How I Teach Auto-PEEP

Applying the Physiology of Expiration

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ABSTRACT

Teaching complex topics in mechanical ventilation can prove challenging for clinical educators, both at the bedside and in the classroom setting. Some of these topics, such as the topic of auto-positive end-expiratory pressure (auto-PEEP), consist of complicated physiological principles that can be difficult to convey in an organized and intuitive manner. In this entry of "How I Teach," we provide an approach to teaching the concept of auto-PEEP to senior residents and fellows working in the intensive care unit. We offer a framework for educators to effectively present the concepts of auto-PEEP to learners, either at the bedside or in the classroom setting, by summarizing key concepts and including concrete examples of the educational techniques we use. This framework includes specific content we emphasize, how to present this content using a variety of educational resources, assessing learner understanding, and how to modify the topic on the basis of location, time, or resource constraints.

The traditional approach to teaching mechanical ventilation often begins with a basic description of the various ventilator modes, their associated settings, and proper adjustment of settings to achieve adequate oxygenation and ventilation. Although these aspects are universally taught to trainees in the intensive care unit (ICU), more advanced concepts are often eschewed. Some fundamental concepts of mechanical ventilation incorporate complex physiological principles. Although educators may possess an intuitive understanding of such principles, effectively conveying these complex topics to a learner can be difficult. This is often the case when confronted with

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the task of explaining auto-positive end-expiratory pressure (auto-PEEP). Auto-PEEP is a common and frequently underrecognized problem in the ICU that can have serious clinical consequences (1). All clinicians managing a mechanically ventilated patient should be familiar with preventing, identifying, and treating auto-PEEP.

What makes auto-PEEP difficult to teach? First, trainees may not be familiar with the physiological factors that dictate expiratory airflow. Learners may also lack familiarity with the interpretation of ventilator scalar waveforms, including normal waveforms. In addition, effectively presenting complex topics can prove challenging, especially under the time constraints frequently encountered in the busy ICU environment. Lastly, there is often difficulty conveying the clinical relevance of physiological concepts thought to be purely academic in nature.

This entry of "How I Teach" provides an overview of our approach to teaching the concept of auto-PEEP to senior residents and fellows working in the ICU. We offer a framework for educators to effectively present the concepts of auto-PEEP to these learners, either at the bedside or in the classroom setting. We summarize the key concepts and include concrete examples of the educational techniques we use to convey the concept of auto-PEEP in a practical manner.

PRESENTING THE TOPIC

We approach the teaching of complex topics in mechanical ventilation by first partitioning them into smaller sections and by asking learners a series of manageable questions that explore critical elements of the subject matter. This approach encourages learner involvement, provides the proper context for the topic, and offers the educator a basic framework for presenting the subject in a logical, well-organized manner (Table 1). Depending on the educational context, such as the learners' degree of training or time constraints, all or just a few of the most relevant questions may be used. We typically begin with a simple question when discussing auto-PEEP: "For a relaxed, passively exhaling patient, what determines how long it takes for the patient to fully expire the inspired tidal volume?"

Answering this question involves introducing the basic elements that dictate expiratory airflow. We start with the principle of Ohm's law. The hydraulic analogy of Ohm's law states that:

$$\text{Pressure Difference } (\Delta P) = \text{Flow } (F) \times \text{Resistance } (R),$$
$$\text{and thus,}$$
$$F = \Delta P \,/\, R.$$

We typically make this physiologic concept more intuitively accessible by drawing two balloons connected via a tube and asking the learners, "What would make the air flow from one balloon to the other?" We then label each balloon with either "P_1" or "P_2" to indicate the pressures that compose the pressure gradient for flow and draw an arrow across the tube from the balloon with higher pressure to the balloon with lower pressure to indicate the direction of flow. We then label the tube with an "R" to indicate resistance and display the completed Ohm's law equation next to the figure. We may also ask, "If there is little flow between the balloons, what may be inferred about the pressures in the two balloons or about the resistance of the tubing?" to help learners understand that a lack of flow can be seen when there is no longer a pressure gradient or in the setting of high resistance.

It is often helpful to designate one of the balloons as representing the alveoli. In this case, one balloon would be labeled P_{alv}, and the other balloon as a compartment representing the proximal airway pressure

Table 1. Question-based format for teaching auto-PEEP

Eight Questions We Ask Learners	Examples of How We Teach
1. For a relaxed patient passively expiring, what determines how long it takes for the patient to fully expire the inspired tidal volume?	Volume–time scalar (Video E1 and Figures 3A and 3B)
2. What happens when a breath is initiated before a patient has completely expired the previous breath?	Thought exercise in which the learner takes breaths, noting the position of the diaphragm with complete vs. incomplete exhalation
3. What are the consequences of auto-PEEP?	Video E1
4. What factors determine how much of an inspired volume (and therefore pressure) remains in the lung at the end of expiration?	Explanation of the natural decay equation
5. How do we estimate the time required for a patient to expire without developing auto-PEEP?	Illustrations (Figure 3A), Videos E1 and E2
6. How do we estimate the expiratory time constant (τ)?	Bedside demonstrations (Videos E1 and E2)
7. What are the signs of auto-PEEP on the ventilator?	Bedside demonstrations and illustrations (Figure 4)
8. How can we address auto-PEEP?	Video E1 and Figure 2

Definition of abbreviation: auto-PEEP = auto-positive end-expiratory pressure.

near the ventilator during expiration labeled as PEEP (Figure 1). Thus, expiratory flow is determined not only by the magnitude of the pressure gradient between the patient's alveolar pressure (P_{alv}) and the ventilator's pressure at expiration (PEEP) but also by the resistance of the respiratory system, including that of the ventilator tubing.

We then introduce the concept of compliance by asking, "What determines the pressure in a given balloon?" Because compliance (C) is the ratio of the change in volume (ΔV) per change in pressure (ΔP), or $C = \Delta V / \Delta P$, the learners can typically deduce, especially with some guidance, that pressure will be higher with larger tidal volumes or with lower compliance. Often, questions such as "What would happen to pressure in the balloon as it fills with more volume?" or "How would pressure in the balloon change if the balloon was 'stiffer' or 'floppier'?" are helpful to guide the discussion. Encouraging group participation and gauging the responses to the aforementioned questions can help inform the teacher as to when they can move on to the subsequent topics. This is particularly important because learners may struggle with the ensuing topics if they cannot adequately articulate the key physiologic concepts presented thus far. If learners appear to be struggling with these concepts, it may be best to defer introducing the natural decay equation in subsequent sections and simply focus on the clinical consequences and

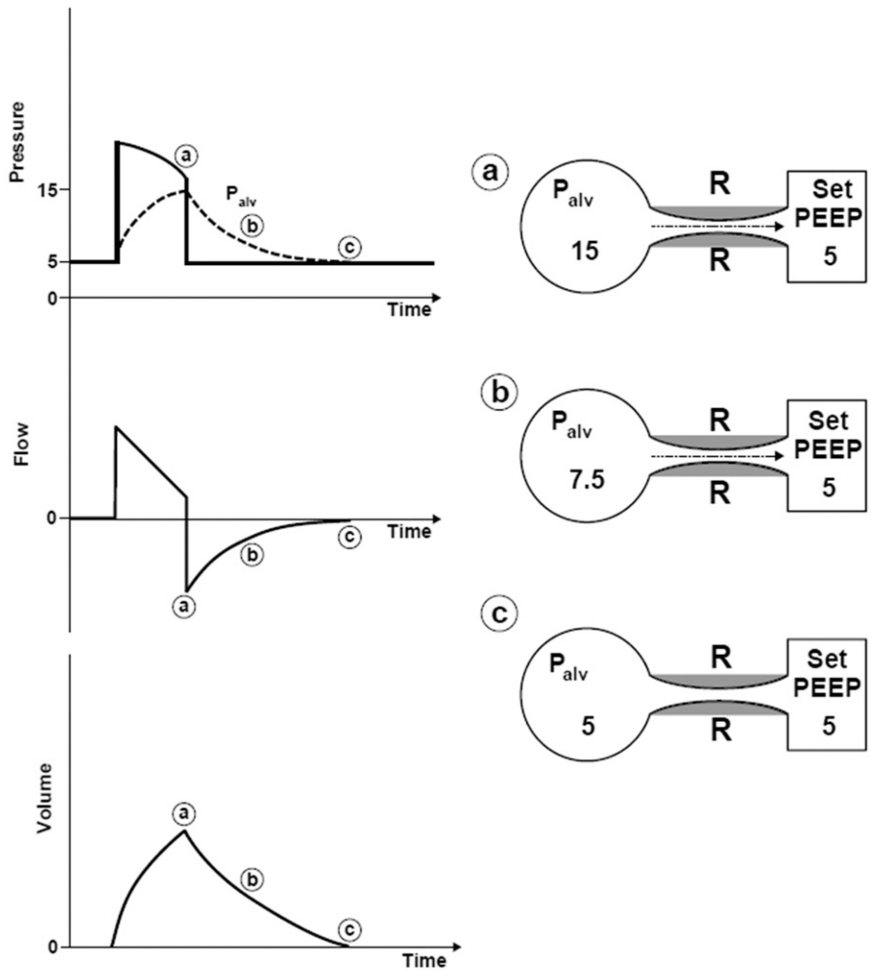

Figure 1. Illustration of the pressure–time, flow–time, and volume–time scalars with a focus on expiration. We emphasize to the learner that, at the onset of expiration, the pressure gradient will be largest and expiratory flow will be at its peak value. As air flows out of the alveoli, alveolar volume and pressure (and therefore flow) will gradually decline in an exponential fashion until alveolar pressure equals the downstream pressure (set PEEP), at which point the flow will cease. The dotted line represents alveolar pressure throughout the respiratory cycle, which is only measurable when the flow is paused. PEEP = positive end-expiratory pressure.

identification of auto-PEEP at the bedside presented later in this article. One can return to these concepts at a later date, as some learners feel more comfortable with this content once they have spent time in the ICU environment and gained additional clinical context for these abstract examples.

At this point, the learner should be able to identify the three key factors that determine the time it takes for a patient to fully expire a tidal volume: *1*) the size of the tidal volume; *2*) the compliance of the respiratory system; and *3*) the resistance of the respiratory system, with the first two factors, in turn, contributing to the alveolar pressure. We reinforce these concepts by comparing volume–time scalars on the ventilator for patients with different respiratory system resistances and compliances. For example, when possible, we compare a volume–time scalar from a patient with chronic obstructive pulmonary disease (COPD) (high R and high C) to a scalar from a patient with acute respiratory distress syndrome (ARDS) (low C) at the bedside. Because real patients are not readily available in a classroom setting, we compare volume–time scalars using a test lung with capacity for variable resistance and compliance to simulate different disease states.

With the factors that dictate expiratory flow firmly in hand, we can now transition more directly into the topic of auto-PEEP. To practically define auto-PEEP, we next ask, "What happens when a breath is initiated before a patient has completely expired the previous breath?"

Although this concept may be intuitive for some learners, it allows us to introduce and further refine our definitions of various types of PEEPs. We begin with the concept that any inspired volume that is not fully exhaled remains in the lung at the beginning of the next breath. Any of this excess volume results in additional pressure above the set PEEP that is programmed into the ventilator ($PEEP_{set}$). This additional pressure above $PEEP_{set}$ is auto-PEEP (also referred to as intrinsic PEEP). The sum of $PEEP_{set}$ and auto-PEEP represents the total PEEP ($PEEP_{total}$). As a thought exercise at the bedside, we ask our learners to take a breath, partially exhale the volume in their lungs, and then take a subsequent breath. We ask the learner to consider the position of the diaphragm with each breath as a result of air trapping.

With a practical definition of auto-PEEP in hand, we introduce the clinical consequences of auto-PEEP by asking, "What are the clinical consequences of auto-PEEP?"

We emphasize that the four main clinical consequences of auto-PEEP are hypotension, ventilator-induced lung injury, patient–ventilator asynchrony, and increased dead space. We write down the responses to this question and, if time permits, go into further detail into the mechanisms of each. Our teaching underscores that auto-PEEP must be considered in any hemodynamically unstable, mechanically ventilated patient. We find that auto-PEEP is an often overlooked cause of hypotension; however, the mechanism of hypotension in patients with auto-PEEP is relatively well understood by learners with some guidance. We explain that hypotension because of auto-PEEP results from several potential mechanisms, including decreased venous return because of increases in intrapleural pressure. Increases in intrapleural pressure decrease the pressure gradient for venous return to the thorax. We may illustrate this concept by drawing two compartments side by side and labeling one as "thorax" and the other as "abdomen," with an arrow flowing from the abdomen to the thorax to signify venous inflow. This also provides an opportunity to reinforce Ohm's law using a slightly different context. We may further explain that, as the lungs hyperinflate, the increase in lung volume causes compression of perialveolar vessels resulting in an increase in pulmonary vascular resistance and afterload of the right ventricle (2). These physiologic derangements may decrease cardiac output and result in hypotension. We also note that alveolar overdistention can cause direct compression of the alveolar capillaries and, in conjunction with a reduction in cardiac output, result in increased dead space (3). This increase in dead space can further cause respiratory acidosis, which may impair cardiac function. In a classroom setting, we typically set up a test lung with the capacity for variable resistance and compliance to illustrate the life-threatening implications of auto-PEEP. Using a high resistance and high compliance test lung system to mimic a patient with COPD, we can easily illustrate air trapping, thereby demonstrating the potential for lung overdistention. Furthermore, by asking learners to imagine the status of the heart situated between such overdistended lungs, the clinical implications of decreased venous return from increased intrapleural pressures become more readily apparent.

We also stress that auto-PEEP may have different consequences on mechanical ventilation depending on the mode of ventilation. In volume-controlled ventilation, the progressive accumulation of auto-PEEP may cause alveolar overdistention and ventilator-induced lung injury. In pressure-controlled ventilation, auto-PEEP decreases the pressure gradient for inspiratory flow (airway pressure − $PEEP_{total}$), resulting in lower tidal volumes and hypoventilation. This is easily illustrated at the bedside or in the classroom setting by drawing the two-compartment model with a ventilator on one side and a balloon (lung) on the other attached by a tube (airway) (similar to Figure 1). In volume control, we illustrate increasing amounts of volume progressively filling the balloon with each successive breath. For pressure control, we illustrate accumulating pressure above $PEEP_{set}$ reducing the pressure gradient for airflow at the start of each breath, thereby resulting in progressively lower tidal volumes with each successive breath.

We find that ineffective triggering, a form of patient–ventilator asynchrony frequently precipitated by auto-PEEP, is often a difficult concept for learners to grasp. Our approach is to draw a diagram that identifies the patient's degree of auto-PEEP, the $PEEP_{set}$, and the pressure below the $PEEP_{set}$ that the airway pressure must reach to trigger the ventilator (Figure 2). This demonstration allows for a visual representation of the additional pressure that must be overcome as a result of auto-PEEP to trigger a breath. This depiction also allows learners to visualize how increasing the $PEEP_{set}$ may reduce the threshold load required to trigger a breath. We then describe how this additional pressure results in an increase in the patient's work of breathing, as well as potential patient discomfort and agitation. For an additional example of how we teach ineffective triggering to our learners, the reader is referred to a previously produced video (4). A frequently asked question is whether or not this concept applies to a flow-triggering mechanism. Because a patient must lower airway pressure below $PEEP_{set}$ to generate flow, this mechanism of ineffective triggering still applies.

Now that the potentially dangerous consequences of auto-PEEP have been emphasized, to identify and treat auto-PEEP, we must familiarize our learners with the factors that determine if a patient is at risk. Our next question is, "What factors determine how much of an inspired volume (and therefore pressure) remains in the lung at the end of expiration?"

We begin by acknowledging that, in a passively exhaling patient, alveolar volume (and pressure) will gradually decline in a characteristically exponential fashion. At this juncture, we introduce the equation that governs this exponential decline, the natural decay equation,

$$V_i = V_o / e^{t/RC},$$

whereby V_i is the volume remaining in the lung at time i during expiration, V_o is the initial volume delivered to the alveoli (i.e., tidal volume), t is the amount of time available for expiration, C is the compliance of the respiratory system, R is the total resistance of the respiratory system, and e is a mathematical constant

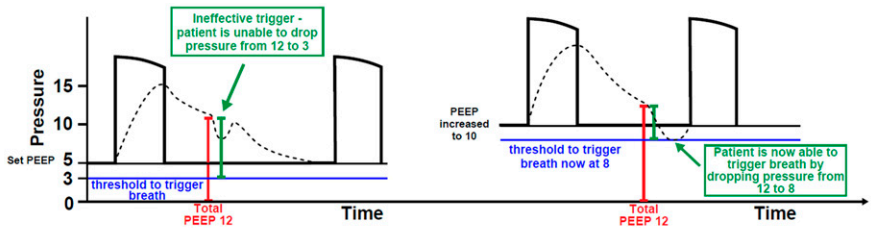

Figure 2. Illustration depicting how auto-PEEP may cause ineffective triggering. In the figure on the left, the trigger threshold is set at 2 cm H_2O below $PEEP_{set}$. Because the $PEEP_{set}$ is 5 cm H_2O, this patient would have to lower alveolar pressure to 3 cm H_2O to trigger a breath. Because this patient has developed 7 cm H_2O of auto-PEEP above the $PEEP_{set}$ of 5 cm H_2O (i.e., $PEEP_{total}$ of 12 cm H_2O), the patient would have to generate at least −9 cm H_2O to lower the alveolar pressure to 3 cm H_20. In the figure on the right, the $PEEP_{set}$ has been raised to 10 cm H_20 for the same patient. The trigger threshold is still set to 2 cm H_2O below the $PEEP_{set}$ of 10 cm H_20 (i.e., 8 cm H_2O). Now the patient would only have to generate negative 4 cm H_2O (i.e., from 12 to 8 cm H_2O) to lower the alveolar pressure below the trigger threshold. auto-PEEP = auto-positive end-expiratory pressure; $PEEP_{set}$ = PEEP set on ventilator; $PEEP_{total}$ = Total PEEP.

at the base of the natural logarithm and is equal to 2.718.

At first glance, most learners find this equation to be somewhat daunting. As a result, we typically do not engage all learners with this equation. However, for fellows and other learners who want to master the concept of auto-PEEP, an explanation of each variable in the equation provides significant clarity and allows learners to recognize the clinical applications of this equation. Each variable on the right represents a factor that contributes to the development of auto-PEEP. We typically circle or highlight each one as they are explained. Starting with V_o, we note that a larger initial volume delivered to the alveoli (i.e., tidal volume) will result in a larger amount of air remaining in the alveoli at any point in time during expiration (V_i). Thus, one risk factor for the development of auto-PEEP is a large tidal volume. Next, we stress that expiratory time (t) is inversely proportional to V_i. Thus, another risk factor for the development of auto-PEEP is a short expiratory time. Finally, we point out that the respiratory system resistance and compliance change in parallel to V_i, and therefore, high R and C are also risk factors for the development of auto-PEEP.

How can we further use concepts from this equation to determine how much time a given patient needs to expire and, therefore, what an appropriate respiratory rate is to avoid auto-PEEP? We now introduce the very important concept of time constants and tau (τ) by asking, "How do we estimate the time required for a patient to expire without developing auto-PEEP?"

As we just explained to the learners, the natural decay equation contains the product of respiratory system resistance and compliance (R × C). The product of R and C is referred to as the expiratory time constant and is represented by the Greek letter tau (τ). The natural decay equation above can now be rewritten as:

$$V_i = V_o / e^{t/\tau}.$$

It is important for the learners to grasp that the expiratory time constant (τ) represents the time required for the lungs to exhale until only approximately 37% of the initial volume remains in the lungs (5). We often start by illustrating this important concept by drawing a graph depicting the decay in volume over time

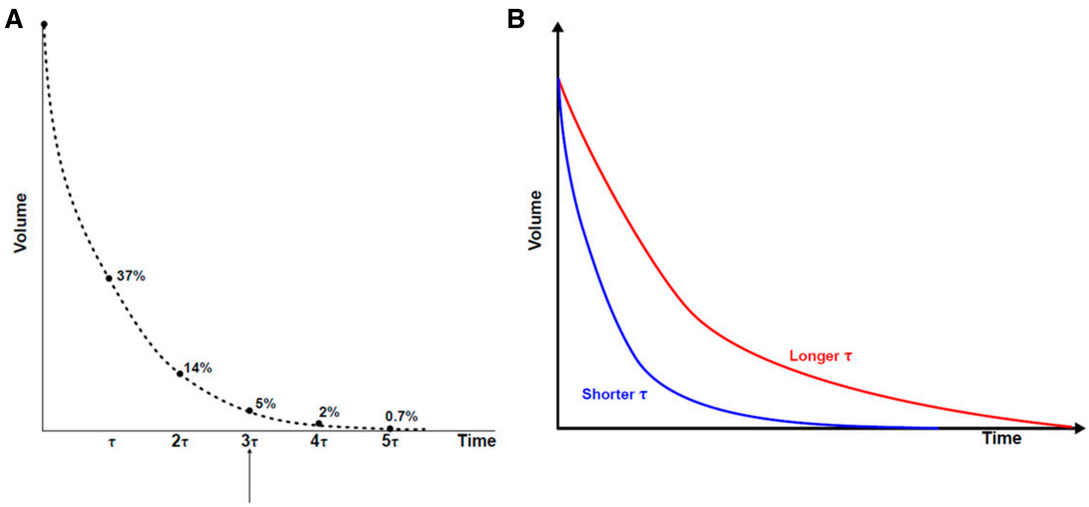

Figure 3. (*A*) Illustration of the decline in tidal volume over time during expiration. The period of time required for volume to decrease to 37% of its initial value is equivalent to one time constant. Each additional time constant represents another 63% reduction in volume from the previous value. We emphasize that, clinically, a patient should have an exhalation time greater than at least three time constants to adequately exhale the tidal volume, as indicated by the arrow, representing a reduction to less than 5% of the initial tidal volume. (*B*) Illustration of two patients with different time constants (tau). We emphasize to the learner how the patient with the longer tau will require a longer expiratory time to exhale a given volume.

(Figure 3A). We label the *y*-axis as volume (tidal volume in this case), the *x*-axis as time, and then draw a typical decay pattern noting that one τ represents the time point at which 37% of the initial volume remains in the lungs. For further clarification, we may demonstrate that by setting τ equal to expiratory time (t) in the natural decay equation, V_i always equals V_o / e, which is 37% of V_o, as 1 / e is approximately equal to 0.37. We then show that each additional time constant represents a further 63% reduction of the previous value such that after two time constants, 14% of the initial tidal volume will remain in the lungs (37% of 37%), and after three time constants, 5% of the initial tidal volume will remain in the lungs during expiration (37% of 14%), and so on (Figure 3A). Therefore, patients need longer than three time constants to appropriately exhale the tidal volume before initiating the next breath. This is a key concept, and we often reemphasize it by asking the learners, “How much time should we ensure the patient has to adequately exhale on the ventilator?” In other words, to minimize auto-PEEP, we must ensure that the patient’s expiratory time (t) is greater than at least 3 τ. Patients with a long τ (high R and C [i.e., COPD]) will require more time to exhale than patients with a short τ (low C [i.e., ARDS]). We often use the analogy of a long τ represented by a grocery bag passively emptying into a tube with a small diameter versus a short τ represented by a stretched rubber tire emptying into a tube with a large diameter (Figure 3B). In the classroom setting, to assess learners’ understanding at this juncture before moving on to the next topic, we have the learners break into groups and have them write out the natural decay equation and then reproduce a graph of the decay of volume over time during expiration. Although a whiteboard may not be readily available in some ICUs, this exercise can still be done on a piece of paper with the learners huddled around the instructor.

Some learners may not immediately grasp the mathematical underpinnings of the time constant. If this is the case, it is often helpful to simply emphasize the general concept that a patient will require at least 3 τ to adequately exhale and that by calculating τ, we now know how much time a patient needs to adequately exhale. Most learners will feel comfortable with this concept and move forward with how we calculate τ in the ensuing sessions.

As previously mentioned, if we know τ, we can therefore determine whether a patient's respiratory rate puts them at risk for auto-PEEP. We now have provided our learners with a deep understanding of the physiology behind the development of auto-PEEP. We can now transition back to the clinical basis of what we have discussed: "How do we estimate the expiratory time constant (τ)?"

We emphasize the importance of routinely calculating τ in critically ill, mechanically ventilated patients to guide our mechanical ventilation settings (respiratory rate, inspiratory flow pattern and rate, and tidal volume). There are several strategies that can be employed at the bedside. We typically teach the following three methods:

1. Measure respiratory system resistance and compliance during a square wave flow, volume control breath (6). As stated earlier, the product of R and C is τ:

   $$\tau = R\ (\text{cm } H_2O/L/s) \times C\ (L/\text{cm } H_2O).$$

   It is often helpful to write out this equation for the learners to notice that multiplying the units of R and C leaves units of seconds, hence, the name time constant. This value is the time constant (τ) of the patient and allows us to estimate the time required for exhalation. We then provide a simple example: a patient with a C of 0.1 L/cm H_20 and R of 10 cm H_20/L/s has a calculated τ of 1 second and will require more than 3 seconds (>3 τ) to adequately exhale the given tidal volume. If we assume an inspiratory time of 1 second, this patient should not develop significant auto-PEEP if the total respiratory rate is less than 15 breaths per minute because the breath-to-breath time is at least 4 seconds. One caveat to inform learners of when using this method is that the values used to calculate R and C are obtained during inspiration and, as a result, represent the inspiratory time constant. If the airway resistance is higher during expiration than inspiration, this approach may underestimate the time constant (7). This exercise can also incorporate the process of calculating respiratory system resistance and compliance at the bedside, a valuable opportunity to expand on respiratory system physiology.
2. Evaluating the volumes. A particularly valuable exercise for learners is to estimate the expiratory τ by examining the volume–time scalar on the ventilator and noting the amount of time required for a given volume to decrease to approximately 37% of its value. This will require freezing the ventilator display and placing two markers on the volume–time scalar that represents the initial chosen volume (V_o) followed by a point at 37% of this initial value. The time period between these two markers represents 1 τ. (Video E1 in the data supplement reviews this approach to assessing τ and provides an example of the way in which we typically assess a learner's understanding of this method.) Note that the initial volume (V_o) should ideally be recorded after the initial rapid deflection of the expiratory flow time curve because the interpretation of the initial portion of this curve is confounded by interference of inertial effects, rapid opening of the expiratory valve, and potential patient effort (8). In our experience, this method is the easiest for the learner to comprehend as it provides a simple visual representation of natural decay and can be performed readily at the bedside.
3. Volume to flow ratio (V/F) approach. Another method for estimating τ that is helpful to demonstrate at the bedside

involves dividing the remaining volume (V) by the exhaled flow rate (F) at the same time point (9):

$$V / F = RC = \tau.$$

We typically encourage our fellows and other learners who want to master the concept of auto-PEEP to derive this from the equation of motion (Index Page E1) as it not only explains τ but also a number of other important physiologic concepts. Calculations of τ at multiple time points can be made, all of which should be similar because the slope of the flow–volume curve in a passive patient should be linear (10). (Video E2 reviews the volume/flow method, as well as the ways in which we assess a learner's understanding of this concept.)

To further assess understanding, we will have trainees calculate τ at the bedside (either on rounds or bedside teaching sessions). We find that the volume/flow method is the most difficult for learners to grasp. However, with practice, it becomes one of the most time-efficient ways of calculating τ. If a learner is having difficulty with the volume/flow method, it is acceptable to move on to subsequent topics and return to this concept another time, especially given that the "evaluating the volumes" method above is typically more intuitively understood.

By teaching these three methods, we emphasize the importance of calculating τ and acknowledging the expiratory time of the patient to help prevent the onset of auto-PEEP. Continuing with the bedside application of what we have learned, we now focus on how to identify the presence of auto-PEEP. We now ask, "What are some signs of auto-PEEP on the ventilator?"

The trainee should recognize that auto-PEEP must be considered in mechanically ventilated patients who have unexplained hypotension, difficulty triggering a breath, or agitation. On the basis of the discussion above, they should also recognize patients at increased risk (i.e., patients with high respiratory rates, short expiratory times, and/or obstructive airway disease). There are also several ventilator waveform patterns suggestive of auto-PEEP worthy of pointing out. We focus on the following four patterns, which are best presented on the ventilator at the bedside but can also be displayed as figures in a classroom setting as well.

1. Asymmetry in the areas of the flow-time curves. We first direct the learner's attention to the flow-time scalar at the bedside (or with a pictorial in the classroom setting) and start by asking, "What does the area under the flow-time curve represent?" We explain that the area under the flow-time curve during inspiration represents inhaled tidal volume; during expiration, this area represents exhaled volume. Patients with significant airway obstruction may have very low expiratory flow rates as a result of high resistance, resulting in significant asymmetry between the inspiratory and expiratory flow-time curves, giving the *appearance* of unequal areas under the curves (the areas become quantitively equal as the patient eventually achieves steady state at a higher end expiratory lung volume). While this sign is indicative of airway obstruction rather than auto-PEEP, patients with obstructive disease are specifically the ones vulnerable to developing auto-PEEP. Such asymmetry should prompt the clinician to further assess for auto-PEEP as this is a common sign (Figure 4A).
2. Persistent end-expiratory flow. We start off teaching this concept by directing the learner's attention to the expiratory flow–time curve and asking, "If flow returns to zero, what does this imply?" This reintroduces the concept of Ohm's law presented earlier, which may require asking the learners to write out the equation again. This will allow the learners to understand that if all

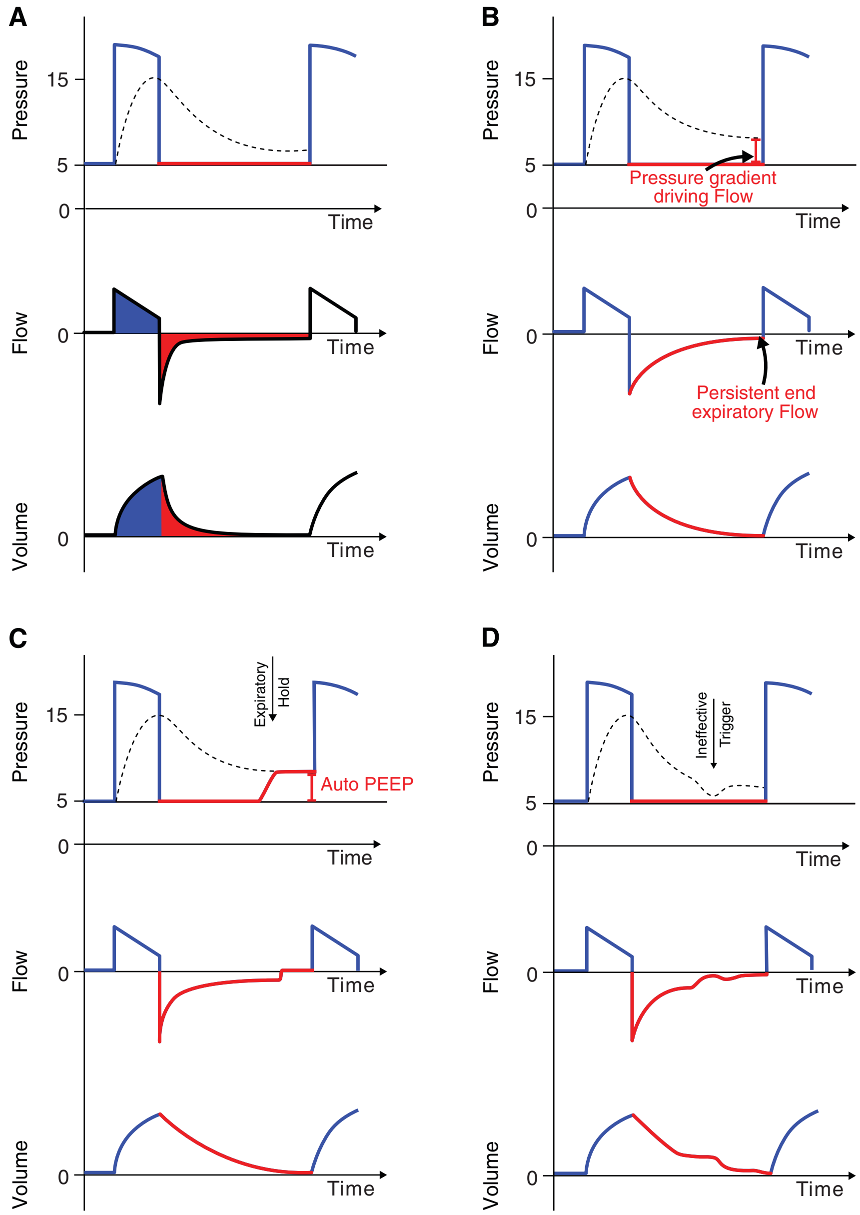

Figure 4. Signs of auto-PEEP. (*A*) Asymmetry of areas under the curve. The area under the inspiratory flow–time scalar *appears* larger than the expiratory flow–time scalar as a result of significant asymmetry of the curves. (*B*) Persistent end-expiratory flow, signifying a persistent pressure gradient between alveolar pressure and $PEEP_{set}$ because of auto-PEEP. (*C*) The end-expiratory hold maneuver. The dotted line represents alveolar pressure throughout the respiratory cycle (which is only able to be measured when the flow is paused). (*D*) Ineffective triggering. In this example, the patient is unable to lower alveolar pressure below the threshold for triggering because of significant auto-PEEP. auto-PEEP = auto-positive end-expiratory pressure; $PEEP_{set}$ = PEEP set on ventilator.

of the inspired tidal volume has been exhaled, the pressure in the alveoli (P_{alv}) should now equal $PEEP_{set}$. Because the pressures are equal, there is no longer a pressure gradient, and flow should be zero (Figure 4B). We then ask the learner, "If there is still flow present at the end of expiration, what does this imply?" Learners should now realize that if the flow is still present at the end of expiration, there is still pressure in the alveoli above $PEEP_{set}$ that is driving flow out of the lungs. This additional pressure is auto-PEEP. Once again, incorporating the two-compartment model, as previously discussed, is very helpful in illustrating this concept.

3. Measurement via an end-expiratory pause. An important (and often misunderstood) concept for learners to understand is that the pressure–time waveform will display $PEEP_{set}$ (determined by the clinician) throughout expiration. P_{alv}, which gradually declines as volume is exhaled, is not directly depicted on the display. We find it helpful to draw a sample pressure–time scalar during expiration with airway pressure as $PEEP_{set}$ (a straight line) and superimpose the alveolar pressure–time curve with an exponential decay in the background. Now we emphasize that with an end-expiratory pause maneuver, the expiratory valve closes, and flow stops. This allows the P_{alv} to equilibrate with the airway pressure; as a result, the pressure–time scalar will now reflect the P_{alv} (Figure 4C). This measured P_{alv} at the end of expiration is the total PEEP ($PEEP_{total}$). The amount of pressure present above the $PEEP_{set}$ is the amount of auto-PEEP present:

$$PEEP_{total} - PEEP_{set} = auto-PEEP.$$

Educators should communicate a few limitations to this measurement. First, the patient must be passive throughout this maneuver so that patient effort does not alter the value. Second, only lung units in communication with the airway will equilibrate with the airway pressure. In the setting of airway closure, some lung units will not be in communication with the airway, and thus, auto-PEEP may be underestimated (12).

4. Ineffective triggering. As described above, auto-PEEP can make it more difficult for a patient to trigger the ventilator, as increased negative pressure must be generated to overcome the intrinsic PEEP. This may impair the patient's ability to trigger a mechanical breath, a phenomenon known as ineffective triggering (13). It may be helpful to begin by asking learners to recall how the patient triggers a mechanical breath on the ventilator and reemphasizing that the patient must generate an appropriate amount of inspiratory muscle effort to overcome the clinician-set pressure or flow triggers. Ineffective triggers can be shown to the learners as deflections on the flow–time scalar representing patient respiratory muscle efforts that fail to trigger mechanical breaths. In addition to pointing this out on the flow–time scalar, it is helpful to once again draw the pressure–time scalar and superimpose the changes in alveolar pressure occurring with an ineffective trigger during expiration (Figure 4D). To further assess learners' understanding, asking the learner about the other causes of ineffective triggering is often helpful. With a little additional guidance, they should realize that a patient with neuromuscular weakness may not have adequate strength to trigger a breath or that a trigger sensitivity threshold that is set too high may make it more difficult for a patient to trigger a breath. However, the learner should understand that, whereas neuromuscular weakness and an insensitive trigger setting may also result in ineffective triggers, auto-PEEP is by far the most common cause (14).

Now that our learners are adept at understanding how to prevent and identify auto-PEEP, we turn to asking, "How can we address auto-PEEP?"

We begin by teaching that in the event of acute hemodynamic instability, the patient may momentarily be disconnected from the ventilator to allow for a full exhalation. However, we stress that strategies to prevent the development and recurrence of auto-PEEP must then be considered. (Video E3 provides an example of how we assess a learner's understanding of the clinical consequences of autoPEEP and the ways in which to manage auto-PEEP.)

To solidify the physiological and mathematical underpinnings of this complex topic, we refer back to the equation of natural decay, highlighting and explaining how each variable can be examined and addressed when approaching our treatment of auto-PEEP. This allows the learner to feel comfortable with the equation and demonstrate its practicality, especially in the ICU setting. Therefore, we first ask the learners to write out the equation of natural decay. We then emphasize that according to this equation, we can reduce the amount of volume remaining in the alveoli at the end of expiration (V_i) and therefore reduce auto-PEEP by decreasing the delivered tidal volume (V_o), increasing exhalation time (t), and decreasing τ. For emphasis and clarity, we typically circle each variable in the equation as we name them individually, and we stress that increasing the expiratory time is best achieved by lowering the respiratory rate. This may involve sedating and/or paralyzing the patient if the patient's intrinsic respiratory rate is higher than the set rate on the ventilator. We often teach this concept by drawing a table and asking learners to fill in the breath-to-breath time, the inspiratory time, and the expiratory time for various respiratory rates (a sample of such tables is given in the Index Page E2). Trainees often note that increasing the set inspiratory flow rate will decrease inspiratory time as the set tidal volume must now be delivered more rapidly. However, this strategy will generally only increase exhalation time by fractions of a second, whereas lowering the respiratory rate will provide much larger increases in expiratory time (Index Page E2). Educators should also emphasize that although lowering tidal volume may appear to be an effective strategy to minimize auto-PEEP, this strategy may be met by a compensatory increase in the patient's intrinsic respiratory rate, which may ultimately decrease the expiratory time (15). Lastly, we ask the learners to recall that τ is the product of R and C and that minimizing the R through the use of interventions such as bronchodilators, corticosteroids, and suctioning of secretions will allow for more rapid exhalation.

We often teach the concept that to improve patient work of breathing and ineffective triggering, the $PEEP_{set}$ may be increased to a point just below the $PEEP_{total}$ (16). Because the patient only needs to lower the airway pressure below $PEEP_{set}$ to trigger the ventilator, this maneuver will decrease the amount of auto-PEEP the patient must overcome to trigger the breath. Our approach usually involves illustrating this concept by drawing pressure–time scalars with superimposed alveolar pressure–time curves, as demonstrated in Figure 2. Alternatively, we use a more interactive approach using the different heights of two participants, as demonstrated in a previously recorded video (4), to demonstrate that the difference between the end-expiratory alveolar pressure and $PEEP_{set}$ increases the effort required to trigger a breath. This teaching strategy also helps to illustrate that decreasing this difference by increasing the $PEEP_{set}$ may make it easier to trigger the breath. Two considerations should be made when teaching this latter point to learners. First, increasing the $PEEP_{set}$ should not increase the $PEEP_{total}$ as long as it remains below $PEEP_{total}$ (17). In order for air to flow from the ventilator to the patient, the pressure in the airway must be higher than the pressure in the alveoli. If $PEEP_{set}$ remains below $PEEP_{total}$, the gradient for airflow remains from the patient toward the ventilator. Second, a common misconception is that this strategy is a treatment for auto-PEEP; instructors must reinforce that this management strategy merely corrects ineffective triggering. In fact, by allowing the patient to trigger the ventilator more frequently, one may theoretically worsen the auto-PEEP.

MODIFYING THE FRAMEWORK

The concepts above can be presented in a classroom setting, during bedside teaching sessions, or on ICU rounds. However, teaching this material using this framework may require modifications depending on the location, context, or constraints of time or resources available. In a classroom setting with a ventilator and a test lung capable of variable R and C, a thorough presentation of the topic typically takes about an hour. If a test lung or ventilator is not available, it may be necessary to provide screenshots of sample ventilator scalar waveforms or illustrate them on a whiteboard. We have also used an interactive, online mechanical ventilation simulator when mechanical ventilators are unavailable or when teaching virtually (available with permission at https://iculearning.com/). Other similar mechanical ventilation simulators are available in an open-access format (18).

Given the time constraints of the ICU, it is often necessary to divide the material and focus on specific aspects in any given session. For instance, when faced on rounds with a patient with severe obstructive lung disease, it may be worthwhile to focus on how the team may approach ventilator settings. In this case, spending 5–10 minutes on introducing the natural decay equation and τ may be time well spent. This may be followed by a quick demonstration of the calculation of τ at the bedside, followed by titration of ventilator settings. In this instance, though they may be briefly mentioned, the specifics regarding the clinical consequences of auto-PEEP or identification of auto-PEEP on the ventilator scalars may be best presented at another time (or vice versa). In our experience, each component of the topic of auto-PEEP presented above has proved quite valuable, even if the topic cannot be presented in totality.

CONCLUSIONS

Teaching the principles of mechanical ventilation involves incorporating a unique and exciting blend of cardiopulmonary physiology and clinical application. This can be an incredibly rewarding yet challenging task. In this article, we provide our framework for teaching the often overlooked principle of auto-PEEP. The approaches we provide can be used at the bedside or in a classroom setting. In addition, given the time constraints often associated with bedside teaching, several of the sections presented above may be effectively presented independently, with some brief context. Most importantly, effective teaching of these concepts requires practice and continued refinement on the educator's part. We hope that this framework provides a cogent guide for teaching this complex topic.

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