratory muscle activity must be suppressed. On the other hand, tensing of abdominal expiratory muscles at end-expiration may cause the measured auto-PEEP to greatly overestimate the end-expiratory elastic recoil pressure.¹⁴

It is also crucial that the airway occlusion be maintained for several seconds to avoid gross underestimation of average end-expiratory alveolar pressure. Some lung units may not communicate with the proximal airway, as the peripheral airways may be blocked by mucous hypersecretion or increased wall thickness, and the alveolar pressure in these noncommunicating lung units will not directly contribute to the pressure measured during airway occlusion (FIGURE 3).²⁵

■ REDUCING AUTO-PEEP

Reducing dynamic hyperinflation and auto-PEEP can have a major impact on the care of mechanically ventilated patients, especially those with exacerbations of COPD and asthma.

If auto-PEEP is suspected, it should be measured and its causative factors should be delineated. Efforts to minimize auto-PEEP should be directed at the contributing factors.

The following methods can be used to avoid or reduce auto-PEEP (TABLE 2):

- Change the ventilator setting to provide the longest expiratory phase compatible with the patient's comfort and adequate gas exchange
- Reduce patient ventilatory demand and minute ventilation
- Minimize airflow resistance.

A discussion of these methods is beyond the scope of this manuscript but can be found in several recent reviews.^{9,10,12} We will discuss the role of external PEEP in the management of patients with auto-PEEP.

How much external PEEP to apply, and why?

In patients with airflow obstruction, external PEEP is employed to decrease the work of breathing and relieve dyspnea, and not as a treatment for the underlying condition.

The seeming paradox of why applying external PEEP does not make auto-PEEP worse has been explained by analogy to a stream with a waterfall (FIGURE 4).^{26,27} In this analogy, the upstream part of the stream is like the distal airways, the downstream part of the stream is like the proximal airways, and the waterfall is like a site of critical airway closure. Pressure in the airway is like the hydrostatic pressure in the stream.

Now suppose the tide comes in (external PEEP is applied), raising the height of the stream below the waterfall. This has no effect on either the flow or the pressure upstream of the waterfall unless the water level rises above the level of the waterfall (if the level of external PEEP exceeds the critical closing pressure). Above this level, external PEEP increases the pressure upstream and exacerbates hyperinflation. However, if external PEEP is kept below 75%²⁸ to 85%,^{9,29} of the

External PEEP to treat auto-PEEP: The analogy of the waterfall

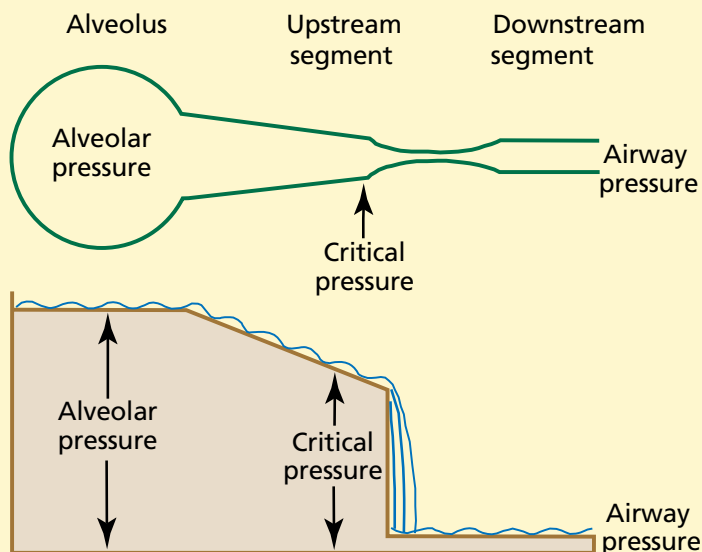


FIGURE 4. Top, expiratory flow limitation within a lung. The alveolar pressure at the end of passive expiration (auto-PEEP) in a dynamically hyperinflated patient exceeds the critical pressure at which dynamic airway compression occurs. External PEEP, applied at the airway opening, will not worsen auto-PEEP if it does not exceed the critical pressure.

Bottom, analogous circumstances governing hydrostatic pressure above and below a waterfall. The amount of flow over the waterfall remains constant until the level of water in the stream below (the airway pressure) reaches the height of waterfall (the critical pressure) but not the stream above (the alveolar pressure).

FROM GOTTFRIED SB: THE ROLE OF PEEP IN MECHANICALLY VENTILATED COPD PATIENT. IN MARINI JJ, ROUSSOS C (EDITORS): VENTILATORY FAILURE. NEW YORK, SPRINGER-VERLAG, 1991:392-418. WITH PERMISSION.

auto-PEEP level, worsening hyperinflation or circulatory depression are unlikely to occur.

But why does external PEEP help? In a patient with auto-PEEP, if the ventilator is set to deliver patient-initiated breaths, the inspiratory muscles have to produce an initial effort to overcome the opposing recoil pressure before the ventilator can be triggered and inspiratory flow can begin. In that respect, auto-PEEP acts as an inspiratory threshold and represents an additional impedance that the respiratory muscles have to face. Under these circumstances,



Will the patient benefit from extrinsic positive end-expiratory pressure (PEEP)?

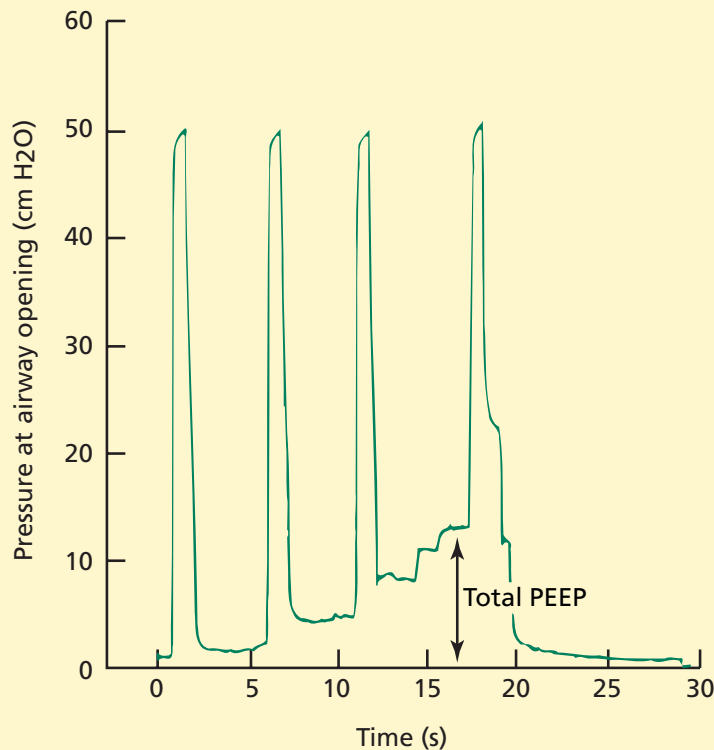


FIGURE 5. Pressure at the airway opening vs time during controlled ventilation in a patient with an acute exacerbation of chronic obstructive pulmonary disease.

Auto-PEEP was measured by end-expiratory airway occlusion. From the first mechanical inflation, extrinsic PEEP was set by the ventilator at 5 cm H₂O (second inflation) and at 10 cm H₂O (third inflation). Then the total PEEP (extrinsic PEEP + auto-PEEP) was measured again by end-expiratory airway occlusion.

Since PEEP partly replaced auto-PEEP, without adding it to it, because of flow limitation, the peak cycling pressure did not change despite increasing PEEP set by the ventilator.

This figure illustrates a similar way to assess the effect of extrinsic PEEP set by the ventilator in patients with auto-PEEP, at least during controlled ventilation.

FROM ROSSI A, POLESE G, BRANDI G, CONTI G. INTRINSIC POSITIVE END-EXPIRATORY PRESSURE (PEEP). *INTENSIVE CARE MED* 1995; 21:522–536. COPYRIGHT SPRINGER-VERLAG; REPRINTED WITH PERMISSION.

applying external PEEP (during mechanical ventilation) or continuous positive airway pressure (during spontaneous breathing) may reduce the work of breathing.

Secondly, by stenting collapsible airways, external PEEP increases expiratory flow, much as pursed-lip breathing does for nonintubated patients with COPD.³⁰

A practical method of determining whether an actively breathing patient may benefit from external PEEP may be to observe the response of ventilator cycling pressures to small increments of external PEEP (FIGURE 5). If the peak dynamic and static cycling pressures change very little when external PEEP is applied or increased, then external PEEP may be helpful. On the other hand, cycling pressures that rise more or less in direct relationship to the level of external PEEP imply additional hyperinflation, and application of external PEEP in these instances may be detrimental to the patient.

In other words, external PEEP should not be applied to all patients with airflow obstruction who are mechanically ventilated—only those with auto-PEEP with flow limitation and dynamic airway compression.

Ranieri et al⁹ suggested that external PEEP less than 85% of the auto-PEEP value measured on zero end-expiratory pressure does not significantly affect lung volume or hemodynamics in patients with COPD.

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