Therapeutic PEEP

Therapeutic PEEP involves using 5 cm H_2O or greater. It is used in the treatment of refractory hypoxemia caused by increased intrapulmonary shunting and $\dot{V}/\dot{Q}$ mismatching accompanied by a decreased FRC and pulmonary compliance.[25] High levels of therapeutic PEEP (e.g., ≥15 cm H_2O) are beneficial for a small percentage of the patients with ARDS. Because high levels of PEEP are often associated with cardiopulmonary complications, physiological response to therapy must be monitored carefully.

Optimal PEEP

The term *optimum* (or best) *PEEP* was coined by Suter and colleagues in 1975.[26] Optimal PEEP is considered the level at which the maximum beneficial effects of PEEP occur (i.e., increased DO_2, FRC, and C_S and decreased $\dot{Q}_S/\dot{Q}_T$). This level of PEEP is also considered optimal because it is not associated with profound cardiopulmonary side effects, such as decreased venous return, decreased cardiac output, decreased blood pressure (BP), increased shunting, increased V_D/V_T, barotrauma, and volutrauma, and it is accomplished at safe levels of inspired O_2 (F_IO_2 <0.40). It is important to note that optimal PEEP should be correlated with criteria other than arterial PO_2 alone.[27,28] Thus optimal PEEP has more recently been defined as the level of PEEP at which static compliance is highest as PEEP is decreased after a **recruitment maneuver** (RM).[29] (RMs are discussed later in this chapter.)

INDICATIONS FOR PEEP AND CPAP

ARDS remains a prime example of a pathophysiological state in which PEEP is used as an effective means of improving oxygenation. Patients with ARDS do not benefit from mechanical ventilatory support without PEEP. Although collapsed alveoli may open during a positive pressure inspiration, unstable alveoli and airways tend to collapse if the airway pressure returns to ambient pressure during expiration. Because approximately two-thirds of the respiratory cycle is spent in expiration, blood passing through these areas of collapsed alveoli during expiration creates a shuntlike state, which perpetuates hypoxemia.

Patients with ARDS benefit from PEEP because it helps prevent collapse of the small airways and alveoli, and thus it aids in recruiting closed lung units. The edema-filled alveoli may have their volumes partially air-filled with this technique as well, leading to the restoration of FRC. Lung compliance (C_L) and gas distribution are enhanced, thereby reducing the shunt effect of venous admixture and improving oxygenation.[30,31] Box 13.6 lists the indications for PEEP therapy.[32,33]

The indications for initiating CPAP are similar to the criteria used for initiating PEEP; the primary difference between using CPAP versus PEEP is that the patient provides the WOB at all times during CPAP. Thus CPAP is appropriate if a patient is capable of breathing spontaneously without difficulty and is able to maintain an acceptable P_aCO_2.

Ultimately, PEEP allows for the reduction of F_IO_2 because it improves oxygenation and helps avoid the complications associated with a high F_IO_2 in certain disorders. Examples of disorders that may benefit from the use of PEEP include the following:

- ARDS
- Cardiogenic pulmonary edema in adults and children
- Bilateral, diffuse pneumonia

BOX 13.6 Indications for Positive End-Expiratory Pressure (PEEP) Therapy

- Bilateral infiltrates on chest radiograph
- Recurrent atelectasis with low functional residual capacity (FRC)
- Reduced lung compliance (C_L)
- P_aO_2 <60 mm Hg on F_IO_2s >0.5
- P_aO_2/ F_IO_2 ratio <300 for ARDS[a]
- Refractory hypoxemia: P_aO_2 increases <10 mm Hg with F_IO_2 increase of 0.2

[a]The level of applied PEEP will vary depending on the severity of ARDS. See section on Acute Respiratory Distress Syndrome.

INITIATING PEEP THERAPY

Once a patient's clinical condition indicates that PEEP or CPAP therapy is warranted, it is prudent to initiate this form of therapy as soon as possible. High plateau pressures (P_{plat} >30 cm H_2O) along with F_IO_2 values of 0.5 or greater may damage alveolar cells (type I and II) in less than 24 hours; therefore PEEP or CPAP should be initiated early in the course of therapy to avoid lung damage from high pressures, volumes, and F_IO_2 (see Chapter 17 for more information on VILI).

SELECTING THE APPROPRIATE PEEP/CPAP LEVEL (OPTIMAL PEEP)

The goal when selecting an appropriate PEEP/CPAP setting for a patient should be to achieve a PEEP/CPAP level that produces maximum beneficial effects and is not associated with profound cardiopulmonary side effects. The medical literature describes several techniques that can be used to determine when the optimum level of PEEP/CPAP for a patient. The consensus of these different approaches is reviewed in the following pages. Specific techniques used in the management of patients with ARDS are discussed later in this chapter.

Application of PEEP Above 5 cm H_2O

For adults, PEEP is usually increased in increments of 3 to 5 cm H_2O. In infants, this range is generally 2 to 3 cm H_2O.[33] Some clinicians follow specific step increases in F_IO_2 and PEEP when performing a PEEP study using the procedure outlined in an ARDSnet study comparing the use of higher and lower tidal volumes (Table 13.2).[34] Other clinicians follow a more rapidly increasing PEEP-F_IO_2 table from a follow-up study (Table 13.3).[35] Both the low and high PEEP titration techniques for establishing the appropriate PEEP level appear to have similar morbidity and mortality rates.[36]

In addition to using either a moderate (low PEEP increments) or more aggressive (high PEEP incremental changes) technique, other practitioners will use techniques such as slow or static pressure-volume loops to determine optimum the PEEP level. Still other clinicians use an RM, which may be accompanied by a decremental PEEP study. Pressure-volume loops and RMs are reviewed later in this chapter.

Regardless of the procedure, an optimal oxygenation point should be targeted that allows adequate tissue oxygenation

TABLE 13.2 Summary of Ventilator Procedures

Variable	Group Receiving Higher Tidal Volumes	Group Receiving Lower Tidal Volumes
Ventilator mode	Volume Assist/Control	Volume assist/control
Initial tidal volume (mL/kg of predicted body weight)[a]	12	6
Plateau pressure (cm of water)	<50	<30
Ventilator rate setting needed to achieve a pH goal of 7.3–7.45 (breaths/min)	6–35	6–35
Ratio of the duration of inspiration to the duration of expiration	1:1–1:3	1:1–1:3
Oxygenation goal	P_aO_2, 55–80 mm Hg, or S_pO_2, 88%–95%	P_aO_2, 55–80 mm Hg, or S_pO_2, 88%–95%
Allowable combinations of F_IO_2 and PEEP (cm of water)[b]	0.3 and 5	0.3 and 5
	0.4 and 5	0.4 and 5
	0.4 and 8	0.4 and 8
	0.5 and 8	0.5 and 8
	0.5 and 10	0.5 and 10
	0.6 and 10	0.6 and 10
	0.7 and 10	0.7 and 10
	0.7 and 12	0.7 and 12
	0.7 and 14	0.7 and 14
	0.8 and 14	0.8 and 14
	0.9 and 14	0.9 and 14
	0.9 and 16	0.9 and 16
	0.9 and 18	0.9 and 18
	1.0 and 18	1.0 and 18
	1.0 and 20	1.0 and 20
	1.0 and 22	1.0 and 22
	1.0 and 24	1.0 and 24
Weaning	By pressure support; required by protocol when F_IO_2 <0.4	By pressure support; required by protocol when F_IO_2 <0.4

[a]Subsequent adjustments in tidal volume (V_T) were made to maintain a plateau pressure of <50 cm of water in the group receiving traditional V_Ts and <30 cm of water in the group receiving lower V_Ts.
[b]Further increases in PEEP, to 34 cm of water, were allowed but not required.
F_IO_2, fraction of inspired O_2; P_aO_2 denotes partial pressure of arterial O_2; PEEP positive end-expiratory pressure; S_pO_2 oxyhemoglobin saturation measured by pulse oximetry.
From the Acute Respiratory Distress Syndrome Network: Ventilation with lower tidal volumes compared with traditional tidal volumes for acute lung injury and the acute respiratory distress syndrome, *N Engl J Med* 341:1301-1308, 2000. © Massachusetts Medical Society.

(optimum O_2 transport) at a safe F_IO_2 and safe ventilating pressures with an acceptable P_aO_2/F_IO_2 ratio[31,32,37,38] (Key Point 13.3). Along with improving oxygenation, cardiovascular status should be monitored to identify adverse side effects of PEEP so that they can be managed appropriately by the attending physician. Excessive PEEP must also be avoided because it can result in lung overinflation, stressing pulmonary cells and potentially resulting in an inflammatory reaction and possible barotraumas (see Chapter 17).

Optimal PEEP Study

Performing an optimal PEEP study is a function most often reserved for patients requiring 10 cm H_2O or more of PEEP. For example, in patients with ARDS, PEEP levels greater than 20 cm H_2O of PEEP may be required. Box 13.7 lists the parameters most often monitored during a PEEP or CPAP study. Boxes 13.3 and 13.8 provide information for shunt calculations, which helps monitor PEEP/CPAP when a pulmonary artery catheter is being used (see Chapter 11).

The following common target goals can be used to assess a patient's response to PEEP:

- A P_aO_2 of 60 mm Hg to 100 mm Hg while receiving an F_IO_2 of 0.4 or less, which represents a S_aO_2 of 90% to 97% at a normal pH. (NOTE: The range of P_aO_2 from the ARDSnet study targeted P_aO_2 from 55–80 mm Hg and S_pO_2 from 88%–95%.[34])
- Optimum O_2 transport is present; normal O_2 transport is about 1000 mL/min of O_2 (5 L/min × 20 vol% × 10). A pulmonary shunt fraction less than 15%, when this parameter is monitored.
- A minimal amount of cardiovascular compromise, which includes adequate systemic BP, a decrease of less than 20% in cardiac output, and stable pulmonary vascular pressures (i.e., pulmonary artery occlusion pressure [PAOP], pulmonary vascular resistance [PVR]).
- Improving C_L and improved lung aeration.[31,39]
- A P_aO_2/F_IO_2 ratio greater than 300.
- The point of minimum arterial to end-tidal PCO_2 gradient.[40]

***Key Point* 13.3** Given that a healthy individual's P_aO_2 is approximately 100 mm Hg while breathing room air (F_IO_2 = 0.21), then the P_aO_2/F_IO_2 ratio is normally about 500.

TABLE 13.3 Summary of Ventilator Procedures in the Lower and Higher PEEP Groups[a]

Procedure	VALUE													
Ventilator Mode	**VOLUME ASSIST/CONTROL**													
Tidal volume goal	6 mL/kg of predicted body weight													
Plateau pressure goal	≤30 cm of water													
Ventilator rate and pH goal	6–35, adjusted to achieve arterial pH ≥7.30 if possible													
Inspiration-to-expiration time	1 :1–1:3													
Oxygenation goal														
P_aO_2	55–80 mm Hg													
S_pO_2	88%–95%													
Weaning	Weaning attempted by means of pressure support when level of arterial oxygenation acceptable with PEEP ≤8 cm of water and F_IO_2 ≤0.40													
Allowable combinations of PEEP and F_IO_2[b]														
Lower PEEP group														
F_IO_2	0.3	0.4	0.4	0.5	0.5	0.6	0.7	0.7	0.7	0.8	0.9	0.9	0.9	1.0
PEEP	5	5	8	8	10	10	10	12	14	14	14	16	18	18–24
Higher PEEP group (before protocol changed to use higher levels of PEEP)														
F_IO_2	0.3	0.3	0.3	0.3	0.3	0.4	0.4	0.5	0.5	0.5–0.8	0.8	0.9	1.0	
PEEP	5	8	10	12	14	14	16	16	18	20	22	22	22–24	
Higher-PEEP group (after protocol changed to use higher levels of PEEP)														
F_IO_2	0.3	0.3	0.4	0.4	0.5	0.5	0.5–0.8	0.8	0.9	1.0				
PEEP	12	14	14	16	16	18	20	22	22	22–24				

[a]Complete ventilator procedures and eligibility criteria are listed in the Supplementary Appendix (available with the full text of this article at www.nejm.org) and at www.ardsnet.org.

[b]In both study groups, additional increases in PEEP to 34 cm of water were allowed but not required after the F_IO_2 had been increased to 1.0 according to the protocol. The combinations of PEEP and F_IO_2 used with PEEP values of less than 12 cm of water were eliminated in the higher-PEEP group after 171 patients had been enrolled in this group.

F_IO_2, fraction of inspired O_2; *P_aO_2*, denotes partial pressure of arterial O_2; *S_pO_2* oxyhemoglobin saturation as measured by pulse oximetry; *PEEP*, positive end-expiratory pressure.

From The National Heart, Lung, and Blood Institute ARDS Clinical Trials Network: Higher versus lower positive end-expiratory pressures in patients with the acute respiratory distress syndrome, *N Engl J Med* 351:4, 2004. ©Massachusetts Medical Society.

BOX 13.7 Parameters Measured and Monitored During a PEEP/CPAP Study

Ventilatory Data

V_T, f, $\dot{V}_E$, peak inspiratory pressure (PIP), plateau pressure (P_{plat}), PEEP, C_D, C_S, breath sounds, ABGs (e.g., P_aO_2, C_aO_2, pH, P_aCO_2), $P_{(A-a)}O_2$ or P_aO_2/F_IO_2 ratio, calculated clinical shunt ($\dot{Q}_S/\dot{Q}_T$), arterial minus end-tidal carbon dioxide gradient ($P_{(a-et)}CO_2$).

Hemodynamic Data

Arterial blood pressure (BP), cardiac output (C.O.) (by thermodilution or noninvasive techniques), arterial-to-venous O_2 difference $C[a-\bar{v}]O_2$, partial pressure of mixed venous O_2 ($P\bar{v}O_2$, $S\bar{v}O_2$), pulmonary artery pressure (PAP), pulmonary artery occlusion pressure (PAOP), pulmonary vascular resistance (PVR), O_2 transport (C.O. × C_aO_2).

BOX 13.8 Clinical Shunt Calculation

When a patient is breathing 100% O_2, $\dot{Q}_S/\dot{Q}_T$ can be *estimated* with the following equation:

Calculate P_AO_2 in the sample calculation.

$$\dot{Q}_s/\dot{Q}_t = (P(A-a)O_2 \times 0.003)/[(P_{(A-a)}O_2 \times 0.003) + (Ca - C\bar{v}O_2)]$$

$\dot{Q}_S/\dot{Q}_T$ is affected by variations in $\dot{V}O_2$ mismatching and by fluctuations in mixed venous O_2 saturations ($S\bar{v}O_2$) and F_IO_2.

Using the factor 0.003 in the calculation above converts the reading from mm Hg to vol% (mL/100 mL) so that it becomes $C_{(A-a)}O_2$, or the alveolar-to-arterial content difference.

The $C[a-\bar{v}]O_2$ portion of the equation is the arterial-to-venous content difference. $C[a-\bar{v}]O_2$ is often assigned the value of 3.5 vol%, the approximate arterial–to–venous O_2 content difference in a critically ill patient. Below is an example of a clinical shunt calculation.

- Optimum mixed venous O_2 values.[40]

In cases of $\dot{V}/\dot{Q}$ mismatch caused by hypoventilation, increasing the F_IO_2 decreases the percentage shunt and increases

P_aO_2, because the increased F_IO_2 results in higher P_aO_2. In contrast, for cases in which there is an absolute shunt present (i.e., perfusion in the absence of ventilation, e.g., atelectasis), the P_aO_2 does not rise with increases in F_IO_2 because there is no improvement in the gas exchange in shunt units and hypoxemia remains severe. Hypoxemia refractory to increases in F_IO_2 therefore suggests that an absolute shunt exists. The use of PEEP or CPAP may be beneficial in treating hypoxemia associated with atelectasis.

The following is an example of a clinical shunt calculation: barometric pressure (P_B) = 747 mm Hg, Hb = 10 g, F_IO_2 = 1.0, P_aO_2 = 85 mm Hg, P_aCO_2 = 40 mm Hg, pH = 7.36, S_aO_2 = 94%, SvO_2 = 39 mm Hg, SvO_2 = 70%, respiratory exchange ratio (R) = 0.8.

$$\frac{\dot{Q}_s}{\dot{Q}_t} = \frac{(P(A-a)O_2 \times 0.003)}{[(P_{(A-a)}O_2 \times 0.003) + (CaO_2 - C\bar{v}O_2)]}$$

Step 1: Calculate P_AO_2

$$P_AO_2 = F_1O_2(Pb - 47) - P_aCO_2(F_1O_2 + [1 - F_1O_2 / R])$$
$$P_AO_2 = 1.0(747 - 47) - 40(1.0 + [1 - 1.0 / 0.8])$$
$$P_AO_2 = 700 - 40 = 660 \text{ mmHg}$$

Step 2: Calculate $P_{(A-a)}O_2 \times 0.003$

$$P_AO_2 = 660$$
$$P_aO_2 = 85$$
$$P_AO_2 - P_aO_2 = 660 - 85 = 575$$
$$P_{(A-a)}O_2 \times 0.003 = 1.73 \text{ vol \%}$$

Step 3: Calculate $C[a - \bar{v}]O_2$

$$C_aO_2 = (P_aO_2 \times 0.003) + (S_aO_2 \times 1.34 \times Hb)$$
$$C_aO_2 = (85 \times 0.003) + (94\% \times 1.34 \times 10)$$
$$C_aO_2 = 0.225 + (0.94 \text{ [asafraction]} \times 1.34 \times 10)$$
$$C_aO_2 = 0.26 + 12.6 = 12.86 \text{ vol \%}$$
$$C\bar{v}O_2 = (P\bar{v}O_2 \times 0.003) + (S\bar{v}O_2 \times 1.34 \times Hb)$$
$$C\bar{v}O_2 = (39 \times 0.003) + [0.70 \text{ (asafraction)} \times 1.34 \times 10]$$
$$C\bar{v}O_2 = 0.117 + 9.38 = 9.5 \text{ vol \%}$$
$$C[a - \bar{v}]O_2 = 12.86 - 9.5 = 3.36 \text{ vol \%}$$

Step 4: Solve for shunt fraction

$$\frac{\dot{Q}_s}{\dot{Q}_t} = [P_{(A-a)}O_20.003]/C(a - v)O_2 + [P(A - a)O_2 \times 0.003]$$
$$\frac{\dot{Q}_s}{\dot{Q}_t} = 1.73 \text{ vol \%} / (3.36 \text{ vol \%} + 1.73 \text{ vol \%})$$
$$\frac{\dot{Q}_S}{\dot{Q}_t} = 0.339 \text{ or } 34\% \text{ shunt}$$

Performing an Optimal PEEP Study

Fig. 13.2 illustrates the effects that PEEP might have as it progressively increases. Fig. 13.3 presents a PEEP study check sheet that can be used for monitoring patients receiving PEEP or CPAP therapy. Once the baseline data (0 cm H_2O) are obtained, 5 cm H_2O of PEEP or CPAP is instituted and PEEP is increased in increments (3–5 cm H_2O). (NOTE: Using a baseline of 5 cm H_2O of PEEP as a starting point is also acceptable.) Fig. 13.4 shows the effects of PEEP on pressure readings. Approximately 15 minutes after an increase in PEEP, all ventilatory and available hemodynamic parameters are measured and derived variables are calculated.[41]

Patient Appearance

A patient's appearance—pale, flushed, cyanotic discoloration of the skin and/or oral mucous membranes, level of consciousness, and evidence of anxiety or pain—is checked frequently to ensure that no apparent distress is present. A sudden deterioration in a patient's condition may indicate the onset of cardiovascular collapse or sudden development of pneumothorax.

Blood Pressure

The patient's BP should be checked within the first few minutes after an increment of PEEP is added. A decrease of more than 20 mm Hg systolic is considered significant because a decrease of this magnitude may indicate hypovolemia or obtunded neurological reflexes that prevent the maintenance of an adequate BP.[42]

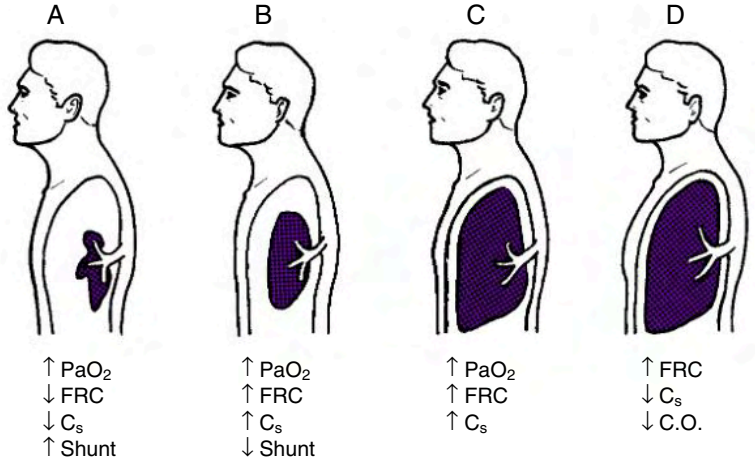


Fig. 13.2 (A) The stiff lungs and increased shunt result in a decrease in functional residual capacity (FRC) and arterial O_2 pressure (P_aO_2). (B and C) As PEEP is increased, C_S and P_aO_2 improve as the FRC increases, resulting in a lowering of the shunt effect. (D) Too much PEEP has been added, and C_S and cardiac output decrease as the FRC is increased above the optimum level.

PEEP (cm H_2O)	0	5	10	15	20	25	30
Minutes/time	15	30	45	60	75	90	105
Blood pressure (mm Hg)	117/80	120/85	120/80	110/70	115/75	115/75	90/65
C_S (mL/cm H_2O)	36	36	37	35	40	45	36
P_aO_2 (F_IO_2 = 1.0)	43	59	65	73	103	152	167
C_aO_2 (vol%)	15.3	17.8	18.3	18.9	19.2	19.4	19.6
P_aCO_2 (mm Hg)	37	37	38	37	39	37	38
pH	7.41	7.42	7.42	7.42	7.40	7.41	7.41
$P(A-a)O_2$ (mm Hg)	607	591	585	577	547	498	483
$P_aCO_2 - P_{et}CO_2$ (mm Hg)	16	15	13	10	9	8	15
$P\bar{v}O_2$ (or $S\bar{v}O_2$) mm Hg (or %)	27	37	38	38	39	40	34
C.O.L/min	4.1	4.2	4.0	4.5	4.4	4.4	3.3
$C(a-\bar{v})O_2$ (vol%)	5.3	5.2	5.4	5.0	4.9	4.9	6.7
PCWP (mm Hg)	3	5	8	11	12	13	18
PAP (mm Hg)	37/21	39/25	41/24	43/25	40/21	38/24	45/30
C.O. × CaO_2 Oxygen transport	627	748	732	851	845	854	647

Fig. 13.3 This figure gives an example of a PEEP study flow sheet including oxygenation and hemodynamic data. Key points to observe when first reviewing a PEEP study are blood pressure (BP), mixed venous O_2, and O_2 transport. Notice that these three values decline at a PEEP of 30 cm H_2O. BP drops to 90/65, PvO_2 drops to 34 mm Hg, and O_2 transport drops to 647 mL/min. A more optimal PEEP level is 25 cm H_2O, where these parameters and others indicate that O_2 transport is improving without significant cardiovascular side effects.

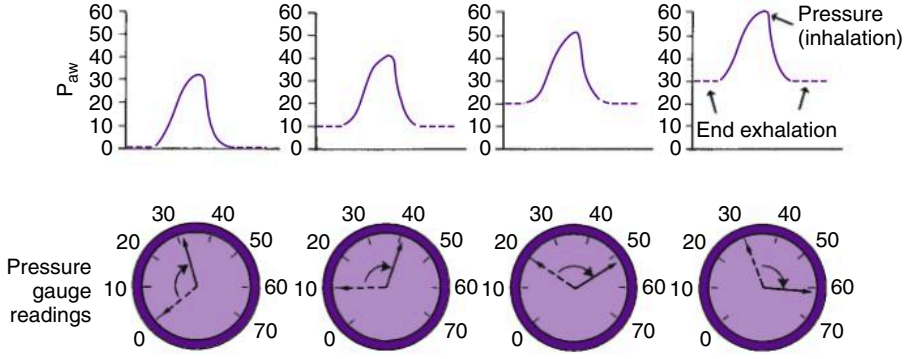


Fig. 13.4 High PEEP levels can be expected to cause PIP and P_{plat} readings to rise on the ventilator manometer. The baseline reading rises above zero and reflects the increase in FRC.

Breath Sounds

A brief examination of the chest (i.e., auscultation, palpation, and percussion) can indicate barotrauma or any other changes in a patient's lung condition that may have occurred.

Ventilator Parameters

Measurement of ventilator parameters, such as $\dot{V}_E$, V_T, *f*, flow, PIP, and P_{plat}, can provide valuable information about changes in the patient's C_L and airway resistance (R_{aw}).

Measuring $\dot{V}_E$ and V_T is relatively easy. One does not expect $\dot{V}_E$ to change as a direct result of using CPAP or PEEP; P_aCO_2 is not directly affected. If a patient has been hyperventilating (low P_aCO_2) because of hypoxemia before the use of CPAP or PEEP, the relief of the hypoxemia with PEEP/CPAP should be accompanied by a decrease in $\dot{V}_E$ and a rise in P_aCO_2.[43] P_aCO_2 may decrease if PEEP improves ventilation to previously perfused alveoli. High levels of PEEP expand the conductive airways, in part because of dilation of terminal and respiratory

bronchioles, which increases dead space and leads to an increased P_aCO_2.

Static Compliance

Compliance is considered a good indicator of the effects of PEEP on the lung.[44] As PEEP progressively restores FRC, compliance should increase (Fig. 13.5). Most ICU ventilators allow for the measurement of C_D and calculation of C_S. (NOTE: The GE Healthcare Engstrom Carescape R860 [GE Healthcare, Chicago, IL] has an option that allows for the measurement of FRC [FRC INview, GE Healthcare]). It is important to recognize, however, that when PEEP reaches a point at which it causes overdistention of the lung, compliance will decrease. Evidence of this reduction in compliance because of overdistention of the alveoli can be seen in the pressure-volume graphic. A characteristic duck-billed appearance occurs at the top of the pressure-volume loop (Fig. 13.6). (NOTE: When calculating static compliance [C_S], calculations of tubing compliance [C_T] must be taken into account and include the PEEP value.[45] If auto-PEEP is present, it must be measured and considered part of the end-expiratory pressure when calculating compliance.)

In patients with chest wall injuries or hypovolemia, the use of C_S alone is not a good indicator of optimal PEEP or cardiovascular changes with PEEP, even at low levels of PEEP. More invasive monitoring techniques, such as the placement of a balloon-tipped pulmonary artery catheter, may be needed. For example, if PEEP levels above 15 to 20 cm H_2O are used, compliance is not a good indication of cardiovascular function and monitoring pulmonary artery pressures may be indicated. Notice that this type of invasive monitoring increases the risk for complications, so implementation must be considered carefully (see Chapter 11).

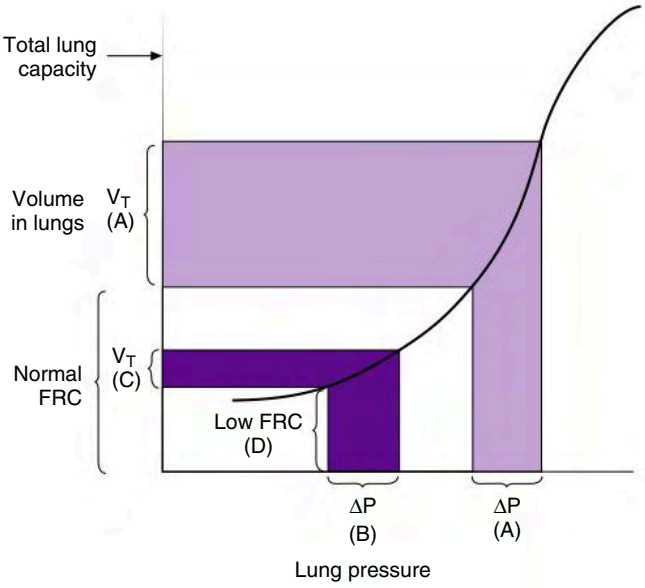


Fig. 13.5 A pressure-volume curve where the *x*-axis is pressure and the *y*-axis is volume. Near the section labeled *Volume in lungs* is a corresponding curve that represents normal lung volumes *(shaded with light* purple*)*. A small change in pressure (ΔP) results in a good tidal volume *(V_T) (A),* at the steepest part of the curve. (Note *Normal FRC.*) At the *bottom left* portion of the curve, the lungs are stiffer (as in ARDS). A change in pressure (ΔP at *B*) produces a small volume change (V_T at *C*). FRC is low *(D)*. Theoretically, by placing a patient with stiff lungs on PEEP, the compliance improves (moves upward and to the right—steeper portion) as the FRC increases *(shaded with dark blue).*

Arterial P_{O_2}, F_IO_2, and P_aO_2/F_IO_2

The usual approach to the management of F_IO_2 and PEEP is to start with high F_IO_2 and incrementally decrease it as PEEP or CPAP improves oxygenation.[37] A target value for P_aO_2/F_IO_2 greater than 300 (e.g., $P_aO_2 = 100$, with $F_IO_2 = 0.33$) is optimum but not always a realistic goal.

Arterial P_aCO_2 and pH

Adequacy of ventilation is determined by regular evaluation of P_aCO_2 and pH as PEEP is increased. If P_aCO_2 and pH are not being maintained near a patient's normal values, appropriate adjustments must be made. Depending on the severity of a patient's condition, permissive hypercapnia may be an acceptable alternative. (See Chapter 12 for a discussion of permissive hypercapnia.)

Alveolar-to-Arterial Oxygen Tension ($P_{(A-a)}O_2$)

With increases in PEEP, the $P_{(A-a)}O_2$ typically decreases, reflecting improvement in $\dot{V}/\dot{Q}$. This can be further evaluated by calculating P_aO_2/P_AO_2 or P_aO_2/F_IO_2 ratios.

Arterial to End-Tidal CO_2 Tension Gradient ($P_{(a-et)}CO_2$)

The arterial to end-tidal CO_2 tension gradient ($P_{(a-et)}CO_2$) is often used as an indirect assessment of the effectiveness of ventilation (i.e., V_D/V_T ratio). It is lowest when gas exchange units are maximally recruited without being overdistended by PEEP. Normal $P_{(a-et)}CO_2$ gradient is 4.5 ± 2.5 mm Hg. An increase in PEEP that leads to increases in the $P_{(a-et)}CO_2$ gradient above minimum acceptable values signifies that too much PEEP has been added and can be expected to produce a drop in cardiac output and an increase in V_D/V_T.[46] The data shown in Table 13.4 provide an example of changes that might be expected in $P_{(a-et)}CO_2$ with increased PEEP.[46] (See Chapter 10 for a discussion of volumetric CO_2 monitoring.)

Hemodynamic Data

In addition to the measurement of arterial BP, hemodynamic monitoring, including the evaluation of $P\bar{v}O_2$ and/or $S\bar{v}O_2$, cardiac output, $C[a-\bar{v}]O_2$, pulmonary artery pressure (PAP), pulmonary artery occlusion pressure (PAOP), and pulmonary

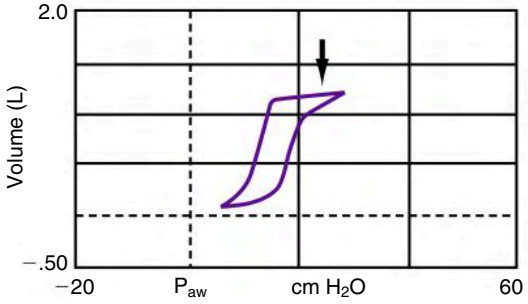


Fig. 13.6 A pressure-volume loop of a patient receiving a volume-targeted breath of 1.2 L with a peak inspiratory pressure of about 30 cm H_2O. The extended upper flat portion of the "beaked" appearance of the curve indicated by the *arrow* suggests overdistention of lung units. (From Wilkins RL, Stoller JK, Scanlan L, editors: *Egan's fundamentals of respiratory care,* ed 9, St. Louis, MO, 2009, Mosby.)

TABLE 13.4 A Positive End-Expiratory Pressure (PEEP) Study to Evaluate Use of $P_{(a-et)}CO_2$, Not P_aCO_2, for Assessing PEEP in an Experimental Model Involving Oleic Acid Injury

PEEP	0	5	10[a]	15	20	25
$P_{(a-et)}CO_2$	17	13	8	8	10	14
$\frac{\dot{Q}_S}{\dot{Q}_T}$ (%)	14	3	2	2	2	2
C_S (mL/cm H_2O)	18	20	16	12	7	9
P_aO_2 (on $F_IO_2 = 0.5$)	95	180	>200	>200	>200	>200
O_2 delivery (mL/min)	250	200	300	280	220	180

[a]10 cm H_2O represents a PEEP level where all parameters are optimal. With greater increases in PEEP, the $P_{(a-et)}CO_2$ rises and the O_2 delivery and C_S fall. Note that shunt ($\dot{Q}_S/\dot{Q}_T$) remains low and P_aO_2 remains high.

Data from Murray JF, Wilkins RL, Jacobsen WK, et al.: Titration of PEEP by the atrial minus end-tidal carbon dioxide gradient, *Chest* 85:100–104, 1984; See also Suter PM, Fairley HB, Isenberg MD: Optimum end-expiratory airway pressure in patients with acute pulmonary failure, *N Engl J Med* 292:284–289, 1975.

vascular resistance (PVR) may be required. (See Chapter 11 for more details on hemodynamic monitoring.)

Arterial-to-Venous Oxygen Content Difference

The arterial-to–mixed venous O_2 content difference ($C[a-\bar{v}]O_2$), which at rest is normally 5 vol%, reflects O_2 utilization by the tissues. An increase in $C[a-\bar{v}]O_2$ with an increase in PEEP may indicate hypovolemia, cardiac malfunction, decreased venous return to the heart, and decreased cardiac output, or increased $\dot{V}O_2$.

A decrease in $C[a-\bar{v}]O_2$ with an increase in PEEP may also be associated with an increase in cardiac output resulting from improved or augmented cardiac function. Reductions in O_2 extraction by the tissues can result from reduced metabolic rate or histotoxic hypoxia.

Mixed Venous Oxygen Tension or Saturation

$P\bar{v}O_2$ is normally about 35 to 40 mm Hg (normal $S\bar{v}O_2 = 75\%$). A $P\bar{v}O_2$ of 28 mm Hg is probably the minimal acceptable level for PvO_2 and represents an $S\bar{v}O_2$ of about 50%.[45]

As PEEP is increased, it often leads to an improvement in P_aO_2 and $P\bar{v}O_2$ with no net change in . This indicates that O_2 transport is improving, with no apparent change in $P[a-\bar{v}]O_2$ cardiac output, and the level of shunting is also decreasing.

PEEP may increase P_aO_2 and $P\bar{v}O_2$, decrease net $C[a-\bar{v}]O_2$, and improve O_2 delivery. If $\dot{V}O_2$ is constant, these changes suggest a rise in cardiac output. On the other hand, in patients in whom $P\bar{v}O_2$ decreases with PEEP and $C[a-\bar{v}]O_2$ increases, cardiac output and O_2 delivery may decrease. However, if $P\bar{v}O_2$ was high to start and then drops to a normal value, no harmful effects may be present[47] (Case Study 13.4).

Cardiac Output

Cardiac output provides key information about a patient's cardiovascular response to PEEP. Thus as PEEP improves $\dot{V}/\dot{Q}$ relationships, oxygenation also improves, which may enhance cardiac performance. As intrapleural pressures increase or as the gas exchange units become overdistended, however, venous return decreases and cardiac function is altered; cardiac output then declines, and the point of optimal PEEP is no longer present (Fig. 13.7 and Table 13.5).[47,48] (NOTE: Cardiac output can be estimated noninvasively using the Respironics NM3 monitor from Philips, Andover, MA)

Some clinicians increase vascular volumes with fluid administration (fluid challenge) and give inotropic agents to maintain cardiac function as PEEP is increased. This approach provides a way to ensure that O_2 transport or delivery, or both, are sufficient to meet the O_2 demand by the tissues.

USE OF PULMONARY VASCULAR PRESSURE MONITORING WITH PEEP

When PEEP greater than 15 cm H_2O is used, it is important to closely evaluate the patient's hemodynamic status, which may require the placement of a balloon-flotation pulmonary artery catheter. After catheter placement, a chest radiograph is obtained

Case Study 13.4

Selecting Optimal PEEP

A PEEP study is being performed on a patient. The following data have been specifically selected from all measured parameters to see if you can solve this problem based only on what is provided. What PEEP level appears to be optimum for the patient? Having selected the level, would you make any other changes?

Time	PEEP (cm H_2O)	F_IO_2	P_aO_2 (mm Hg)	BP (mm Hg)	$P\bar{v}O_2$ (mm Hg)
1:00	5	1.0	43	125/90	28
1:30	10	1.0	57	120/85	33
2:00	15	1.0	104	120/85	38
2:30	20	1.0	143	100/70	31

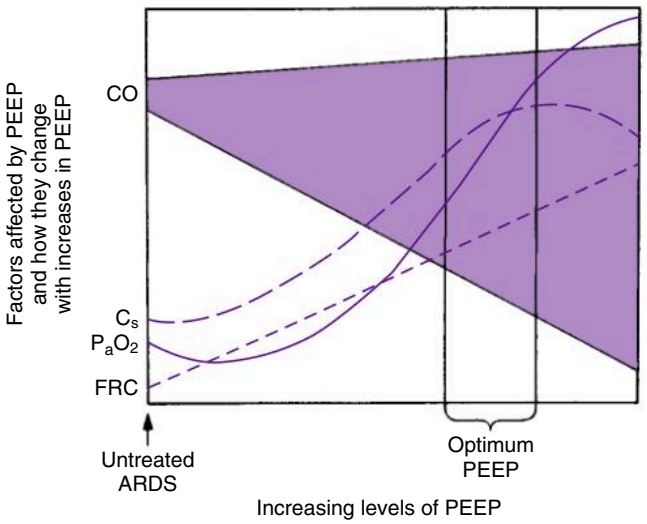


Fig. 13.7 The curves above represent physiological factors that change during the application of PEEP or CPAP. As the PEEP level is increased, P_aO_2, FRC, and C_S normally increase. Cardiac output (C.O.), represented by the *shaded area,* can increase slightly, stay the same, or decrease. The optimal PEEP level can be expected to occur when P_aO_2, FRC, and C_S are high. C.O. should be maintained near normal so that O_2 transport to the tissues remains high.

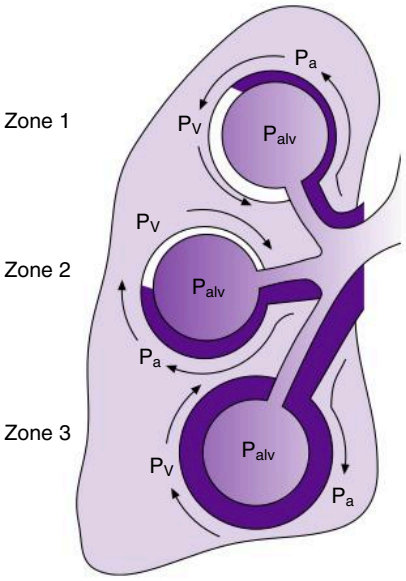


Fig. 13.8 In a normal lung the greatest amount of perfusion and ventilation are to the dependent (lower) lung zones. The zone 3 regions represent lung areas where pulmonary artery pressure (P_a, deoxygenated blood) exceeds pulmonary venous pressure (P_V, oxygenated blood), which exceeds pulmonary alveolar pressure (P_{alv}). In zone 2 lung areas (normally the middle region), pulmonary artery pressure exceeds pulmonary alveolar pressure, which exceeds pulmonary venous pressure ($P_a > P_{alv} > P_v$). In zone 1 lung areas (normally the upper regions), pulmonary alveolar pressure exceeds pulmonary artery pressure, which exceeds pulmonary venous pressure ($P_A > P_a > P_v$). Pulmonary vascular pressure monitoring is most accurate if the catheter is in zone 3.

TABLE 13.5 Effects of Increased PEEP on PvO_2 and Related Parameters

PEEP (cm H_2O)	0	5	10*	15	20
PvO_2 (mm Hg)	35	37	39	37	35
$C[a-\bar{v}]O_2$ (mL/100 mL)	3.7	3.7	3.6	3.8	4.1
C.O. (L/min)	7.0	7.0	7.5	6.7	6.5
C.O. × C_aO_2 (mL/min) (O_2 transport)	850	875	950	850	825

*10 cm H_2O of PEEP represents a point where PvO_2 is nearest normal, and cardiac output (C.O.) and O_2 transport are at their highest. Note that as PEEP continues to increase, the $C[a-\bar{v}]O_2$ continues to rise and PvO_2 falls. The cardiac output falls, reflecting a slower perfusion rate and more time for O_2 extraction at the tissues.

to ensure the catheter tip is located in a dependent (zone 3) area of the lung. If the catheter is not located in a dependent area of the lung, PAOP may not be a true reflection of pressures on the left side of the heart but rather reflect alveolar or airway pressures (Fig. 13.8). It is important to remember that as PEEP is increased, vascular pressures will also increase. Note that PEEP is not removed to measure vascular pressures because doing so might precipitate severe hypoxemia because of alveolar collapse, which can be difficult to reverse.[49–51] However, there is some controversy about discontinuing ventilation for cardiovascular measurements.[52] If PEEP is removed, the effect of PEEP on the vascular pressures would not be reflected in the measurement. Generally, pulmonary vascular pressures are recorded at end exhalation. (See Chapter 11 for additional information on hemodynamic monitoring.) If the PAOP markedly rises as PEEP is increased, the lungs may be overinflated and PEEP may need to be reduced (Fig. 13.9). Falsely elevated vascular pressures do not give an accurate picture of the true filling of the left side of the heart. On the other hand, when PEEP rises, PAOP may be markedly decreased because pulmonary blood flow is reduced as a result of decreased venous return to the right side of the heart. This situation is often referred to as a *PEEP-induced relative hypovolemia* and requires either a reduction in the amount of PEEP being used or administration of fluids to increase vascular volume.

O_2 delivery (cardiac output × C_aO_2) can be an effective method for evaluating the effect of PEEP and is important because it reflects cardiac and pulmonary functions in addition to the carrying capacity of the blood. The normal value for O_2 delivery is approximately 1000 mL/min. If cardiac output is low, it may be enhanced by slightly reducing the PEEP level or using volume loading (administration of fluids) and/or inotropic agents (e.g., dopamine hydrochloride). A low C_aO_2 may be improved by increasing PEEP and F_IO_2, or normalizing Hb levels (i.e., giving blood, if the patient is anemic).

An example of the effect of PEEP on the cardiovascular responses of a patient with ARDS is shown in Table 13.6. In this example, the P_aO_2 increased substantially with PEEP. Central venous pressure increased slightly; cardiac output did not change significantly. The increase in PAOP was matched by an increase in PAP.

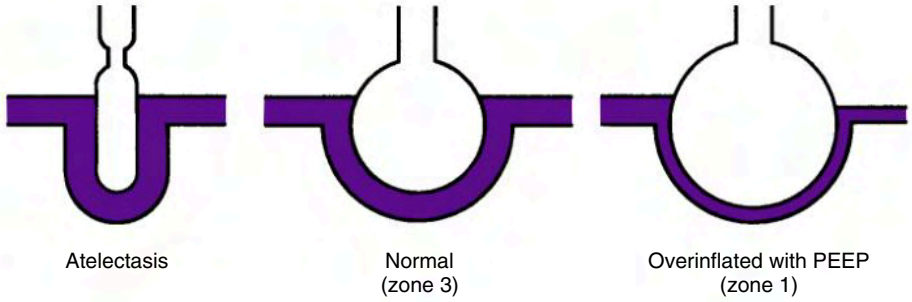


Fig. 13.9 ARDS creates many lung regions with atelectasis and edema *(left figure)*. With PEEP, these affected areas can be reexpanded, creating more zone 3 lung areas *(central figure);* however, overexpansion with PEEP can reduce perfusion to ventilated alveoli and create zone 1 areas of lung *(right figure)*.

TABLE 13.6 Effects of Increased Positive End-Expiratory Pressure (PEEP) on Pulmonary Artery Occlusion Pressure (PAOP)

PEEP (cm H_2O)	0	5	10	15
P_aO_2 (mm Hg) ($F_IO_2 = 1.0$)	90	160	280	450
PAP (mm Hg)	39/15	43/18	45/20	47/23
PAOP (mm Hg)	9	13	16	21
CVP (cm H_2O)	9	11	13	14
C.O. (L/min)	4.5	4.8	4.6	4.7

P_aO_2 increases substantially. CVP increases slightly. C.O. did not change significantly. The increase in PAOP is matched by an increase in PAP.
C.O., Cardiac output; *CVP,* central venous pressure; *PAP,* pulmonary artery pressure.

CONTRAINDICATIONS AND PHYSIOLOGICAL EFFECTS OF PEEP

PEEP, particularly at the levels often needed in patients with ARDS, has contraindications and physiological effects that can have an effect on the patient's safety. Practitioners must monitor the patient for any adverse effects when PEEP is instituted and before instituting lung RMs (described later).

Contraindications for PEEP

PEEP can be detrimental to a patient's cardiovascular status because it can reduce cardiac output and compromise circulation, leading to a reduction in BP. A relative contraindication for PEEP is hypovolemia. A patient who is hypovolemic as a result of hemorrhage or dehydration must be treated, and vascular volumes must be replenished before beginning PEEP therapy. Patients can be treated with fluids, volume expanders, or inotropic agents to enhance blood volume and cardiac output.

An absolute contraindication for PEEP is an untreated significant pneumothorax or a tension pneumothorax. Note that this is also true of a lung RM. Increasing positive pressure might further increase the air present in the intrapleural space and cause death. PEEP and RMs must also be used with caution in patients with bronchopleural fistulas or other types of barotrauma (e.g., pneumopericardium). In addition, PEEP should be used cautiously in patients who have recently had lung surgery, so a pneumothorax does not develop. In patients with elevated intracranial pressures (ICPs), PEEP may further elevate ICP by increasing central venous pressure. This should not prevent the use of PEEP in these patients, especially if they are severely hypoxemic. The hypoxemia is likely to be fatal if not treated. Thus if PEEP is used in these patients, ICP should be carefully monitored and treated appropriately.

The beneficial effects of PEEP and lung recruitment occur when they are used to increase FRC by recruiting collapsed alveoli. These effects do not occur, however, in patients with preexisting hyperinflation (e.g., emphysema). Areas of the lung that are already hyperinflated may be further distended, which can lead to compression of adjacent capillaries and the redirecting of blood to areas that are not as well ventilated, resulting in increased shunting, venous admixture, and hypoxemia. The use of low PEEP (3–5 cm H_2O) may, however, be beneficial for these patients if it compensates for the reduced FRC resulting from intubation or the supine position or aids in triggering ventilator breaths when auto-PEEP is present (see Chapter 7). Otherwise, use of PEEP in these individuals is not typically beneficial (Key Point 13.4 and Box 13.9).

Pulmonary Effects of PEEP

The most frequently studied pulmonary disorder in relation to the effects of PEEP is ARDS. ARDS studies provide valuable insight into the behavior of PEEP on various lung units and the advantages of using protective lung strategies. The changes in pulmonary mechanics associated with ARDS cause an uneven distribution of ventilation. In the lungs of a supine patient, in whom the independent zones (ventral areas) receive most of the breath, delivery of a large volume (>10 mL/kg) may cause overexpansion and high ventilating pressures. During patient monitoring, this appears as a decrease in C_L.[15,30,31]

As PEEP is applied in increasing levels, it recruits a certain number of collapsed alveoli. For independent (ventral) portions of

***Key Point* 13.4** Lungs can be overdistended without being hyperinflated. PEEP can have unexpected and undesirable side effects on blood distribution and lung ventilation if it is used on patients with pathological conditions that involve only one lung, such as in unilateral pneumonia or lobar pneumonia. For this reason, unilateral lung disorders may represent a relative contraindication to the use of PEEP and may be better managed by using a double-lumen endotracheal tube and unilateral or independent lung ventilation with two ventilators.[53]

BOX 13.9 Overdistention or Hyperinflation?

There is a difference between overdistention and hyperinflation.[63]

Overdistention, or overstretching lung tissue, increases alveolar wall tension or alveolar distending pressure above normal. Lungs may be overdistended (severe ARDS) and not hyperinflated. Studies have demonstrated that overdistention is associated with the presence of increased levels of inflammatory mediators.

In contrast, *hyperinflation* may be thought of as gas overfilling. As defined by computed tomography, hyperinflation is a higher than normal ratio of gas to tissue. For example, the lungs of a patient with emphysema may be hyperinflated but not overdistended.

the lungs, recruitment is negligible; PEEP simply expands already open lung units. As more PEEP is added, ventral units become overstretched, which decreases their compliance. As a result, the distribution of a V_T breath to this area decreases as PEEP increases. For this reason, it has been emphasized that the patient's P_{plat} should be maintained below 30 cm H_2O.

The same overstretching may occur in the middle portions of the lungs (between the ventral and dorsal regions of supine patients), where it not only stretches alveoli open but also recruits areas that were previously collapsed. In this situation, two opposing compliance changes are likely to occur. Compliance decreases in some units from overstretching, whereas the compliance of other units improves as they reopen.[31]

In the dependent (dorsal) areas, fewer lung units are open at FRC (end exhalation; 0 cm H_2O PEEP). But as a sustained high-pressure breath is delivered (e.g., RM) or as PEEP is increased, more units are recruited and remain open, increasing compliance in the dependent area and resulting in an enhanced distribution of gas to the dependent units. However, there will be some alveoli that remain collapsed, and these may be scattered throughout the lung. The overall effect is to make the lung more homogeneous when PEEP is increased. An upper limit of PEEP beyond which there is no benefit to lung volume exists for all patients with ARDS. This range usually begins at about 15 cm H_2O and may increase beyond that point.[27,31,54] Results are variable.

Table 13.7 shows one classic case study in which increasing increments of PEEP had no significant effects until 15 cm H_2O was used, at which time the P_aO_2 improved markedly.[55] This represents the point at which alveolar recruitment probably occurred.

Transmission of Airway Pressure to Pleural Space

Transmission of airway pressures to the intrapleural space, mediastinum, and thoracic vessels is a concern when positive pressure is applied to the respiratory system. When chest wall compliance is normal and C_L is low, less of the airway pressure (P_{aw}) is transmitted to the pleural space; however, if C_L is near normal and chest wall compliance is low, more pressure is transmitted to the pleural space.

Uses of PEEP for Problems Other Than ARDS

PEEP and Congestive Heart Failure

Patients with moderate-to-severe congestive heart failure (CHF) present with reduced cardiac output and impaired cardiac function. They progressively develop pulmonary edema (cardiogenic pulmonary edema) that differs from edema associated with ARDS. The permeability characteristics of the pulmonary vessels and alveoli remain normal, but the pulmonary hydrostatic pressures rise because blood backs up in pulmonary circulation from the left side of the heart. As a result, edema develops in the lungs and the patient becomes hypoxemic. Pulmonary vascular resistance increases and eventually the work of the right side of the heart increases, leading to right heart failure (cor pulmonale) and the presence of peripheral edema.

Patients with untreated CHF admitted to the hospital typically present with pink, frothy secretions and bilateral crackles (rales) indicative of pulmonary edema. These patients usually benefit from positive pressure therapy. Positive pressure reduces the venous return to the heart and the amount of blood that the heart must pump, which reduces the work of the heart. Increased F_IO_2 values and positive pressure may also help improve myocardial oxygenation and function. It is worth noting that the beneficial effects of PEEP or positive pressure ventilation in some patients with CHF is not always predictable. In patients with aortic or mitral valve replacement, PEEP has been associated with changes in V_D/V_T and decreased cardiac index (CI).

TABLE 13.7 Data from a Patient With Acute Respiratory Distress Syndrome on Mechanical Ventilation 24 Hours After Admission

PEEP (cm H_2O)	BP (mm Hg)	HR (beats/min)	PAOP (mm Hg)	C.O. (L/min)	C_s (mL/cm H_2O)	PIP (cm H_2O)	P_aO_2 (mm Hg)	PvO_2 (mm Hg)
0	130/65	130	16	4.8	28	50	40	27
5	120/55	135	13	4.2	31	58	45	37
10	135/65	125	18	5.8	33	60	50	35
15	130/70	120	19	5.9	36	55	115	37
20	110/50	130	25	4.1	27	63	150	29

ARDS, Acute respiratory distress syndrome; *BP,* blood pressure; *C.O.,* cardiac output; C_S, static compliance; *HR,* heart rate; *PAOP,* pulmonary artery occlusion pressure; *PIP,* peak inspiratory pressure; PvO_2, mixed venous O_2 partial pressure; $\dot{V}_E$, minute ventilation. The following are constant: $V_T = 1100$ mL, $f = 6$ breaths/min, $\dot{V}_E = 6.6$ L/min, $F_IO_2 = 0.8$. P_aCO_2 and pH do not change significantly.

Modified from Bone RC: Complications of mechanical ventilation and positive end-expiratory pressure, *Respir Care* 27:402–407, 1982.

Mask CPAP as a Treatment for Postoperative Atelectasis and Hypoxemia

CPAP delivered by mask can be used to help prevent postoperative atelectasis and improve oxygenation. It has been shown to return baseline lung volumes to normal more quickly in patients who had undergone upper abdominal surgery than in patients treated with frequent coughing and deep breathing alone. Levels of CPAP range from about 5 to 15 cm H_2O and are administered for varying intervals (from hourly to every 8 hours) and durations (from 25–35 breaths/treatment to continuously for 6–10 hours). The exact levels of CPAP required to accomplish the desired results remain undetermined. The effectiveness of CPAP may be similar to the use of an RM in postoperative patients.[56]

Sleep Apnea

Nasal and mask CPAP have been shown to be effective techniques for treating many patients with obstructive sleep apnea. Levels from 5 to 15 cm H_2O can provide a pneumatic splint that helps prevent pharyngeal obstruction. It may also increase FRC in these patients.

Cystic Fibrosis

Application of PEP by mask or mouthpiece using a one-way inspiratory valve and a one-way expiratory flow resistor has been shown to be beneficial for removal of secretions from patients with cystic fibrosis (PEP therapy). PEP devices provide expiratory pressures of 10 to 20 cm H_2O at midexhalation that can be used for 15- to 20-minute periods, three to four times a day to help improve expectoration of secretions, reduce residual volume (less hyperinflation), and improve airway stability.[3] It should be mentioned that PEP therapy has also been successfully used to treat patients with a weak cough reflex and unable to produce effective airway clearance of thick tenacious secretions to prevent or reverse atelectasis.

Airway Suctioning With PEEP

Some patients cannot tolerate the removal of PEEP for the purposes of suctioning. Therefore it is prudent in these circumstances to use a closed-suction system (see Chapter 12). If this is not possible, a resuscitation bag equipped with a PEEP valve can be used during the suctioning procedure. The suctioning procedure itself removes air and volume from the lung and can reduce C_S. RM after suction may be indicated, but only future studies can determine the role of RM in this circumstance.[57] (RMs are described later in this chapter.)

WEANING FROM PEEP

The exact length of time that PEEP is needed before the alveoli are stable in patients with ARDS is not known. Premature weaning from PEEP is not without problems. Patients whose P_aO_2 drops to 65 mm Hg or lower with a reduction of 5 cm H_2O in PEEP may still need PEEP to maintain lung recruitment (Box 13.10).[58,59]

Several criteria may indicate when a patient is ready for a trial reduction in PEEP. The patient must demonstrate an acceptable P_aO_2 on an F_IO_2 of less than 0.50 and must be hemodynamically stable and nonseptic. If ARDS was previously diagnosed, the patient's lung conditions should have improved. For example, if C_L is improved (C_S >25 mL/cm H_2O) and P_aO_2/F_IO_2 ratio is high (>250), the chances of successfully lowering PEEP are good. A recommended procedure for weaning from PEEP is described in Table 13.8, and Box 13.11 shows some examples of weaning from PEEP.

ACUTE RESPIRATORY DISTRESS SYNDROME

ARDS is one of the most frequently studied pulmonary disorders in terms of how severe hypoxemia is managed. Because of the severity of hypoxemia and shunting encountered in this disorder, selecting the most effective ventilatory strategy remains controversial and a topic of intense discussion. The following discussion addresses some of these pertinent issues related to the pathophysiology and management of ARDS.

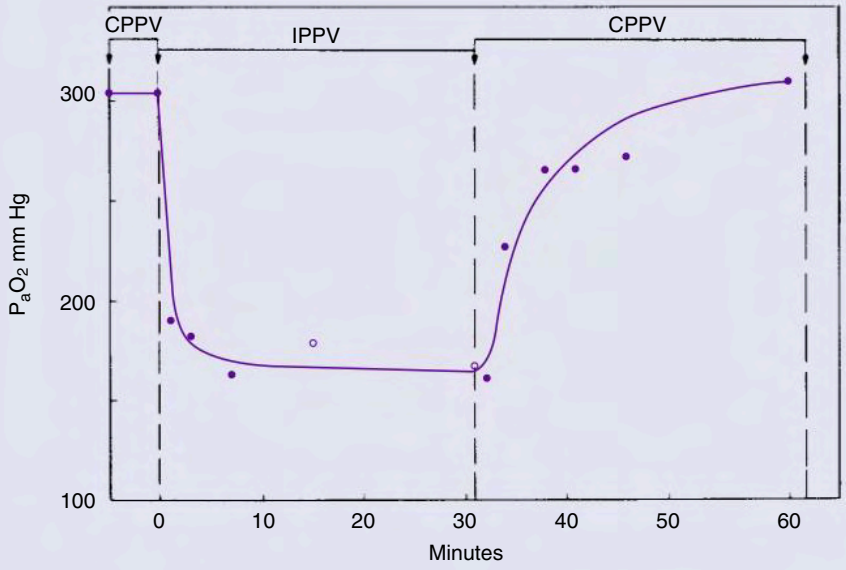
ARDS was originally described in a study by Ashbaugh and associates[60] that was published in *The Lancet* in 1967: "The clinical pattern which we will refer to as the respiratory distress syndrome, includes severe dyspnea, tachypnea, hypoxemia that is refractory to O_2 therapy, stiff, low compliance lungs (i.e., reduced C_L) and diffuse alveolar infiltration seen on chest x-ray." Since this initial description of ARDS, several definitions have been proposed and used to provide guidance for clinicians treating patients with ARDS and to facilitate clinical trials and resource allocation.[61,62] In 1994, the American-European Consensus Conference (AECC) published a landmark article that provided a list of criteria that could better guide critical care clinicians and researchers caring for individuals afflicted with ARDS.[61] The AECC consensus statement included an overarching definition of acute lung injury (ALI) for patients with a P_aO_2/F_IO_2 ratio 300 mm Hg or less with ARDS representing a subset of patients with a P_aO_2/F_IO_2 ratio of 200 mm Hg or less. The AECC definition also specified that patients demonstrate the presence of bilateral infiltrates on frontal chest radiograph, with no evidence of left atrial hypertension.[61]

Although the AECC definition provided much needed guidance for clinicians and researchers, it became evident that a number of issues required clarification. In 2011, an international consensus group was convened in Berlin, Germany, to update the definition of ARDS to include current epidemiological, physiological, and clinical data.[62] It was proposed that the new definition *(the Berlin definition)* should provide a framework that identifies explicit criteria regarding (1) the time frame of onset of ARDS, (2) criteria for gauging the severity of the syndrome, (3) better clarification of the radiological and hemodynamic criteria and their role in the diagnosis and treatment of patients, and (4) identification of risk factors for the development of ARDS.[62,63] Table 13.9 provides a comparison of the limitations of the AECC definition and issues addressed in the Berlin definition of ARDS.

The Berlin definition now specifies that the *onset* of ARDS must occur within 1 week of a known clinical insult or the presence of new or worsening respiratory symptoms.[62] A summary of the final draft of the Berlin definition of ARDS is shown in Table 13.10. The definition also provides clarification of radiographic and hemodynamic changes used in the diagnosis of ARDS. Radiographic criteria include bilateral opacities in at least three quadrants for the lung that cannot be fully explained by effusions, lung collapse, or the presence of nodules.[63] Because high pulmonary artery wedge pressure (PAWP) (i.e., PAOP) can coexist with ARDS, the PAWP requirement for identifying the etiology of

BOX 13.10 PEEP Withdrawal

It has been known for more than four decades that P_aO_2 drops precipitously when PEEP is withdrawn from patients with acute lung injury. It is now known that this is associated with lung derecruitment. The drop in P_aO_2 and lung volume occurs quickly. In a study performed on patients with ARDS in 1970, it was shown that removal of PEEP in patients whose lungs were not stable resulted in an immediate and dramatic drop in P_aO_2 (see figure).



The figure shows the time sequence of P_aO_2 changes with altered ventilation patterns in eight patients. The mean P_aO_2 with continuous positive pressure ventilation (CPPV; now known as CMV + PEEP) at 13 cm H_2O was 304 mm Hg. After changing to intermittent positive pressure ventilation (IPPV; now called CMV without PEEP), it fell 129 mm Hg within 1 minute and over the next 3 minutes fell 32 mm Hg. *Open circles* represent mean values of only six patients. (In one patient, a large fall in P_aO_2 required reapplication of CPPV after 6 minutes; a second value was not available because of clotting of the blood sample.) On reapplication of CPPV (i.e., CMV + PEEP), the P_aO_2 gradually rose to its initial value.

From Kumar A, Konrad JF, Gerrin B, et al.: Continuous positive pressure ventilation in acute respiratory failure: effects on hemodynamics and lung function, *N Engl J Med* 283:1430–1436, 1970.

TABLE 13.8 Examples of Weaning Patients From PEEP/CPAP

EXAMPLE 1

Time (h)	PEEP (cm H_2O)	P_aO_2 (mm Hg)	Blood Pressure (mm Hg)	Static Compliance (mL/cm H_2O)
01:00	12	90	115/65	30
01:03	7	60	120/75	30

Note that P_aO_2 drops significantly. It is better to leave PEEP where it was for several more hours.

Example 2

Time (h)	*PEEP (cm H_2O)*	*P_aO_2 (mm Hg)*	*Blood Pressure (mm Hg)*	*Static Compliance (mL/cm H_2O)*
02:00	15	98	112/70	32
02:03	10	85	118/70	32

Note that P_aO_2 remains at an acceptable level after the reduction of PEEP. Assuming that the clinical condition of the patient remains stable, PEEP can be reduced to 10 cm H_2O.

pulmonary edema has been removed.[61–63] It is noteworthy that the Berlin definition does not include the term *acute lung injury (ALI)* but relies on a classification of the severity of ARDS based on oxygenation status. The severity of ARDS is determined by using the P_aO_2/F_IO_2 ratio value when a defined minimal level of PEEP or CPAP is being administered (e.g., ≥5 cm H_2O of PEEP or CPAP). Lastly, the definition identifies risk factors for the development of ARDS.

BOX 13.11 Procedures for Weaning From PEEP

A. Obtain baseline ABG values and determine that the criteria have been met. Acceptable P_aO_2 (90 mm Hg) on an F_IO_2 of ≤0.40, hemodynamic stability; not septic. Lung compliance is improved (e.g., C_S >25 mL/cm H_2O) and P_aO_2/F_IO_2 ratio >250 to 300.
B. Reduce PEEP by 5 cm H_2O.
C. Monitor S_pO_2 to determine the effect of PEEP reduction. If an ABG is drawn at this time, it is advisable to return the PEEP to the previous level (at step 1) until results from the ABG are obtained. A lung recruitment maneuver may be in order.
D. If S_pO_2 (or P_aO_2) falls by less than 20% of its value at the previous PEEP level, the patient is ready to tolerate the lower PEEP level.
E. If the patient has more than a 20% reduction in S_pO_2 or P_aO_2, the patient is not ready to have the PEEP reduced. PEEP is kept at its previous level.
F. Wait between reductions in PEEP and reevaluate the initial criteria. If the patient is stable, reduce PEEP by another 5 cm H_2O. This might take only 1 hour or may require as long as 6 hours or more.
G. When a patient is at 5 cm H_2O, an additional evaluation is necessary. If reducing the PEEP to zero results in a worsening of the patient's condition, it may be appropriate to leave the patient at 5 cm H_2O until it is time for extubation. Complete removal of PEEP before extubation may not be necessary and may be detrimental to patients with compromised lung-thorax mechanisms, leading to a deterioration of FRC and P_aO_2.

PATHOPHYSIOLOGY

In ARDS, inflammation of the pulmonary capillary endothelium and alveolar epithelium results in increased permeability of these tissue layers (Fig. 13.10). Injury to the lung parenchyma ultimately leads to leaking of protein-rich plasma out of the capillary, first into the interstitial space (interstitium) and then the alveolar space.

Computed tomography (CT) of the thorax in ARDS shows a gravity-dependent, ground-glass opacification appearance. This is thought to be associated with an active inflammatory process that involves the interstitium and alveoli of both lungs. The inflammation produces abnormal thickening of the alveolar epithelium and incomplete filling of alveolar space with inflammatory cells, cellular debris, and edema.[64,65] Acini are either completely airless or almost airless. Consequently, some alveoli are collapsed (atelectatic) and can be potentially recruited.

In general, ARDS produces stiff lungs (reduced lung compliance) and reduced lung volumes (decreased FRC). There appear to be marked regional differences and varying amounts of inflammation present. Parenchymal injury may also affect the airways, particularly the bronchioles and alveolar ducts. As these small airways become narrow and collapse, they may contribute to the reduced ventilation and lead to areas of trapped air.

CHANGES IN COMPUTED TOMOGRAM WITH ARDS

ARDS can be divided into two phases. The first is an acute **exudative** phase characterized by inflammation and alveolar filling. The second is a subacute phase, in which **fibrosing alveolitis** occurs.[65] During the first week, three distinct areas of the lungs can be discerned on chest CT. Initially, normal lung usually

TABLE 13.9 The AECC Definition—Limitations and Methods to Address These in the Berlin Definition

	AECC Definition	AECC Limitations	Addressed in Berlin Definition
Timing	Acute onset	No definition of acute time frame	Acute time frame specified
ALI category	All patients with P_aO_2/F_IO_2 <300 mm Hg	Misinterpreted as P_aO_2/F_IO_2 = 201–300, leading to confusing ALI/ARDS term	Three mutually exclusive subgroups of ARDS by severity ALI term removed
Oxygenation	P_aO_2/F_IO_2 ≤300 mm Hg (regardless of PEEP)	Inconsistency of P_aO_2/F_IO_2 ration because of the effect of PEEP and/or F_IO_2	Minimal PEEP level added across subgroups F_IO_2 effect less relevant in severe ARDS group
Chest radiograph	Bilateral infiltrates observed on frontal chest radiograph	Poor interobserver reliability of chest radiograph interpretation	Chest radiograph criteria clarified Example radiographs created
PAWP	PAWP ≤18 mm Hg when measured or no clinical evidence of left atrial hypertension	High PAWP and ARDS may coexist Poor interobserver reliability of PAWP and clinical assessments of left atrial hypertension	PAWP requirement removed Hydrostatic edema not the primary cause of respiratory failure Clinical vignettes created to help exclude hydrostatic edema
Risk factor	None	Not formally included in definition[4]	Included When none identified, need to objectively rule out hydrostatic edema (e.g., echocardiography)

AECC, American-European Consensus Conference; *ALI,* acute lung injury; *ARDS,* acute respiratory distress syndrome; F_IO_2, fraction of inspired O_2; P_aO_2, arterial partial pressure of O_2; *PAWP,* pulmonary artery wedge pressure; *PEEP,* positive end-expiratory pressure.
From ARDS Definition Task Force, Ranieri VM, Rubenfeld GD: Acute respiratory distress syndrome: the Berlin De finition, *JAMA* 307(3):2526–2533, 2012.

TABLE 13.10 The Berlin Definition of Acute Respiratory Distress Syndrome

ACUTE RESPIRATORY DISTRESS SYNDROME	
Timing	Within 1 week of a known clinical insult or new or worsening respiratory symptoms
Chest imaging[a]	Bilateral opacities—not fully explained by effusions lobar/lung collapse or nodules
Origin of edema	Respiratory failure not fully explained by cardiac failure or fluid overload
	Need objective assessment (e.g., echocardiography) to exclude hydrostatic edema if no risk factor present
Oxygenation[b]	200 mm Hg $< P_aO_2/F_IO_2 \leq 300$ mm Hg with PEEP or CPAP ≥ 5 cm H_2O[c]
Mild	100 mm Hg $< P_aO_2/F_IO_2 \leq 200$ mm Hg with PEEP ≥ 5 cm H_2O
Moderate	$P_aO_2/F_IO_2 \leq 100$ mm Hg with PEEP ≥ 5 cm H_2O
Severe	

[a]Chest radiograph or computed tomography scan.
[b]If altitude is higher than 1000 m, the correction factor should be calculated as follows: $P_aO_2/F_IO_2 \times$ barometric pressure/760.
[c]This may be delivered noninvasively in the mild acute respiratory distress syndrome group.
CPAP, continuous positive airway pressure; F_IO_2, fraction of inspired O_2; P_aO_2, arterial partial pressure of O_2; *PEEP,* positive end-expiratory pressure.
From ARDS Definition Task Force, Ranieri VM, Rubenfeld GD: Acute respiratory distress syndrome: the Berlin De finition, *JAMA* 307(3):2526–2533, 2012.

appears in nondependent areas (ventral area in the supine patient). Next, a ground-glass appearance is present in the middle area of lung along the vertical axis from sternum to spine. Finally, a consolidated area appears in the dependent region (dorsal in the supine patient). From the ventral to the dorsal area, there is a progressive increase in density (Fig. 13.11).[64]

There is also an increase in density on CT that is seen on a horizontal line in the supine patient from the head area (cephalad) to the base of the spine (caudad). The weight of the heart and the upward push from abdominal pressure may increase the amount of atelectasis in the dorsal area, near the spine, and caudad, near the diaphragm.

Normally, the capillary osmotic pressure tends to pull fluid out of the alveolus and interstitial space and into the microvasculature of the pulmonary circulation. This normal fluid movement is lost in ARDS, resulting in the development of pulmonary edema. The

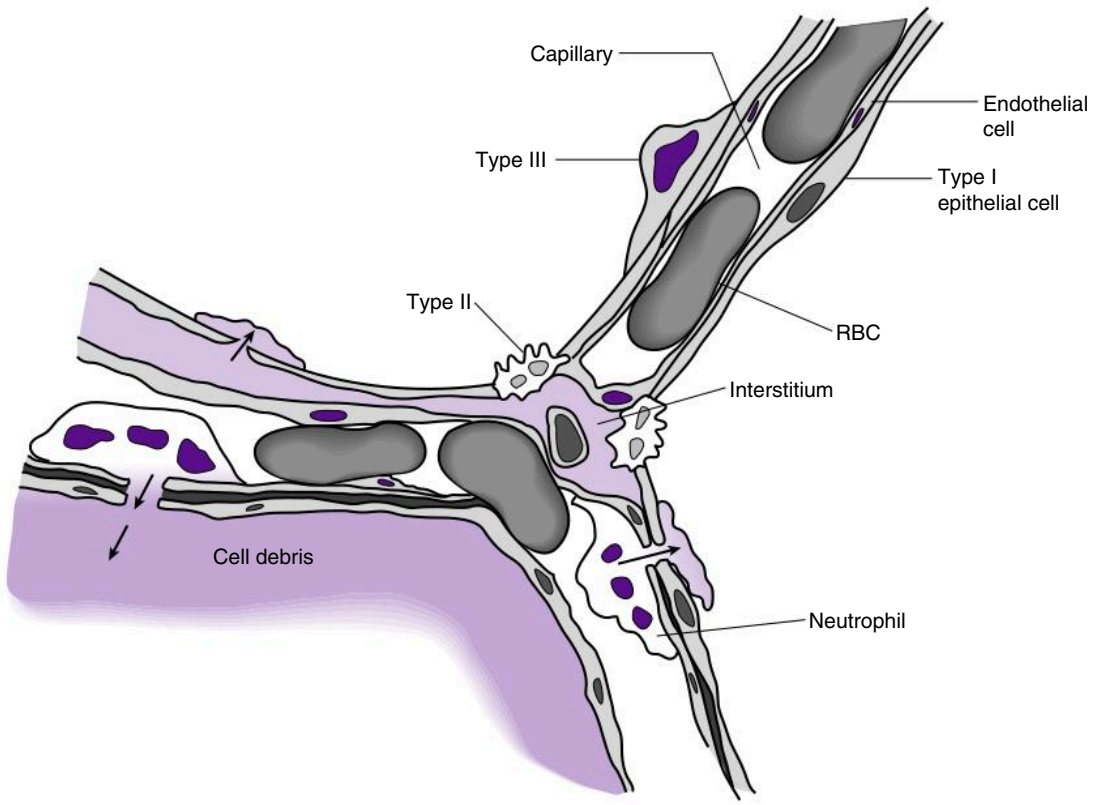


Fig. 13.10 A drawing of the histology of the lung under normal conditions *(top right section)* and during the acute phase of ARDS *(middle and bottom)* showing the following: red blood cell (RBC), white blood cell, type I pulmonary epithelial cell, pulmonary type II cell (responsible for surfactant production), pulmonary type III cell (macrophage), the capillary, and capillary endothelial cell. During ARDS, leaking occurs into the interstitial space and alveolus. (See text for additional information.)

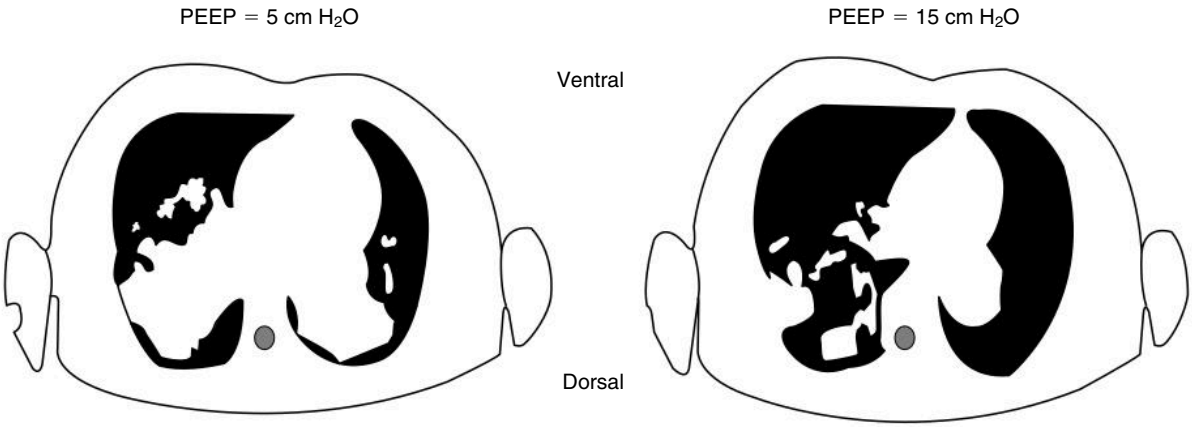


Fig. 13.11 Representative drawings of computed tomogram (CTs) of the thorax of a supine patient. The *left CT* was taken when the PEEP was set at 5 cm H_2O. The *dark areas* are aerated lung. These dark areas are in the nondependent portions of the chest near the anterior chest wall (sternum). The greatest densities *(white areas)* are in the dependent regions of the lung, toward the spine. As PEEP is increased to 15 cm H_2O, the amount of aeration increases. (Redrawn from Gattinoni L, Pesenti A, Bombino M, et al.: Relationships between lung computed tomographic density, gas exchange, and PEEP in acute respiratory failure, *Anesthesiology* 69:824—832, 1988.)

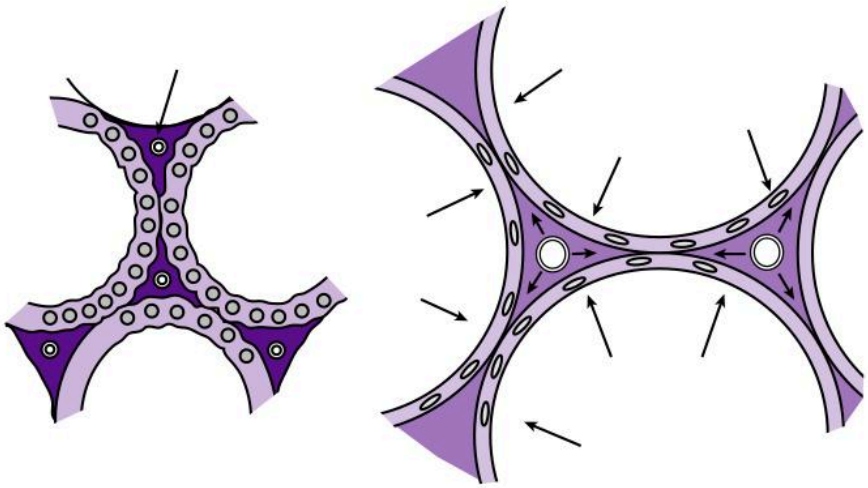


Fig. 13.12 A drawing showing the effect of low lung volume and high lung volume on the pulmonary microvasculature. Note that during low lung volumes *(left),* pulmonary capillaries are most open and corner vessels between the alveoli are most narrow. The reverse is true during high lung volumes. Pulmonary capillaries tend to be compressed, and corner vessels increase in diameter. This creates an area of lower pressure around the corner vessel. Edema fluid can build up in this area of the lung. (Courtesy John Marini, MD, Minneapolis, Minn. Redrawn for this text.)

amount of the edema present depends on the pressure gradient between the space inside the pulmonary microvasculature and the space around these vessels (perivascular space). Thus even when pulmonary blood pressures are normal, edema can still form. This is a result of expanded lung tissue during application of PEEP or high lung volumes pulling on the corner vessels and adjacent tissue, creating a negative pressure gradient from inside the corner vessel to outside the vessel (Fig. 13.12).

If fluid management is aggressively pursued in patients with ARDS, the pressure in the microvasculature of the lung can increase. The pulmonary capillaries may leak more. This is followed by increased production of biochemical mediators (procollagens and fibronectin).[66] Thus it is important to use conservative fluid management when possible. The goal of this approach is to reduce extravascular lung water and thus improve oxygenation and reduce morbidity and mortality in ARDS. It is important to mention that the effectiveness of this approach has not been proved.[37] Indeed, some practitioners prefer to use higher volumes of fluid to avoid hypoperfusion of the peripheral tissues and organs.

ARDS AS AN INFLAMMATORY PROCESS

The inflammatory process associated with ARDS involves a complex interaction among platelets, leukocytes, mononuclear

BOX 13.12 Possible Chemicals That Mediate the Inflammatory Response in ARDS[65]

- Reactive oxygen species
- Nitric oxide
- Leukotrienes
- Cytokines
- Proteases
- Platelet-activating factor (PAF)
- Cationic proteins
- Interleukins (IL-1, IL-6, IL-8, IL-10)
- Tumor necrosis factor-α (TNF-α)

BOX 13.13 Terminology of Computed Tomography

- *Ground glass opacification* is the appearance of a hazy increase in lung density, while the bronchial and vascular margins are preserved.
- *Consolidation* is a homogenous increase in lung density that obscures bronchovascular margins where an air-bronchogram may be present.
- *Reticular pattern* is the presence of many (innumerable) interlacing line shadows that may be fine, intermittent, or coarse.

cells, macrophages, and epithelial cells.[66] In diffuse lung injury present with ARDS, cytokines and other inflammatory and **thrombotic mediators** are released into the bloodstream from the lung. The interaction of these mediators with other body organs can lead to multiple organ failure, also called *multisystem organ failure* and *multiple organ dysfunction syndrome.* ARDS should therefore be viewed as a systemic syndrome and not just a pulmonary problem. Box 13.12 provides a partial list of inflammatory mediators that have been implicated in ARDS.

Two Categories of ARDS

Clinicians sometimes divide ARDS into two categories: *direct* and *indirect.* Direct ARDS is also referred to as *primary* or *pulmonary* ARDS and includes disorders of the lung that directly affect lung tissue, such as pneumonia, aspiration, and near-drowning. Indirect ARDS is referred to as *secondary* or *nonpulmonary* ARDS, because injury to the lung is not the result of a direct lung insult. Nonpulmonary ARDS is associated with an acute systemic inflammatory process, such as acute sepsis and acute pancreatitis.

In primary ARDS (direct), lungs are mostly consolidated. In secondary ARDS (indirect), alveolar collapse is predominant. Note that a lung RM is more likely to improve oxygenation and compliance of the lung in secondary ARDS (see section on Lung Recruitment later in this chapter).[67,68]

CT scans of the lungs of patients with direct ARDS differ considerably from those with indirect ARDS. Primary or direct ARDS tends to be asymmetrical with a mix of parenchymal opacification and ground-glass opacification (Box 13.13).[63,68] Extrapulmonary or secondary ARDS CTs have predominantly symmetrical and ground-glass opacification and dorsal consolidation (atelectasis). One problem when trying to be too diligent about classifying ARDS is that the two conditions could coexist. For example, one or more lobes might have had a direct insult, and both lungs may have indirect ARDS at the same time. Thus a CT cannot reliably be used to distinguish the two.

ARDS: A Heterogeneous Disorder—Normal Lung versus ARDS

Gattinoni and colleagues[65] published a study in 1988 examining the CT scans of a patient with ARDS. The results of their study showed that the injury in ARDS is disseminated (see Fig. 13.11). In fact, the distribution of fluid accumulation and lung collapse appeared to be influenced by gravity (i.e., the involved lung was in the dependent zones).

During the 1980s, it was not uncommon for clinicians to set V_T at 10 to 15 mL/kg for ventilated patients.[69] For patients with ARDS, these large volumes primarily entered the normally aerated tissue in the independent regions. Thus a relatively small area of the lungs received most of the volume, causing overdistention and injury to alveoli in independent lung regions. As a result, lung compliance appeared to be low. Gattinoni used the term *baby lung* to describe this phenomenon because it received a large share of the V_T.[64] It is important to note that this is one rationale for using pressure-controlled ventilation in patients with ARDS because it limits the amount of pressure and distention to all lung regions.

Gattinoni and his group[68,70] also found that PEEP could improve outcomes in ARDS. These researchers found that when they increased PEEP from 5 to 15 cm H_2O, more of the lung appeared aerated on the CT (see Fig. 13.11).[64,68,70]

Since that time, researchers have compared CTs of patients with normal lungs to patients with ARDS. The findings in normal lungs in supine patients show that there is a normal distribution of densities that occurs throughout the lungs. These densities are related to the thoracic shape, lung weight, and gravitational distribution of blood. The greater densities on CT occur in the dependent areas in supine patients and are associated with an increase in the pleural pressure from the sternum to spine. The increase in pleural pressure resulted in a decrease in the transpulmonary pressure (alveolar pressure minus pleural pressure), which is the distending force of the lungs. Thus lung units in dependent areas are less open than in nondependent areas (Key Point 13.5).

The changes noted in ARDS compared with normal lungs are not the thoracic shape or gravitational distribution of blood but rather the superimposed weight (pressure) of the lung. In ARDS the weight of the lung is double or triple that of the normal lung. This increased weight is probably caused by inflammation and edema. The increased mass in ARDS leads to "gas squeezing" out of the lung units in the dependent areas.[63] The ventral-dorsal compression can be caused by two factors: interstitial edema can

***Key Point* 13.5** Transpulmonary pressure is often defined in two ways: (1) alveolar pressure minus pleural pressure and (2) airway pressure minus pleural pressure. In general, when "airway pressure" is used in this situation, it is airway pressure measured during an inspiratory pause. Thus the airway pressure in this context is an estimate of plateau pressure or alveolar pressure.

lead to lung collapse and alveoli may be filled with edema. When the superimposed gravitation pressure exceeds the distending pressure, end-expiratory alveolar and small airway collapse increases.[70] Lung collapse can be associated with not only the weight of the lung but also loss of surfactant and very low $\dot{V}/\dot{Q}$ ratios, which may reach collapse pressures.

In the late stage of ARDS, the CT may show the resolution of the pathological process. In other patients, when ARDS is present for more than 1 week, the early exudative phase changes to an organized phase. Fluids are reabsorbed from the lung, and lung density decreases. As time progresses, pulmonary fibrosis causes an abnormal distortion of the interstitial and bronchovascular markings. Between 1 and 2 weeks, there is an increase in subpleural cysts or bullae. These bullae vary in size. The appearance of these bullae is believed to correlate with the length of mechanical ventilation. These bullae appear in all areas of the lung.[63] Some of these bullae may be caused by cavitation of lung abscesses and some may be caused by VILI (see Chapter 17 for a discussion of VILI).

In areas of the lung where small airways were narrow early in the disease, this narrowing may contribute to air trapping later in the disease, which may be a factor in later cyst formation that can occur during the healing process.[71,72]

PEEP AND THE VERTICAL GRADIENT IN ARDS

In ARDS, PEEP works by counteracting the superimposed lung pressures caused by the weight of the lung. PEEP must be greater than or equal to the gravitational pressure of the lung weight to keep the dependent regions of the lung open. In contrast, less PEEP is required to keep the lung open in the middle area of the lung, because the superimposed pressure is less and no PEEP is required in the nondependent lung region because there is no compression on this lung parenchyma.[63] Overdistention of nondependent areas may be a potential risk for PEEP.

As lungs are maintained in an open position, the dependent lung regions become more compliant. Previously collapsed regions stay open and may increase slightly in volume as they accept more gas. Regional changes in compliance may be one way in which PEEP benefits gas exchange and improves oxygenation.[63] The nondependent regions become less compliant during positive pressure ventilation, probably because of stretching lung units that are already open.

LUNG-PROTECTIVE STRATEGIES: SETTING TIDAL VOLUME AND PRESSURES IN ARDS

To avoid damage from excessive pressures and volumes in patients with ARDS, P_{plat} must be maintained at less than 30 cm H_2O. The lowest PEEP required to keep the lungs open at end exhalation and provide an acceptable P_aO_2 should be used.[73–77] The PIP (i.e., PEEP plus the inspiratory pressure used to deliver the inspired V_T) should not exceed the **upper inflection point** (UIP) and total lung capacity.[74]

The ARDS Network trial and other studies provide evidence in support of using V_T of 4 to 6 mL/kg and a P_{plat} less than 30 cm H_2O when providing ventilation in patients with ARDS. Significant differences in survival have been reported when these settings are used compared with using a V_T of 12 mL/kg.[34,62,69,79–82] Adequate levels of PEEP reduce the potential for injury that is associated with repeated reopening and collapsing of lung tissue, keeping the recruited lung open at end expiration.[31] However, many physicians choose not to use levels higher than 10 cm H_2O.[83] Recent studies have advocated using driving pressures (P_{plat} − PEEP) of 15 cm H_2O or less as part of the lung protective strategies.[84,85] These studies have suggested that although raising the level of PEEP during RM can improve lung recruitment, it can also raise the P_{plat} level, which in turn can exceed the accepted level of 30 mm Hg. Monitoring the driving pressure rather than reducing the tidal volume may be a viable method to reduce the incidences of VILI.[86]

Several basic points should be kept in mind when managing ventilated patients with ARDS using an open-lung or lung-protective strategy:

1. Use of low V_T in ARDS (4–6 mL/kg) has been shown to be effective. Clinical studies have confirmed that the use of high V_T can be harmful in ARDS.[69] Use of low V_T should be accompanied by the use of a PEEP level to avoid alveolar collapse.[34,74]
2. PEEP has a protective effect against lung damage, and it helps keep the lung open.[35,44,86] Maintaining a minimum end-expiratory volume with PEEP helps avoid the widespread alveolar edema, bronchial damage, and shear stress between alveoli that can occur when lung units are repeatedly opened and closed at low lung volumes[34,43,86,87–89] (Box 13.14).
3. As PEEP is increased, P_aO_2 increases. It should be remembered, however, that using P_aO_2 alone is not always a good indicator of an appropriate PEEP level.[37] P_aO_2 increases because of recruitment of lung tissue in alveoli open in a perfused area (i.e., shunt fraction is reduced). $\dot{V}_A$ increases and P_aCO_2 decreases. When $\bar{P}_{aw}$ increases, cardiac output usually decreases. In addition, blood can be shifted from one area of the lung to another if alveoli become overdistended. Thus ventilation can be directed to nonperfused areas.
4. PEEP should be applied early (during first 7–10 days after diagnosis of ARDS). The level of applied PEEP should be set 3 to 4 cm H_2O above the UIP of the deflation limb of the pressure-volume curve to help maintain an open lung.[74] This may require a PEEP of 15 cm H_2O or greater.[74,77,90,91] Establishing the **lower inflection point** should be done after lung recruitment with a slow derecruitment maneuver (Key Point 13.6).[92,93] This may require small, slow, stepwise decreases in pressure after a deep inflation (RM) (2.5 cm H_2O every 5–10 minutes) until the collapse point occurs. Both C_S and P_aO_2 will decrease when significant collapse occurs. During this maneuver, C_S is probably the single best indicator of recruitment and best indicator of closing point. Note that a rerecruitment maneuver (reinflation of the lung) is required after derecruitment (collapse of the lung).

BOX 13.14 Measures of Decreased Blood Oxygenation or Lung Injury

- Decreased P_aO_2 and S_pO_2
- Decreased P_aO_2/F_IO_2 ratio
- Increased $P_{(A-a)}O_2$
- Increased shunt/venous admixture

Key Point 13.6 "Moreover, because it now seems sensible to titrate PEEP 'from above downward' along the deflation limb of the PV curve to the lowest tolerated level, recruitment maneuvers are an inherent part of this empirical process."[92]

5. If it becomes difficult to maintain low pressures during volume-controlled ventilation, switch to pressure-controlled ventilation and monitor V_T delivery.[93,94] If it is necessary to improve P_aO_2, increase the $\bar{P}_{aw}$ by extending inspiratory time (T_I) during pressure ventilation.
6. There is the risk that areas of the lung that appear normal may become overinflated at end inspiration during tidal breathing as PEEP is increased.[93] Overdistention of alveolar tissues and terminal airways may be avoided by avoiding high transpulmonary pressures; keep P_{plat} below 30 cm H_2O to keep lung volumes lower than total lung capacity (TLC).[37,43,63,74,86] When P_aCO_2 increases with increased PEEP (same V_T), lung overdistention is present.
7. When ventilation cannot be maintained at a normal level without risking damage to lung tissue and/or auto-PEEP is present, consider allowing P_aCO_2 to rise (i.e., permissive hypercapnia; see Chapter 12). The need to maintain normal P_aCO_2 has never been demonstrated, especially when pH changes are gradual and oxygenation is maintained. Rapid changes in pH, on the other hand, can result in central nervous system dysfunction, increased cerebral perfusion and intracranial hypertension, muscle weakness, cardiovascular dysfunction, and intracellular acidosis.[45,87] When permissive hypercapnia is used, the patient usually requires sedation because it is uncomfortable.

It is important to recognize that low V_T settings without adequate PEEP can result in alveolar derecruitment[69,80] (Key Point 13.7).

Prone positioning is another technique used by some clinicians to improve oxygenation in patients with ARDS. More information about prone positioning can be found in later in this chapter.

LONG-TERM FOLLOW-UP ON ARDS

Some survivors of ARDS show distinct changes in CT of their lungs. These individuals typically demonstrate a reticular pattern in the nondependent areas of the lung. This is the area of the lung that actually possessed normal lung function during the disease process. The appearance of this fibrotic pattern is correlated with the length of mechanical ventilation and whether IRV was used. Furthermore, this reticular pattern (fibrosis) is generally not seen in the dependent areas, which are probably those areas of the lungs least exposed to high ventilating pressures and high F_IO_2.

Key Point 13.7 "The reason to use PEEP in patients with acute lung injury is as part of a lung-protective strategy, rather than simply as a way that we can increase the P_aO_2 and lower the F_IO_2."[36]

Both obstructive and restrictive patterns are seen in long-term follow-up studies of pulmonary function of ARDS patients. Whereas functional exercise is moderately limited in survivors, this limitation was not associated with pulmonary problems and may be a result of muscle weakness and wasting and abnormal neuromuscular function. The health-related quality of life in ARDS survivors is generally associated with muscle loss and weakness.

Many ARDS survivors have substantial neuropsychological dysfunction. This includes cognitive and affective impairment after hospital discharge that may persist for more than a year. Patients may suffer posttraumatic stress disorder with recollection of traumatic ICU events. Others may experience hallucinations, paranoia, depressed personality, and personality changes.[95] Additional studies are needed to further evaluate ARDS survivors and the best strategies to improve their ICU experience and long-term outcomes.

PRESSURE-VOLUME LOOPS AND RECRUITMENT MANEUVERS IN SETTING PEEP IN ARDS

In addition to protecting the lung in ARDS by restricting V_Ts and P_{plat} pressures, the clinician also must address the challenge of improving oxygenation. Current strategies for treating hypoxemia in ARDS are directed at recruiting as much lung as possible, which helps restore FRC and improve lung compliance. It also includes setting an appropriate level of PEEP.

In the previous discussion, traditional techniques for managing hypoxemia through increasing PEEP and F_IO_2 were reviewed. This section reviews several other approaches that have received attention during the past decade. These techniques include recruiting the lung by inflating it to or near TLC and then identifying the optimum level of PEEP, which will maintain the lung as open (recruited) as possible. Methods that will be described include slow or static pressure–volume (SPV) loops and lung recruitment using techniques alternative to the SPV loop.

Patient Evaluation for Lung Recruitment

Before performing an RM, it may be beneficial to obtain a chest CT to rule out the presence of bullae (blebs) or pneumothorax because these conditions are contraindications to recruitment. In addition, an RM is probably not beneficial for unilateral lung conditions, such as unilateral pneumonia. It is also important to perform RMs early in the course of treatment of patients with ARDS. As mentioned earlier, patients with primary ARDS (direct lung injury) are less likely to benefit from an RM than those with secondary or indirect ARDS. Because recruitment procedures require sustained positive pressure, use of sedation is appropriate.

The procedure requires at least two people at the bedside: one to perform the maneuver and monitor the ventilator, the other to monitor the patient and provide sedation. During the procedure, monitoring typically includes evaluation of S_pO_2, C_S, BP, heart rate, electrocardiogram (ECG), ventilating volumes and pressures, *f*, and the patient's overall appearance. There is no gold standard for evaluating recruitment. In other words, no single parameter provides the best way to monitor the success or failure of the procedure.

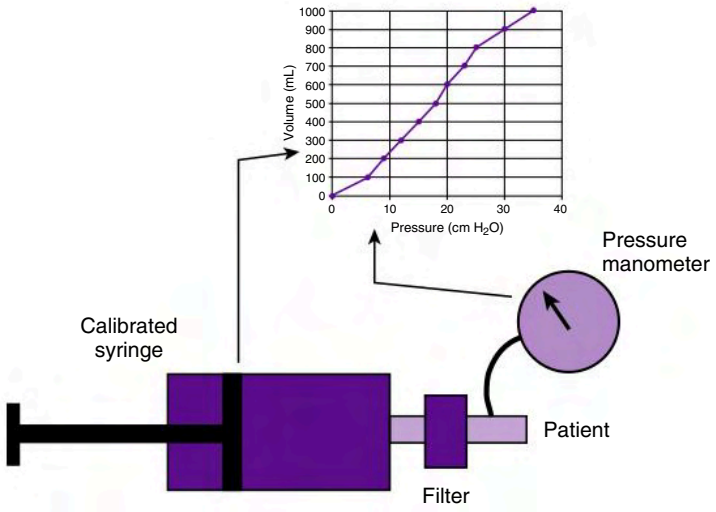


Fig. 13.13 Equipment used to measure a pressure-volume curve using a super syringe. (From Hess DR, Kacmarek RM: *Essentials of mechanical ventilation,* ed 2, New York, NY, 2002, McGraw-Hill.)

Pressure-Volume Loops in Setting PEEP

SPV curves have been used to select an optimal PEEP level and V_T in patients with ALI.[26,96-102] The SPV curve generally has a sigmoid shape. The factors believed to be responsible for the shape include all the individual alveolar pressure-volume curves, plus changes in alveolar duct and airway size, and the elastic forces in the pulmonary parenchyma and chest wall as the lung is inflated.[103] Each of these components has its own time constant that influences curve shape.[66,104]

The purpose of performing a slow pressure-volume loop or SPV loop is to first recruit the lungs and then identify the upper inflection point (UIP—also referred to as the **deflection point**) that correlates with the pressure at which major portions of the lung begin to collapse on expiration. Although there are several ways to accomplish an SPV loop measurement, the two most commonly used methods include the super-syringe technique (which is the true "static"-pressure loop) and the slow-flow technique (also known as the *quasistatic method*).

Super-Syringe Technique

The super-syringe method was originally used in the mid-1990s before ventilators were technically capable of performing an SPV loop. It is performed in the following manner. A calibrated super syringe (3 L) with a pressure-measuring device (pressure transducer) is placed in line with the patient connector[54,77,105] (Fig. 13.13). The ventilator pressure display can be used for this purpose. The ET cuff is completely inflated so that no leaks are present.[54,77,106] Note that this procedure cannot be performed accurately in the presence of a bronchopleural fistula. No spontaneous breathing can occur during the testing period. Thus the ventilator rate is set on zero (mode set at CPAP/spontaneous), and the patient is sedated and may require short-term paralysis.

Air is injected in volumes of either 50 or 100 mL into the patient's lungs. The resulting P_{plat} (3- to 10-second pause) is then measured after injection is completed.[107] The resulting pressure-volume values are graphed by hand on paper. Fig. 13.14 illustrates a static pressure-volume loop obtained using the super-syringe technique in which the values are continuously monitored.

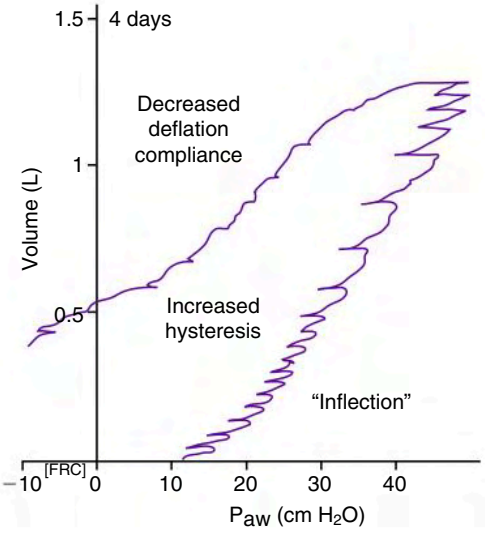


Fig. 13.14 A pressure-volume loop created using the super-syringe technique in a patient diagnosed with ARDS (4 days previously). The *scalloped border* of the curve illustrates real-time recording of pressure-volume changes as gas is injected into the patient's lungs. Note the reduced compliance. (From Matamis D, LeMaire F, Harf A, et al.: Total respiratory pressure-volume curves in the adult respiratory distress syndrome, *Chest* 86:58, 1984.)

Fig. 13.15 shows examples of pressure-volume curves of the respiratory system in a healthy person and in a patient with ARDS.[74,108-110] The syringe procedure takes about 1 to 1.5 minutes to perform, excluding setup time and calculations.

Although hypoxemia and hypotension can occur, the procedure is generally considered safe. S_pO_2 values less than 85% and BP less than 90 mm Hg are indications that the procedure is having adverse effects and should be discontinued.[74,107,109] Notice that the expiratory limb can also be constructed by performing the same procedure to deflate the lung.

The inspiratory portion is intended to recruit the lung and open as many areas of the lung as possible. The deflation curve

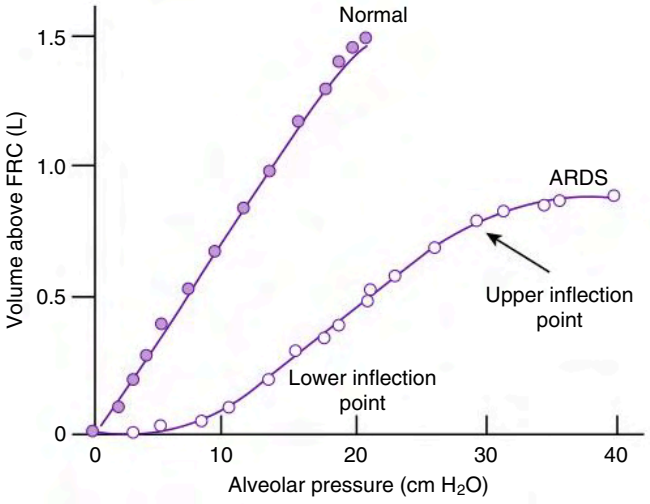


Fig. 13.15 Example of a static, inspiratory pressure-volume curve of the respiratory system in a patient with ARDS compared with a healthy subject. Upper (~30 cm H_2O) and lower inflection points (~10 cm H_2O) are present in the patient with ARDS. (From Hess DR, Kacmarek RM: *Essentials of mechanical ventilation,* ed 2, New York, NY, 2002, McGraw-Hill.)

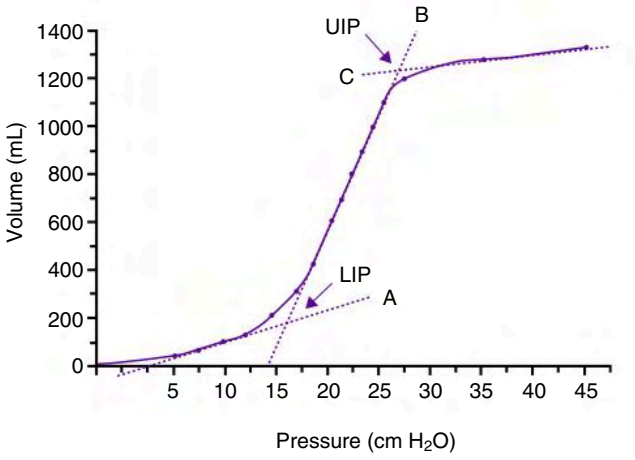


Fig. 13.16 A static pressure-volume curve in a patient with acute respiratory distress syndrome (ARDS). Volume is increased in increments of approximately 100 mL, inspiratory P_{plat} is measured, and a pressure-volume curve is plotted. *Straight lines* (*A, B,* and *C*) are drawn tangent to the curve, and the lower inflection point *(LIP)* and upper inflection point *(UIP)* are identified. The flatter the slope, the less compliant the lung. (From Kacmarek RM, Stoller JK, Heuer AJ, editors: *Egan's fundamentals of respiratory care,* ed 10, St. Louis, MO, 2013, Mosby.)

allows the clinician to determine the point at which the lung begins to collapse. This point would be identified as the point at which the curve takes the sharpest downward turn. After the **deflation point** is identified, the lung is reinflated to reopen collapsed areas and the PEEP is set about 2 cm H_2O above the identified deflation pressure point. This marks the optimum level for the patient.

Low-Flow (Quasi-Static) Technique

The low-flow or slow-flow technique (also called the *constant flow technique*) for static pressure-volume measurement uses a single breath delivered at 2 L/min until pressure reaches 45 cm H_2O.[105] It is also referred to as the *quasistatic* pressure-volume curve because flow is slow, but not interrupted for measurements, so periods of "no-flow" do not occur. As in the previous techniques, the patient must be sedated and paralyzed. The results of the slow-flow SPV technique are similar to those obtained with the manually performed syringe technique.[111,112] The low-flow inspiratory technique can be used with any ventilator that has a long inspiratory time, a slow constant flow setting, and a screen that will display a pressure-volume loop. Use of slightly higher flows (9 L/min vs. 3 L/min) causes a slight shift to the right of the resulting pressure-volume curve.[113]

Features of the SPV Loop

Several key features of an SPV curve include the following:

- *Lower inflection point on the inspiratory limb (LIPi), sometimes called P_{flex}.* The LIPi is that point on the curve where the slope of the line changes significantly (Fig. 13.16). It was originally thought that this point represented the opening of the majority of collapsed alveoli. Clinicians would then set PEEP levels at about 2 cm H_2O above this point. It is now understood that alveoli open continually along the entire slope of the curve.[63,98]
- *Upper inflection point on the inspiratory limb (UIPi).* The UIPi may not be identified if alveoli are still being recruited in some parts of the lungs.
- *The slope of the line between the LIPi and UIPi points.* This represents the respiratory system compliance as alveolar recruitment occurs throughout the inspiratory maneuver.
- *The upper plateau portion of the inspiratory loop representing potential recruitment and possible overdistention of the lungs.* Compliance decreased as areas of the lung are overinflated (overdistended) with pressure. Although pressure can still be increased past the UIP, volume increases little, if at all. It is advisable not to allow ventilating pressures (pressure from V_T delivery plus PEEP) to exceed the UIP during mechanical ventilation of patients.
- *The upper inflection point on the deflation portion of the curve (UIPd), also called deflection point or deflation point.* The rapid change in slope of the curve during deflation identifies the UIPd during deflation. Current theory suggests that it is more important to set PEEP 2 to 3 cm H_2O above the upper inflection point detected during deflation of the lungs (UIPd).[93,98]

ICU ventilators now have software programs that provide the clinician with an option to perform a slow pressure-volume loop. For example, the Hamilton G5 can perform a slow pressure-volume loop. The "PVtool Pro" uses a pressure ramping technique to construct a slow pressure-volume loop. The user selects a starting PEEP level, pressurization rise rate, upper pressure limit, and end-expiratory PEEP level. A pause equal to five time constants is automatically applied at the start of the maneuver to allow exhalation to FRC. On completion of the inspiratory and expiratory pressure-volume loop, about 20 seconds, the LIP and UIPd values are automatically displayed, with the option to manually identify inflection points. In addition, the point of the maximal hysteresis is numerically and graphically displayed, showing the ability of the lungs to be recruited. If significant inflection points or hysteresis are identified, a second maneuver with a pause maneuver can be programmed to perform an automated RM. The user sets the final maneuver PEEP level to that obtained from the

inflection points or point of maximal hysteresis to restore and maintain recruitment.

Regardless of the procedure used to establish an appropriate PEEP level, the ventilating pressures should not be allowed to exceed the UIP on the UIPi, because injury to lungs can occur if the lungs become overstretched. The appearance of the UIP on the graphic display may be influenced by the type of recruitment procedure used. For example, in one study when the V_T was set low (5–6 mL/kg), the UIP was 26 cm H_2O. However, when the V_T was set at 10 to 12 mL/kg, the UIP was about 22 cm H_2O. These findings suggest that the UIP probably depends on previous tidal alveolar recruitment.

Recruitment Maneuvers

An RM is a sustained increase in pressure in the lungs with the goal of opening as many collapsed lung units as possible.[67] It is performed in the management of patients with ARDS and may also be used in the postoperative treatment of atelectasis in post-anesthesia patients.[114] It is also suggested for use after suctioning maneuvers in some patients on ventilation.[57]

Recruitment occurs across the entire range of lung volume from residual volume to TLC. Once the lungs are recruited, they are kept open by maintaining an adequate PEEP above the LIP of an inspiratory maneuver or, preferably, above the UIP of a deflation (expiratory) maneuver (Key Points 13.8 and 13.9).[36,115] Lungs are protected from overdistention by keeping PIP lower than the inspiratory maneuver UIP (Box 13.15).[70,88]

***Key Point* 13.8** Choosing a PEEP level on the basis of the inspiratory portion of the limb is inappropriate. What stays open with PEEP is what has been opened by the preceding inspiratory pressures.[63]

***Key Point* 13.9** "If a collapsed lung is indeed a nidus (center) for further lung injury and inflammation, then a new paradigm in ARDS may be to open the lung with a recruitment maneuver and then keep it open by using PEEP set at a pressure above the level where substantial decruitment begins."[115]

BOX 13.15 PEEP and F_{IO_2} Levels With ARDS

The ARDSnet study mentioned earlier in this chapter used a table of PEEP-F_IO_2 combinations to guide the setting of PEEP and F_IO_2.[34] In that study, PEEP ranged from 5 to 24 cm H_2O. Some researchers felt that this table progressed too slowly in the application of PEEP. Their opinion was that PEEP should be increased to 15 cm H_2O early in the management of ARDS.

A subsequent study by the ARDSnet relied on a lung recruitment maneuver and a newer PEEP/F_IO_2 scale that was more aggressive in maintaining PEEP.[35] Either of the tables set by the ARDSnet group may be suitable as clinical guides for setting PEEP.

Illustration of a Recruitment Maneuver

Fig. 13.17 illustrates the concept behind an RM. An isolated animal lung is completely collapsed before inflation begins. Corresponding pressure is zero on the pressure-volume loop. Pressure is increased in increments of 4 cm H_2O. The corresponding pressure-volume point is plotted on the graph. It takes 8 to 12 cm H_2O (LIP on the inspiratory limb) before the lung visibly begins to open. The inspiratory LIP is probably at, or slightly above, 8 cm H_2O. At 16 cm H_2O the lung is well inflated. At 20 cm H_2O the lung appears fully inflated. On the pressure-volume loop at 20 cm H_2O the top of the curve begins to flatten out. This portion of the curve has a "beaklike" or "duck-bill" appearance. This decrease in compliance represents overdistention.

During the deflation (expiratory portion) portion of the loop, the pressure is reduced in increments of 4 cm H_2O and the corresponding points are plotted on the pressure-volume loop (see Fig. 13.17, photos below the pressure-volume loop). When one compares the photos of the lung during inspiration with those during expiration, it becomes apparent that as more lung tissue is recruited during inspiration, more remains open on exhalation.[116,117] Once the lung units are opened, lung inflation can be maintained with lower pressures.

Lung derecruitment begins at about 8 cm H_2O. Below 4 cm H_2O the lung completely collapses (see Fig. 13.17). Maintaining the PEEP at 11 to 12 cm H_2O (3–4 cm H_2O above the deflection point), after the lung is rerecruited, would seem like a reasonable level of PEEP that would maintain the lung in an inflated position. Although this situation represents a lung that is removed from the thorax, it provides a visual image of recruitment and derecruitment as they might occur.

During the deflation stage, at the point during which a significant number of lung units collapses, an accompanying drop occurs in P_aO_2 and in compliance. C_S is probably the best single indicator of the closing point, and it is considerably less expensive to obtain than an ABG at each step in the process.[118]

After identification of this point, the lung is again reinflated or rerecruited to its maximum capacity (TLC). The pressure is then reduced to a PEEP level 2 to 4 cm H_2O above the deflection point. The lung will remain open only after rerecruitment if an appropriate amount of PEEP is applied to prevent unstable alveoli from collapsing. The superimposed pressure of the lung (and heart) is a key determinant of lung collapse. As long as the applied PEEP is greater than any superimposed gravitational pressures from lung tissue and PEEP is not interrupted, the alveoli tend to stay open for a longer time.[31,63,119] When gravitational pressure from the lung and heart exceeds PEEP, end-expiratory collapse occurs.[71] Some researchers have suggested that an RM may need to be repeated more than once to gain maximum benefit[63,120] (Key Point 13.10). Others have emphasized the importance of recruiting the lung early to potentially reverse hypoxemia in early ARDS.[121]

Function of Lung Recruitment

Fig. 13.18 shows a series of CT scans that provide direct evidence that recruitment is "pan-inspiratory"; that is, it occurs throughout inspiration.[63] Note that previously it was thought that recruitment was essentially complete above the LIP.

The "sigmoid" shape of the curve suggests that different areas of the lung open at different pressures. Consequently, regional variations exist in opening pressures. The opening pressure for lung units can range from a few centimeters of water to inflation pressures as high as 55 to 60 cm H_2O.[71,115,117] This extreme range

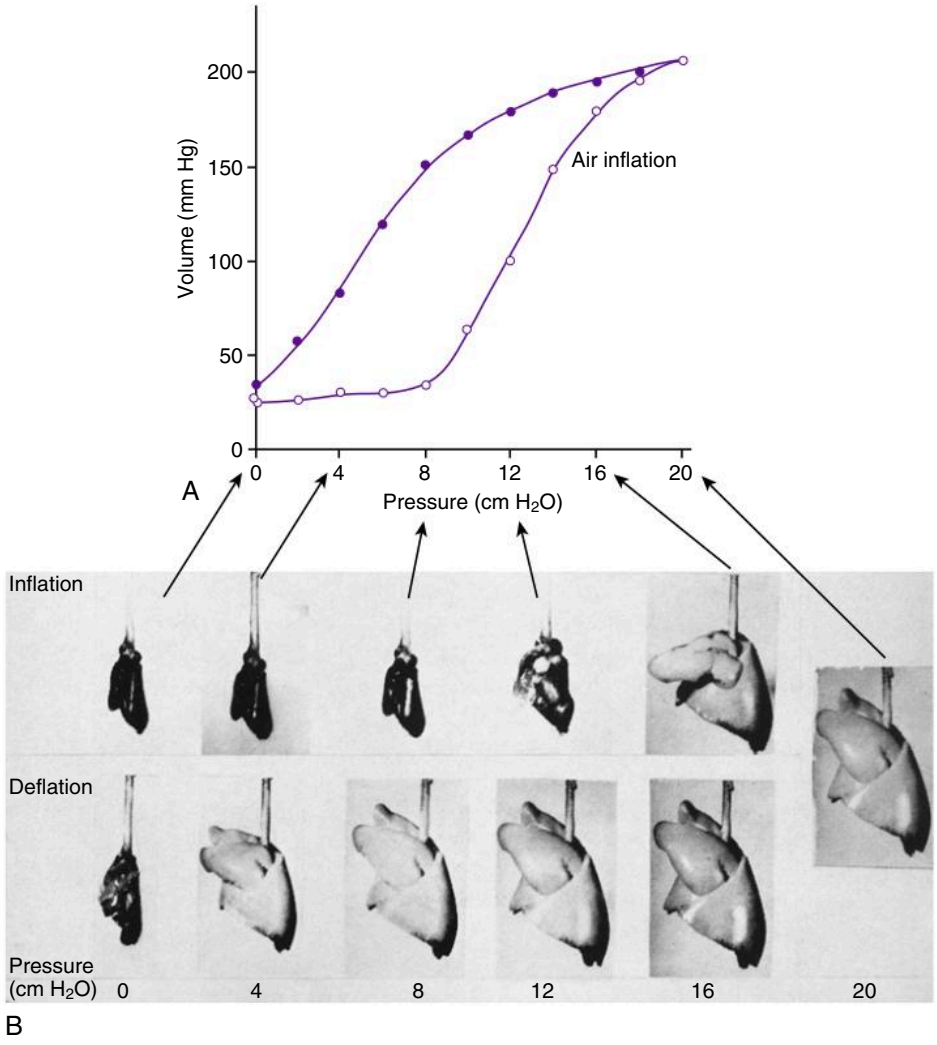


Fig. 13.17 (A) Illustration of a pressure-volume loop. (B) A series of photographs showing a suspended animal lung with progressively increasing pressures during inspiration and progressively different pressures during exhalation. Notice that once the lung is recruited at 20 cm H_2O, when expiration occurs, a high lung volume can be maintained for a similar pressure (expiration vs. inspiration). (See text for further explanation.) (A, Modified from Radford EP, Jr: Recent studies of mechanical properties of mammalian lungs. In Remington JW, editor: *Tissue elasticity,* Washington, DC, 1957, American Physiological Society. B, From Fenn WO, Rahn H: Respiration. Vol 1. In Fenn WO, Rahn H, editors: *Handbook of physiology: a critical, comprehensive presentation of physiological knowledge and concepts,* Washington, DC, 1964, American Physiological Society.)

***Key Point* 13.10** It is recommended that an RM is performed if PEEP is inadvertently withdrawn because of a circuit disconnect or leak after suctioning or in cases in which significant changes in P_aO_2 occur.

of inflation pressures is probably a result of differing types of atelectasis.

The opening pressure required for small airway collapse that is associated with compression atelectasis is in the range of 20 cm H_2O. This type of atelectasis might also be called *loose atelectasis.* One example of compression atelectasis is that which occurs in normal lungs during anesthesia.[63] In contrast, the opening pressure required to recruit alveoli collapsed as a result of "sticky atelectasis," such as might occur with ARDS, is much higher (range, 30–40 cm H_2O).[104,122] The true opening pressure for lung units is the transmural pressure—that is, the pressure applied to the airways and alveoli minus pleural pressure.

In addition to selecting an appropriate opening pressure, time is required for recruitment to occur. Indeed, reopening collapsed alveoli takes time, more for some alveoli than for others. In examining the different types of RM used, the reader will see that most RMs are performed with pressure sustained for 40 seconds or more.

Fig. 13.19 illustrates how the alveoli might open during an RM. Normal alveoli may become progressively inflated until they are overinflated. Those lung units in the dependent areas of the lung may eventually open and overcome the weight of the overlying lung tissue.

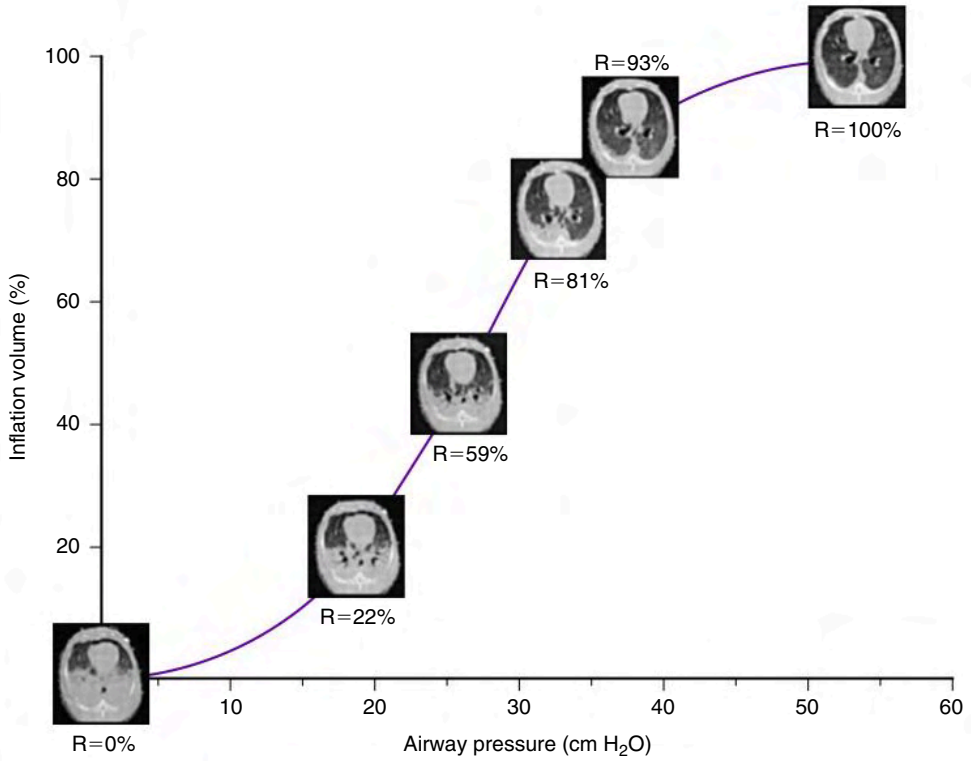


Fig. 13.18 An inspiratory pressure-volume curve in a lung model with acute respiratory distress syndrome (ARDS). CT images of the lung are shown at varying points along the curve. Note that increased aeration of the lungs occurs along the entire curve. (From Gattinoni L, Caironi P, Pelosi P, et al.: What has computed tomography taught us about the acute respiratory distress syndrome? *Am J Respir Crit Care Med* 164:1701—1711, 2001.)

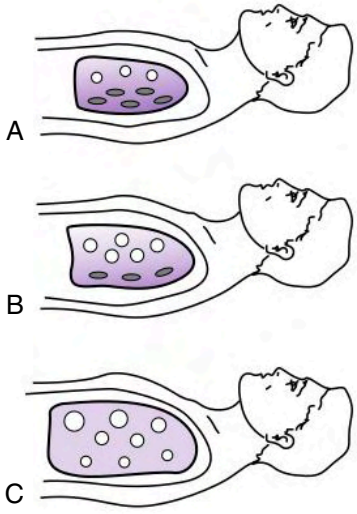


Fig. 13.19 Theoretical model of a recruitment maneuver (RM) in a supine patient opening lung units. In (A), only nondependent lung units are open. In (B), as RM is performed more lung units in the middle area begin to open. In (C), lung units in the dependent zones of the lung open and those in the nondependent zones begin to overexpand from overinflation (overdistention).

Hazards of Recruitment Maneuvers

Significant increases in thoracic pressure for an extended period (≥40 seconds) can cause a significant decrease in venous return to the thorax, a drop in cardiac output, and a drop in BP. Pressure can also affect the lung unevenly, with some areas receiving more pressure, thus causing a shifting of blood to other areas of the lung.

On the other hand, in patients who respond to an RM, a drop in BP and cardiac output during the maneuver may not occur. In fact, an RM performed with a patient who is hypotensive may actually improve hemodynamics. One explanation for this phenomenon is that as the alveolar PO_2 improves, pulmonary vessels may open, causing a reduction in pulmonary vascular resistance. This reduces the work of the right side of the heart and may improve cardiac performance.

Variability Among Patients

RMs can produce varying results among patients. In patients who respond to an RM, P_aO_2 increases, P_aCO_2 decreases, and the change in pressure (ΔP) required to cause an acceptable V_T decreases. In other words, if recruitment improves C_S, ventilation can be applied with an appropriate V_T at much lower pressures than before recruitment. In contrast, when the RM is not beneficial for the patient, increasing levels of PEEP do not significantly increase lung aeration and as a result there may be no improvement in P_aO_2, P_aCO_2, or C_S.

Effects of Chest Wall Compliance on Lung Recruitment

Changes in chest wall compliance will affect the pressures needed to open the lungs. Chest wall compliance includes forces from the overlying ribs and muscles, force from the diaphragm, and pressures from abdominal contents that affect the diaphragm. Low

chest wall compliance tends to act like a tight vest around the thorax, which increases pleural pressure. Low chest wall compliance (high chest wall elastance) can occur in obese patients, in patients with severe abdominal disease, in patients with abdominal distention (e.g., ascites), and from prone positioning.

In critically ill patients, it is not unusual for abdominal pressures to be higher than normal. Elevated abdominal pressure not only affects the position of the diaphragm but also puts pressure on the vena cava. This augments venous return to the thorax. Thus with increased abdominal pressure, there is a shift of blood into the thorax. If the lung is injured and leaking, this increases lung fluid.

As chest wall compliance decreases, more lung units collapse and thus affect the recruitment of collapsed alveoli. For example, in an obese patient with peritonitis, an airway pressure of 30 cm H_2O may not be adequate to recruit the lung. As a result, airway pressures might be higher than 40 to 45 cm H_2O to reach a sufficient transpulmonary pressure to open the lung.

To summarize, in ARDS a wide range of airway pressures may be needed to open various alveolar ducts and small airways and overcome the elastic forces in the lung parenchyma and chest wall.[103,115]

Potential Complications During Lung Recruitment

Hypotension has been reported, and brief episodes of hypoxemia can also occur. Most of the time, these changes are not sufficient to discontinue the process. However, if the hemodynamic status becomes significantly unstable with a severe drop in BP, the procedure should be discontinued.[115]

The occurrence of barotrauma, such as pneumothorax, subcutaneous emphysema, and pneumomediastinum, has not been reported as a significant finding compared with patients receiving standard mechanical ventilation.[38] These remain a potential concern, however, when performing an RM. Breath sounds should be evaluated during the procedure if vital signs and ventilatory parameters suggest that a pneumothorax may be present.[115]

Compliance is a good indication of how much of the lung is open in ARDS patients. Monitoring compliance can also help determine the amount of lung that is recruitable. Changes in compliance and P_aO_2 during recruitment and derecruitment are not linear.[29]

If the hemodynamic status of the patient does not change during the procedure, increases in P_aO_2 and S_pO_2 suggest that there is a decrease in intrapulmonary shunt after recruitment. An improvement in lung compliance is also likely to occur. An effective RM can also be verified with a chest CT, although this is not practical.

Types of Recruitment Maneuvers

In addition to SPV loops, several types of RMs have been used in the clinical setting. These include a sustained high pressure in the CPAP mode, pressure-controlled continuous mandatory ventilation (PC-CMV) with a single high PEEP level imposed, PC-CMV with progressive increases in PEEP level, and sigh maneuvers.

Sustained inflation. The technique of sustained inflation has received the most attention of the several techniques used. Sustained inflation is accomplished by providing a sustained high pressure. The ventilator is set to CPAP/spontaneous mode (mandatory rate = zero), and CPAP is increased to 30 to 40 cm H_2O for about 40 seconds.[56] PEEP levels as high as 50 cm H_2O have been suggested to recruit the lungs maximally to achieve the lowest possible shunt fraction. However, this approach is not as commonly accepted.[75]

PC-CMV with a high PEEP level. Another technique uses PC-CMV with a set pressure at about 20 cm H_2O above PEEP and a mandatory rate of about 10 to 12 breaths/min. PEEP is then increased so that PIP is at least 40 cm H_2O. The high pressure is sustained for 40 to 60 seconds and then decreased to a level appropriate to sustain inflation and prevent derecruitment. Ventilation is then continued in the PC-CMV mode.

PC-CMV with increased PEEP. Another RM uses PC-CMV but increases PEEP in increments of about 5 cm H_2O. Each increase is held for several minutes (2–5 minutes). For example, the pressure control level might be set to 20 cm H_2O, with the baseline PEEP at 15 cm H_2O, PIP = 35 cm H_2O, mandatory rate of 10 breaths/min, and I/E of 1:1 or 1:2. PEEP is then progressively increased while other parameters are held constant and compliance is monitored. PEEP is then progressively decreased until compliance decreases (derecruitment). The point of decreased compliance represents the UIPd of the lungs. The lung is once again reinflated to allow reopening of lung units. The PEEP is once again decreased until a pressure 2 to 4 cm H_2O above the UIPd is obtained.

Recruitment and decremental PEEP. An alternative technique for recruiting the lung and determining optimal PEEP is called a *decremental PEEP study*.[44] After a full inflation of the lungs, PEEP is progressively decreased in increments of about 5 cm H_2O (adult) until the compliance of the lungs decreases. This point represents the UIPd for the lungs. After this maneuver, the lungs are fully reinflated and then the PEEP is set to about 2 to 4 cm H_2O above the UIPd.[44,96]

Sigh techniques. As mentioned in Chapter 12, the use of sigh breaths was originally advocated in the 1960s to prevent atelectasis associated with low-volume, monotonous breathing patterns used during anesthesia. The use of sighs was eventually abandoned, probably because higher V_T settings became popular (V_T 10–15 mL/kg) and atelectasis was less likely. Another reason may have been that sigh breaths were set too infrequently and were not of sufficient pressure and length to be effective.[67]

With the use of lower V_T settings (4–6 mL/kg) in ARDS, there is a renewed interest in the sigh.[123] A few different sigh techniques have been suggested:

- Three consecutive breaths per minute at a P_{plat} of 45 cm H_2O[121]
- Twice V_T every 25 breaths, with optimal PEEP set[124]
- Holding V_T constant while increasing PEEP from a low level (~9.5 cm H_2O) to a high level of about 16 cm H_2O for two breaths every 30 seconds.[125] (NOTE: This technique is not as effective in sustaining improvements as continuous application of PEEP at a higher level [16 cm H_2O].)
- Increasing PEEP in a stepwise fashion to 30 cm H_2O while V_T is decreased, resulting in elevated airway pressures over several minutes. (Procedure: Each of the following settings is held for a 1-minute interval. The procedure is then repeated a second time.) (NOTE: This sigh technique was shown to modestly sustain improvement in P_aO_2 and respiratory system compliance.)[123]

- Increasing inspiratory pressure to 20 to 30 cm H_2O for 1 to 3 seconds at a rate of 2 to 3 sighs/min. This technique has been used in patients recovering from ARDS who are given pressure support. This type of sigh can be set using such ventilator parameters as the PCV+ mode on the Dräger Evita 4 and Bilevel mode on the Puritan Bennett 840 as examples.[67]
- Use of APRV or HFOV to recruit the lungs. (See Chapter 23 for additional information on APRV and HFOV.)

Derecruitment Maneuver

As mentioned, part of the RM is the deflation or derecruitment to establish the point at which lung collapse is likely to occur. Some clinicians do not perform a derecruitment and simply set PEEP at a high level such as 15 cm H_2O. This is a reasonable target for a minimum PEEP in ARDS.[77]

Derecruitment can be performed in small steps (2.5–5 cm H_2O), with each being held for 5 to 10 seconds to evaluate compliance and S_pO_2. P_aO_2 can be evaluated, but obtaining ABG samples is more expensive. C_S may be just as effective to determine the point at which significant lung collapse occurs.[126]

The following clinical scenario provides an example of a patient in whom an RM was successful in improving clinical parameters.[115]

Clinical Scenario: Case Report in Lung Recruitment

A 32-year-old woman with ARDS was treated with repeated recruitment maneuvers (RMs) in an effort to improve oxygenation. The RMs consisted of progressively higher PEEP levels (30, 35, 40 cm H_2O) sustained for 2 minutes at each level. At 40 cm H_2O PEEP, the PIP was 60 cm H_2O and P_{plat} was 55 cm H_2O. The ventilator settings during the maneuvers were PC-CMV at 20 cm H_2O above PEEP, rate of 10 breaths/min and T_I of 3 seconds. The lower inflection point in this patient was in the range of 16 to 18 cm H_2O. After the maneuvers, PEEP was maintained at 20 cm H_2O.

Although oxygenation and V_T delivery improved (increased C_S) after the maneuver, these parameters would progressively decline over the next 2 to 3 hours. Finally, a fourth RM was performed and the PEEP was set at 25 cm H_2O. V_T, oxygenation, and gas exchange remained stable after this maneuver.

Their conclusion was that setting PEEP based on the lower inflection point does not prevent derecruitment of the lung. It may be impossible in some patients to determine an ideal point of recruitment (LIP) or overdistention (UIP). Using the deflation (expiratory) limb of the pressure-volume curve may better identify optimal PEEP to prevent derecruitment of the lung.

SUMMARY OF RECRUITMENT MANEUVERS IN ARDS

To summarize the current human reports of the use of RMs, the following are noted:

- RMs may improve oxygenation, reduce shunt, and increase lung compliance by opening collapsed lung units.
- Lung recruitment is effective during the early treatment of ARDS and in patients without impaired chest wall mechanics.[127]
- RMs are more effective in patients with secondary (nonpulmonary) ARDS than in primary ARDS.[128]
- RMs may reduce atelectasis after general anesthesia.[56]
- This procedure is generally safe in studies reported to date.[129–132] However, hypotension and hypoxemia can occur during the procedure, and barotrauma is a potential risk.[132]
- Lung recruitment based on CT scan does not produce excessive hyperinflation of the lung.[123,129,131]
- It is important to set the PEEP at a level above UIP on the derecruitment curve to prevent alveolar collapse.[124,133]
- An RM without adequate PEEP can result in unstable alveoli and may ultimately lead to VILI.[119,125]
- RM with PEEP maintained above the deflation point may be more effective in improving respiratory lung mechanics and oxygenation when combined with prone positioning.[16,130]
- Given the uncertain benefits of improved oxygenation in ARDS and the lack of information about their effect on outcomes, the routine use of RMs cannot be either recommended or discouraged at this time.[134] A number of questions remain unanswered. Lung units that can be recruited may represent less than 10% of the densities seen on CT. Is it important to recruit this 10%? In addition, some units cannot be kept open at reasonable PEEP levels. For example, at 35 cm H_2O, some lung units are not open. These units probably cannot be recruited. What are the consequences associated with leaving these alveoli collapsed? Must atelectasis be reversed? Is prevention of lung units closing essential? In everyday clinical practice it is common to hear basilar crackles in obese patients. These crackles represent opening and closing of lung units. Is this opening and closing harmful or inconsequential?

Although lung recruitment holds promise in the management of ARDS, additional studies are needed to determine whether it really affects outcomes such as morbidity and mortality.[38] To date no significant difference in hospital mortality or barotrauma occurs compared with an established low V_T ventilator protocol, but oxygenation is improved and duration of mechanical ventilation is reduced.[135] Indeed, some clinicians choose not to use RMs as standard practice in the care of patients with ARDS. On the other hand, some find the use of recruitment an important part of patient management (Key Point 13.11). Fig. 13.20 illustrates one protocol that might be used in the management of ARDS.[126]

***Key Point* 13.11** "Recruitment maneuvers have become an entrenched part of my own practice, as an RM clarifies the extent to which benefit can be expected from higher levels of PEEP and defines the patient's sensitivity to alterations of the heart's loading conditions."[136]

IMPORTANCE OF BODY POSITION DURING POSITIVE PRESSURE VENTILATION

Hospitalized patients, especially those receiving mechanical ventilatory support, are often immobilized. The rationale for turning patients on ventilation frequently during the day is to help prevent pulmonary complications such as atelectasis and

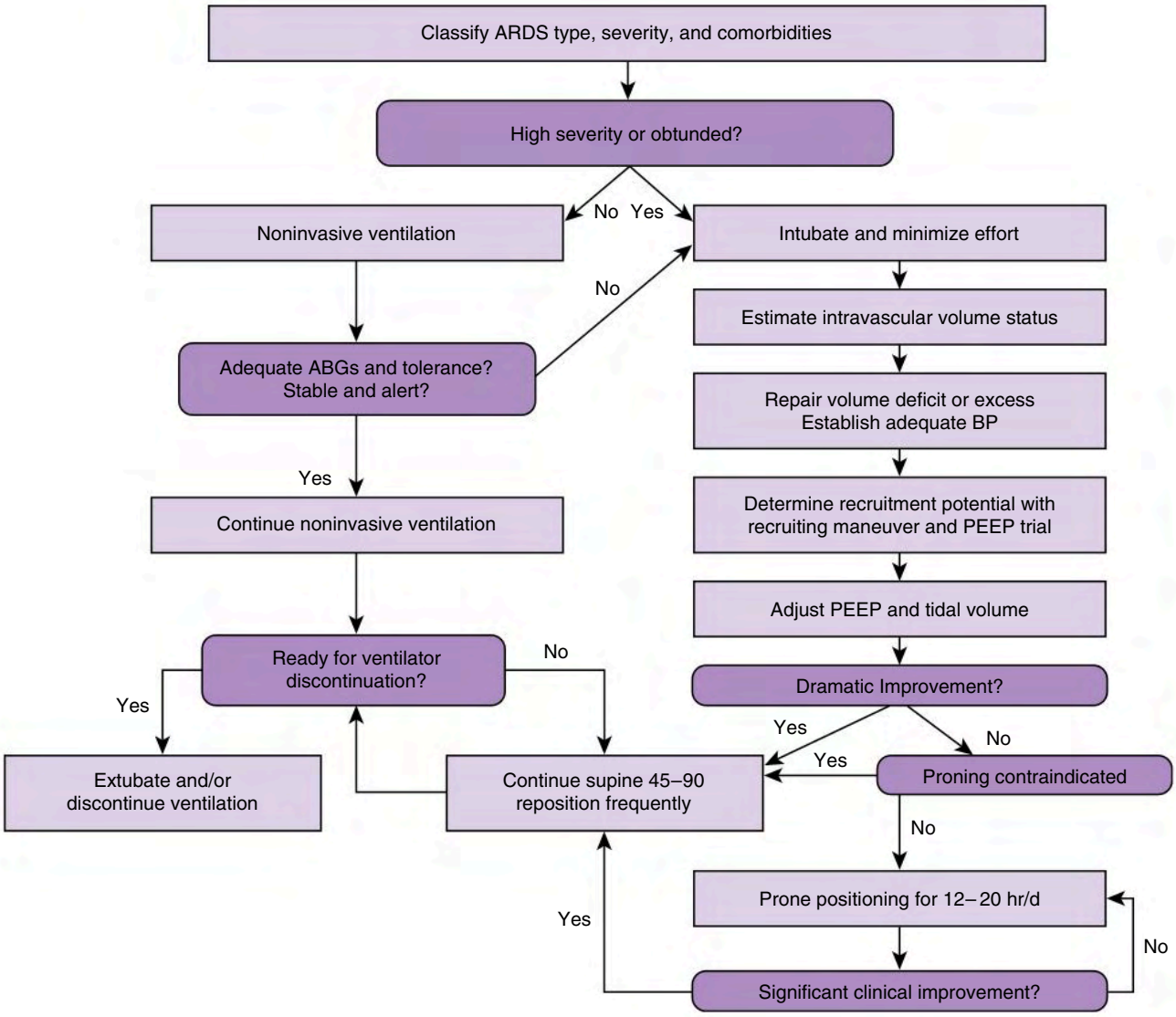


Fig. 13.20 An example of a protocol for the management of a patient with ARDS. (From Marini JJ, Gattinoni L: Ventilatory management of acute respiratory distress syndrome: a consensus of two, *Crit Care Med* 32:250—255, 2004.)

hypoxemia. Frequent rotation is important because it also reduces the risk for decubitus (skin breakdown).

Kinetic beds automatically turn the patient from side to side on a continuous rotation up to a 45- to 60-degree lateral position. These beds may help reduce the risk for pneumonias and may help mobilize secretions. They are often used in patients who are immobilized because of strokes, spinal injuries, or coma and in obese patients who are otherwise difficult to turn. Precautions are needed with kinetic beds because they can result in stretching and breaking of electrical cords and lines, disconnecting the patient from the ventilator, accidental extubation, and accidental aspiration of condensate from the ventilator circuit.[135]

Other complications associated with kinetic beds include the following:

- Patient agitation and intolerance of the bed
- Worsening of dyspnea and hypoxemia
- Cardiac arrhythmias
- Increased ICP
- Difficulty in examining the patient

Selecting an appropriate body position for a patient may also be beneficial for certain types of pulmonary disorders by ensuring optimum ventilation and perfusion. Positioning is a particularly important issue in two lung pathologic conditions: ARDS and unilateral lung disease.

Positioning in a Patient With ARDS: Prone Positioning

It is well established that body position can affect the distribution of ventilation. Normally during spontaneous breathing, ventilation is higher in dependent areas of the lungs because pleural pressure changes during breathing are greater in dependent areas compared with independent areas. This may not be true in diseases such as ALI and ARDS because edema and injury occur primarily in the dependent (dorsal) lung region of the supine patient.

Placing the patient with ARDS in a prone position may improve oxygenation (increases in P_aO_2 can range from

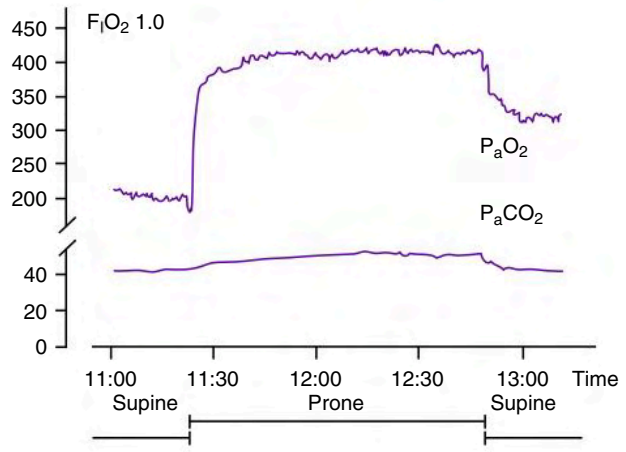


Fig. 13.21 Continuous P_aO_2 and P_aCO_2 values during supine and prone positioning (while on $F_IO_2 = 1.0$) in a patient with ARDS. (From Pappert D, Rossaint R, Slama K, et al.: Influence of positioning on ventilation-perfusion relationships in severe adult respiratory distress syndrome, *Chest* 106:1511, 1994.)

10–50 mm Hg or ≥20%) and decrease the degree of shunt present in the lungs (range in one study from 25%–12%)[136] (Fig. 13.21). These changes occur in about 75% of patients with ARDS.[136–142] It is important to state that not all patients respond equally well to prone positioning. An improvement of 10 mm Hg in P_aO_2 within 30 minutes of being in the prone position helps distinguish patients who are responders from nonresponders (i.e., those who do not improve).[143] For some patients, improvement allows the set F_IO_2 and PEEP levels to be reduced. Prone positioning in some patients also results in a decrease in P_aCO_2, suggesting that the V_D/V_T ratio (physiological dead space ratio) is improving.[144]

Potential Mechanisms of Improved Oxygenation in Prone Positioning

The precise mechanisms associated with improvement in $\dot{V}/\dot{Q}$ ratio with prone positioning are not well understood. Within lung tissue, the distribution of the interstitial water and intravascular blood and the anatomical configuration of the lung are all influenced by gravity. As an example, the lungs can be thought of as wet sponges hanging inside the thorax. In a supine patient, hydrostatic pressure is higher in the dependent regions where blood tends to flow. Lung edema formation is more likely in these regions as well. At the same time, the nondependent portions are receiving the greatest amount of ventilation with less perfusion. Note that an important difference between normal subjects and those with ARDS in this aspect is that patients with ARDS have an increased tissue mass compared with what is normal.

When any patient is changed from the supine to prone position, blood redistributes to the gravity-dependent areas, which are now located on the ventral (sternal) side (the "new" dependent region). Blood moves from areas that are not well ventilated in the supine position to areas that are better ventilated in the prone position, resulting in better $\dot{V}/\dot{Q}$ ratios.[139,140] It is thought that partially opened or closed lung units are moved into a position in which they can be distended or recruited (reopened) and better perfused, resulting in improved $\dot{V}/\dot{Q}$.[139] These factors result in an increase in expiratory lung volumes, oxygenation, and pulmonary compliance.[145–149]

Gravity also plays a significant part in gas distribution in supine patients. Areas of lung in nondependent regions overlie lung units in the dorsal (dependent) regions of the chest. In other words, the lung is actually pressing on itself. This pressure is exerted along a vertical gradient from the anterior chest wall to the spine, resulting in lower pulmonary distending pressure in the dorsal alveoli, which are located in the dependent areas of the supine patient's lungs.[145] This results in collapse of potentially recruitable alveoli in these areas.[146,147] In addition, the heart and great vessels also compress underlying lung tissue and bronchi. Also, abdominal contents press on the lower diaphragm, particularly in paralyzed patients, resulting in abdominal organs encroaching dorsally and into the thorax.[150–152] All these factors contribute to alveolar compression and collapse in the dorsal lung regions of the supine patient.

Prone positioning changes the position of the heart and great vessels so that these structures are no longer pressing on the lungs. Change in the regional movement of the diaphragm also occurs, which may assist in the reopening of collapsed alveoli and areas of atelectasis.

To summarize, the mechanisms thought to improve oxygenation with prone positioning are as follows:

- Blood is redistributed to areas that are better ventilated.
- Blood redistribution may also improve alveolar recruitment in previously closed areas of the lung.
- Redistribution of fluid and gas results in an improved relation between ventilation and perfusion.
- Prone positioning changes the position of the heart so that it no longer puts weight on underlying lung tissue.
- Pleural pressure is more uniformly distributed, which could improve alveolar recruitment.
- Prone positioning changes the regional diaphragm motion.

Technical Aspects of Prone Positioning

Before placing a patient in the prone position, potential complications must be weighed against the advantages.[153] Box 13.16 lists some of the contraindications to prone positioning.[154] Moving the patient from supine to prone position presents many technical challenges. Adequate sedation is essential. Some patients may even require a brief period of paralysis. The procedure is labor intensive, often requiring the assistance of a team of four individuals, which might include two nurses, a respiratory therapist, and a physician—one team member to turn the head and protect the ET, one to turn the trunk, one to turn the legs, and the fourth to control and move the venous and arterial lines and other catheters.[155]

BOX 13.16 Contraindications to Prone Positioning

Absolute Contraindication
- Spinal cord instability

Strong Relative Contraindications
- Hemodynamic abnormalities
- Cardiac rhythm disturbances

Relative Contraindications
- Thoracic and abdominal surgeries

BOX 13.17 Protocol for Prone Positioning

Preparation for prone positioning includes the following:
- Adequate sedation of the patient
- Clear assignment of responsibilities between team members
- Moving the patient to one side of the bed
- Checking all lines for length
- Checking the security of the endotracheal tube (ET)
- Endotracheal suctioning before turning
- Hyperoxygenation with 100% O_2
- Checking all vital signs

The procedure includes the following:
- Tilting the patient to the side
- Unhooking ECG leads
- Turning the patient prone
- Turning the patient's head toward the ventilator
- Reattaching ECG leads

Care after the prone positioning is accomplished includes the following:
- Checking all lines
- Checking ventilator pressure and volume
- Monitoring vital signs
- Repositioning and recalibrating pressure transducers

Pillow supports should be placed on each side of the patient's chest and forehead so that the ET and head are not compressed.

Modified from Kacmarek RM, Stoller JK, Heuer A, editors: *Egan's fundamentals of respiratory care,* ed 11, St. Louis, MO, 2017, Mosby.

Care must be taken to avoid accidental extubation or loss of vascular (intravenous) lines, urinary catheters, and other critical equipment. Box 13.17 outlines a protocol for prone positioning.[156] Once the patient is repositioned, a survey of the ET and all catheters is made to ensure that no displacement has occurred. Special attention should be paid to areas where the skin is in contact with tubes, intravascular lines, and Foley catheters. One of the side effects of prone positioning is facial and eyelid edema, which is resolved once the patient is returned to supine or sitting position.[142] The head requires frequent turning to avoid facial edema. Care must be taken so that the tape securing the ET does not cut into the corner of the mouth. Most of the body that touches the bed does not have a fat layer to cushion it (e.g., knees, forehead, elbows). Protective cushions are placed under the shoulders, hips, and ankles to help prevent pressure lesions and compression of the abdomen.[109,153-155] Proper arm position is important. The swimmer's position can be used to angle the arm, but a 90-degree angle should be avoided to prevent pressure on the brachial plexus.

Immediately after repositioning, the patient may experience transient hemodynamic instability and O_2 desaturation. This instability can be minimized by preoxygenating the patient with 100% O_2 and using sedatives.[111] Placing the patient in prone position puts pressure on the chest wall, reducing chest wall compliance.[149] This may actually improve the uniformity of V_T distribution.[138] Moving a patient to prone position is one procedure in which it is acceptable to use ventilation with P_{plat} higher than 30 cm H_2O because of the reduced anterior chest wall movement. (NOTE: A safe P_{plat} when providing ventilation to patients who are in the prone position has not been determined.)

There is no consensus about the length of time a patient can be placed in the prone position. Recommendations range from 2 to 24 hours, although it may require up to 12 hours of positioning daily to improve a patient's oxygenation status.[114] One case study reported a period of 72 hours of prone positioning.[155] It would seem that if prone positioning is to be of benefit, the position needs to be maintained for at least 20 hours/day, allowing return to the supine position for daily nursing care.[154]

The patient must be examined periodically for skin lesions. Patient feeding by the *transpyloric* enteral route may reduce the risk for vomiting and aspiration associated with gastric compression caused by the prone position.[155]

The effect of prone positioning has been shown to be an effective method to improve oxygenation in patients with ARDS.[156–159] It may also be indicated for patients who fail to respond to lung recruitment maneuvers (high levels of PEEP [>12 cm H_2O]) and high inspired O_2 (≥60%).[154]

Patient Position in Unilateral Lung Disease

Two methods are typically used to manage the ventilatory status of patients with unilateral lung disease. The first method involves **independent lung ventilation**, which requires two ventilators and a double-lumen ET. Each lung is ventilated separately. Although it is an effective method to treat unilateral lung disease, not all facilities are able to provide this technique.

Another method that has received a considerable amount of interest is to place the patient in a lateral position so that the "good" lung is in the down, or dependent, position (Fig. 13.22).[160–161] In cases in which it is difficult or impossible to place the patient in a lateral position, a kinetic bed may be used.

The pathological findings in unilateral lung disease include severe hypoxemia resulting from the persistence of pulmonary blood flow through the consolidated lung. The persistent blood flow through the consolidated lung units occurs because of failure of hypoxic vasoconstriction.

When one lung is affected by a pathological process (e.g., atelectasis, consolidation, or infiltrates), and the affected lung is in the dependent position (down), the P_aO_2 value is lower than when the normal lung is in the dependent position.[160–162] Normally, the dependent portion of the lung is better perfused. When the affected lung is dependent, the blood flow to it also increases. However, ventilation to this lung does not increase proportionally. The decreased ventilation to the dependent diseased lung could be a result of the disease process itself; that is, the alveoli may be filled with exudate. It may also be caused by an increased distribution of ventilation to the nondependent areas, particularly if the patient is on positive pressure ventilation. Lateral positioning dramatically improves gas exchange by improving $\dot{V}/\dot{Q}$ matching without causing any hemodynamic complications, thus potentially allowing a decrease in F_IO_2 (Case Study 13.5).[160]

Administration of PEEP in unilateral lung disease can cause an uneven distribution of PEEP to the normal lung when the patient is ventilated with a standard ET. Using PEEP in this case would cause increased shunting of pulmonary blood flow away from the healthy lung as a result of overinflation of the normal lung. If this is coupled with an increased blood flow to the diseased lung, $\dot{V}/\dot{Q}$ and altered gas exchange occur. For this reason, unilateral lung ventilation or proper positioning may be more effective than PEEP

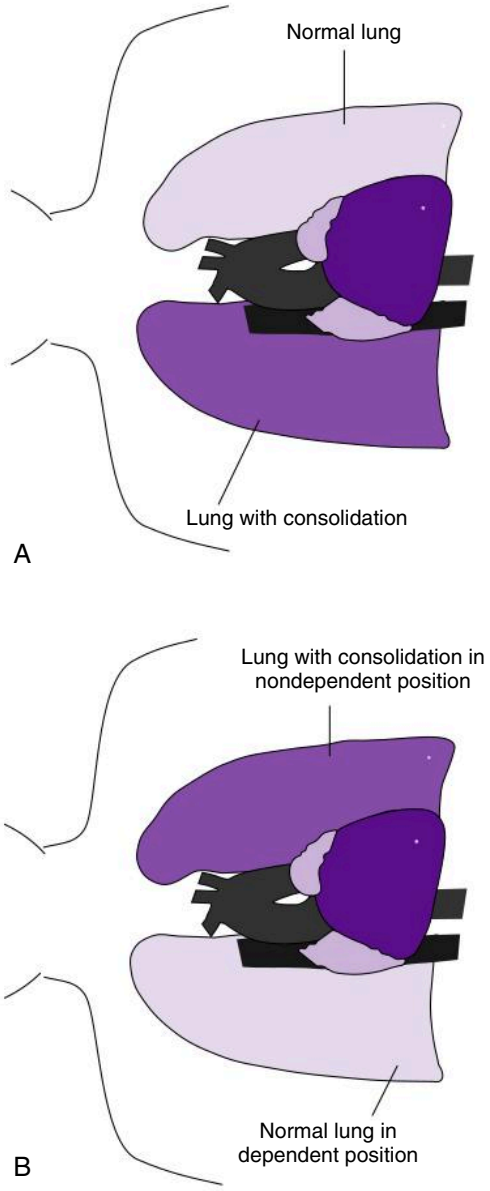


Fig. 13.22 (A) Normal lung in the nondependent position and lung with consolidation in the dependent ("down") position. (B) Normal lung in the dependent ("down") position and consolidated lung in the nondependent position. (See text for additional information.)

Case Study 13.5

Changing Patient Position

A patient with pneumonia involving the right lung is receiving mechanical ventilation. The nurse repositions the patient on the right side for a procedure, and the pulse oximetry low-oxygen alarm activates. What is the most likely cause of this problem?

to improve oxygenation compared with standard ventilation in unilateral lung disease.

ADDITIONAL PATIENT CASES

Clinical Scenario: Acute Respiratory Distress Syndrome

In Chapter 7, the case of a 60-year-old trauma victim was presented. He developed severe dyspnea and hypoxemia and required mechanical ventilation. He was later diagnosed with ARDS.

Ventilator settings were VC-IMV + PSV, V_T = 600 mL, f = 16 breaths/min, flow = 100 L/min using a descending ramp waveform, PEEP = + 5 cm H_2O, and F_IO_2 = 1.0.

The following information relates to the patient after being on ventilatory support with the previous settings for 30 min:

- *ABGs:* pH = 7.43, P_aCO_2 = 38 mm Hg, P_aO_2 = 189 mm Hg, HCO_3- = 22 mEq/L on F_IO_2 = 1.0
- *Pressures:* PIP = 24 cm H_2O, P_{plat} = 18 cm H_2O, PEEP = + 5 cm H_2O, PSV = 10 cm H_2O

A recruitment maneuver is performed. PEEP is set at 2 to 4 cm H_2O above the UIPd measured during derecruitment. The patient is placed on pressure-controlled continuous mandatory ventilation (PC-CMV) with the following settings: F_IO_2 = 0.8, set pressure = 15 cm H_2O, f = 12 breaths/min, PEEP = + 15 cm H_2O (PIP = 30 cm H_2O), I:E ratio = 1:2, measured V_T = 525 mL. ABGs on these settings are as follows: pH = 7.36, P_aCO_2 = 48 mm Hg, P_aO_2 = 224 mm Hg, HCO_3^- = 29 mEq/L. At this point the F_IO_2 is decreased to 0.5 to bring it into a safer range. The P_aO_2 will be kept at greater than 60 mm Hg. The acid-base status is acceptable.

The patient is successfully managed over the next 2 weeks, during which ventilator support is progressively reduced. He is eventually discontinued from ventilation and extubated.

Clinical Scenario: Congestive Heart Failure

A patient with CHF has been in the ICU receiving mechanical ventilatory support since admission 2 days ago. Current ventilator parameters and hemodynamic data include volume-control continuous mandatory ventilation (VC-CMV), V_T = 480 mL (7 mL/kg), f = 12 breaths/min, PIP = 23 cm H_2O, P_{plat} = 16 cm H_2O, PEEP = 0 cm H_2O. ABGs are pH = 7.37, P_aCO_2 = 37 mm Hg, P_aO_2 = 58 mm Hg, HCO_3^- = 23 mEq/L on F_IO_2 = 0.5, PAP = 45/21, PAOP = 26 mm Hg, and cardiac index (CI) = 2.9 L/min/m^2. Chest radiographs show increased vascular markings and fluffy infiltrates in a butterfly-like pattern near the hilar region of the lungs. Auscultation reveals bilateral moist crackles. Physical, radiographic, and hemodynamic findings indicate the presence of pulmonary edema. The diagnosis is cardiogenic pulmonary edema.

A PEEP study is performed and the following table presents it in an abbreviated form.

Time	PEEP (cm H_2O)	F_IO_2	P_aO_2 (mm Hg)	CI (L/min/m^2)	C_S (mL/cm H_2O)
11:00	5	0.5	65	3.1	24
11:30	10	0.5	78	3.3	31
12:00	15	0.5	123	3.9	35
12:30	20	0.5	153	3.5	30

These findings indicate an improvement in parameters up to a PEEP of +15 cm H_2O. At +20 cm H_2O, PEEP, CI, and compliance became worse, suggesting lung overdistention and decreased cardiac output. The use of PEEP in cardiogenic pulmonary edema can improve O_2 transport by increasing not only P_aO_2 but also cardiac output in some cases (see Chapter 16).

SUMMARY

- The most common parameters used to assess oxygenation status of patients are the F_IO_2, arterial blood gases (ABGs), CO-oximetry, and hemodynamic measurements.
- A linear relationship exists between P_aO_2 and F_IO_2 for any patient as long as the cardiopulmonary status remains fairly constant.
- Although the exact level of F_IO_2 that is safe for mechanically ventilated patients is not known at this time, it is generally agreed that maintaining a high F_IO_2 (>0.6) can result in O_2 toxicity.
- Mean airway pressure is a major determinant of oxygenation in patients with ARDS because it affects mean alveolar pressure ($M_{alv}P$) and alveolar recruitment.
- The treatment of acute atelectasis involves identifying the cause and then initiating an appropriate corrective action.
- The goals of PEEP/CPAP therapy are to enhance tissue oxygenation; maintain a P_aO_2 above 60 mm Hg and S_pO_2 ≥90%, at an acceptable pH; recruit alveoli and maintain them in an aerated state; and restore functional residual capacity.
- PEEP as it is commonly used implies that the patient is receiving ventilatory support and the baseline pressure is above zero; CPAP is pressure above the ambient pressure maintained during spontaneous ventilation.
- Two levels or ranges of PEEP can be employed: minimum or low PEEP, also called "physiological PEEP," and therapeutic PEEP.
- Therapeutic PEEP is used in the treatment of refractory hypoxemia caused by increased intrapulmonary shunting and ventilation-perfusion mismatching accompanied by a decreased FRC and pulmonary compliance.
- PEEP is beneficial for the treatment of patients with ARDS because it helps prevent the collapse of the small airways and alveoli and thus aids in recruiting closed lung units.
- C_S is considered a good indicator of the effects of PEEP on the lung.
- When PEEP greater than 15 cm H_2O is used, it is important to evaluate the patient's hemodynamic status closely, which may require the placement of a balloon-flotation pulmonary artery catheter.
- Static pressure-volume (SPV) loops have been used to select an optimal PEEP level and V_T in ALI. Current theory suggests that it is more important to set PEEP above the upper inflection point detected during deflation of the lung (UIPd).
- PEEP can be detrimental to a patient's cardiovascular status because it can reduce cardiac output and compromise circulation, leading to a reduction in BP. A relative contraindication for PEEP is hypovolemia.
- Classification of the severity of ARDS is based on the P_aO_2/F_IO_2 ratio. Mild ARDS is defined as a P_aO_2/F_IO_2 ratio of between 300 and 200 mm Hg, moderate ARDS is defined as between 200 and 100 mm Hg, and severe ARDS is defined as a ratio of 100 mm Hg or less.
- ARDS can be divided into two phases: an acute exudative phase characterized by inflammation and alveolar filling and a subacute phase, in which fibrosing alveolitis occurs.
- Clinicians sometimes divide ARDS into two categories: *direct* and *indirect*. *Direct* ARDS includes disorders of the lung that directly affect lung tissue; *indirect* ARDS is referred to as *secondary* or *nonpulmonary* ARDS, because injury to the lung is not the result of a direct lung insult.
- The ARDS Network trial and other studies provide strong evidence in support of using V_Ts of 6 mL/kg or lower and a P_{plat} less than 30 cm H_2O when providing ventilation for patients with ARDS.
- A recruitment maneuver (RM) is a sustained increase in pressure in the lungs with the goal of opening as many collapsed lung units as possible.
- Recruitment occurs across the entire range of lung volume from residual volume to TLC. Once the lungs are recruited, they are kept open by maintaining an adequate PEEP above the LIP of an inspiratory maneuver or, preferably, above the UIP of a deflation (expiratory) maneuver.
- Lung recruitment maneuvers are more likely to improve oxygenation and lung compliance in patients with secondary ARDS.
- Placing a patient with ARDS in a prone position may improve oxygenation and decrease the degree of shunt in the patient's lungs.

REVIEW QUESTIONS (*See Appendix A for answers.*)

1. A 25-year-old woman is recovering from severe pneumonia and has been receiving ventilatory support for 2 days. Current F_IO_2 is 0.6, and the patient's P_aO_2 on this setting is 200 mm Hg. What change in F_IO_2 would achieve a target P_aO_2 of 80 mm Hg?

A. 0.75
B. 0.25
C. 0.50
D. 0.40