The optimisation of PEEP with mechanical ventilation

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1. Positive end-expiratory pressure (PEEP)

1.1 Definition of PEEP

Positive end-expiratory pressure (PEEP) is the maintenance of pressure greater than atmospheric pressure within the alveoli at the end of expiration. [1–3] PEEP can be either extrinsic when applied by the ventilator, or intrinsic due to inadequate expiratory times, airway collapse or increased resistance.[4] Extrinsic PEEP has been utilised to improve oxygenation during mechanical ventilation since the first descriptions of acute respiratory distress syndrome in people in 1967.[1,2]

1.2 Benefits of PEEP

Applying extrinsic PEEP has been shown to improve arterial oxygenation, reduce tidal lung stress/strain, and prevent airway collapse.[1] Applying PEEP aims to restore functional residual capacity of lung by the recruitment of alveoli, prevention of alveolar collapse, decreasing shunt fraction and reducing ventilator-induced lung injury. Alveolar recruitment leads to higher end-expiratory lung volumes, which leads to reduced lung strain and improved compliance and a reduction in driving pressure (distending pressure above PEEP required to generate tidal volume). [3,5] Studies using PEEP levels greater than 5-12cm H_2O minimized the cyclical alveolar collapse and corresponding shearing injury to the lungs in patients with pulmonary oedema and alveolar collapse.[3,6]

1.3 Negative effects from PEEP

An increase in PEEP can also have negative cardiovascular and pulmonary consequences.[6] PEEP decreased cardiac output by increasing intrathoracic pressure and causing increased right atrial pressure and decreased venous return.[7] PEEP also increases pulmonary vascular resistance, which results in increased right ventricular afterload.[1]

2. Setting optimal PEEP

2.1 The optimal PEEP is the value associated with the best oxygen delivery and dead space reduction. It is patient-dependent and determined based on assessment of arterial oxygenation, haemodynamics and respiratory mechanics.[8]

There are many techniques for setting PEEP based on: PEEP/FiO2 tables (Tables 1 &2)[9,10], Pressure-Volume (PV) loop assessment[11,12], static compliance[13,14], driving pressure (DP) calculations,[15,16] stress index, [1,17] transpulmonary pressure measurements[16], diagnostic imaging (Computer tomography and ultrasound)18–21, and electrical impedance tomography.[22–24] A recent narrative review suggested PEEP/FIO_2 tables, PV loops and inflection points, compliance measurements and DP to be the most clinically significant.[3]

The ARDS Network published PEEP/FIO_2 tables to help guide patient management in with acute respiratory distress syndrome after documenting better survival with lower applied tidal volume and using Table 1, but improved oxygenation with use of Table 2. They aim to maintain a plateau pressure <30cm H_20 but adjusting PEEP based on the table until patient has an SpO_2 of 88-95% and/or PaO_2 55-80mmHG, by increasing PEEP prior to increasing FiO_2.[1] There has been no difference in mortality with lower or higher PEEP Tables.[9]

PV loops can be used for setting PEEP by either setting PEEP 2cmH_20 higher than the inspiratory limb lower inflection point or by setting PEEP to the value of the upper inflection point of the expiratory limb.[11,12] While this method is patient-dependent, it can be difficult to do if the PV loop is unreliable and may require neuromuscular blockade and breath holding for static assessment of the loop. [3]

PEEP can also be set based on the best static compliance (Cs), which is calculated by tidal volume divided by the plateau pressure minus the end-expiratory pressure. Following a recruitment manoeuvre, PEEP should be increased and the steadily decreased with ongoing calculation of Cs.[12] This strategy has the benefit of being patient dependent, however time-consuming and not noted to lead to an improvement in arterial oxygenation or oxygen delivery index when using Cs or Cs + 2 cmH_20.[25] This may stem from compliance calculations being global estimates and not accounting for the heterogenous lung that may have alveolar recruitment or overdistension.[26]

DP reflects the amount of pressure needed above PEEP to achieve ventilation.[3] It is calculated as the difference between inspiratory plateau pressure and PEEP, or the ratio of tidal volume to compliance.[16] By calculating the DP at different levels of PEEP with constant tidal volume it is possible to determine the optimal PEEP to allow for increased compliance and alveolar recruitment without hyperinflation.[1,3] Should aim for the lowest DP with the highest PEEP. DP is associated with lung stress and associated with higher mortality.[15,27]

Any of the above techniques may be used to set PEEP, but ultimately the optimal PEEP is patient dependent and requires regular reassessment.

3. Maintaining PEEP

3.1 Change in PEEP

When PEEP is increased, it can take over an hour for venous admixture and arterial oxygen saturation to equilibrate. However, when PEEP is lost or decreased, venous admixture and atrial oxygen reach equilibrium within 5 minutes.[27] Disconnection from the ventilator and the sudden loss of PEEP can lead to lung collapse and atelectasis that can take valuable time to recoup and may be detrimental to the patient. Therefore, it is important to minimise loss of PEEP as much as possible during ventilation.

3.2 Effect of suctioning and disconnection

Endotracheal aspiration often needs to be performed for ventilated patients to clear airway secretions. It can be performed with open endotracheal suction systems (OES) or closed-endotracheal suction systems (CES).[28,29] Conventional endotracheal suctioning requires disconnection of the patients from the ventilator to allow catheter insertion. This diminishes PEEP and oxygen supply and may lead to changes in cardiopulmonary function.[28] In contrast, CES does not require disconnection and hence allows maintenance of PEEP and oxygen supply during suction and improving blood oxygenation. At this stage, there is a paucity of studies comparing CES to OES in veterinary patients.

4. Closed suctioning vs open suctioning

4.1 Haemodynamic effects

Endotracheal aspiration can directly stimulate the trachea or indirectly lead to lung hyperinflation which can lead to autonomic changes in heart rate and blood pressure.[28] There has been no significant difference noted in critically ill adults between using open or closed suction, however both have resulted in an increase in mean heart rate.[29,30] Open suctioning has been associated with a significant increase in mean arterial pressure during the suctioning and a significantly higher incidence of arrhythmias in 14 adult people.

4.2 Lung volume

OES is associated with a significantly higher loss in lung volume compared to CES.[31] Reductions in lung volume were similar between quasi-closed and CES, but significantly higher with OES. Pre-oxygenation did not induce additive effects in lung volume changes. With and without pre-oxygenation, lung volume returned to baseline within 10 minutes. Suctioning with CES reduces the substantial losses in lung volume observed with OES. In patients without severe lung disease these changes were transient and rapidly reversible.[32]

Volume or pressure-controlled ventilation appears to affect lung volume after OES and CES. Tidal volume compliance and PaO2 were decreased for 30 minutes post suctioning in pressure controlled mechanical ventilation. PaCO2 and venous admixture were increased in the pressure control group. Suctioning appeared to only decrease compliance and plateau pressure in the volume-controlled patients, and this resolved within 30 minutes.[32]

4.3 Oxygenation

Suctioning, open or closed causes a reduction in intrapulmonary pressure which leads to a decrease in oxygen saturation and retention of carbon dioxide.[28] However, arterial oxygen saturation and systemic venous oxygen saturation decreased with open suctioning in critically ill adults. In contrast, arterial oxygen saturation and systemic venous oxygen saturation increased with the closed suction method.[29–31]

4.4 Compliance and resistance

In the short-term suction will reduce lung compliance.[28] Airway resistance and pulmonary resistance increases after closed suctioning techniques but returns to baseline values within 1 minute. Intrinsic PEEP progressively decreased until 10 minutes post suctioning and then remained reduced for 30 minutes. CES evokes a transient bronchoconstrictor response but does not reduce respiratory resistance below pre-suctioning values. The decrease in intrinsic PEEP suggests an increased expiratory flow.[33]

4.5 Lung recruitment

Recruitment manoeuvres are used to recruit collapsed alveoli and involve a temporary increase in the pressure or volume or time this is being given by the ventilator. There are different techniques for recruitment: inspiratory holds, increasing PEEP and end inspiratory pressure, increasing airway pressure, incremental PEEP increase or continuous positive airway pressure.[3] A lung recruitment manoeuvre immediately following OES was, as an adjunct to PEEP, effective in rapidly counteracting the deterioration in PaO2, and lung volume caused by OES.[34] So far there are no studies comparing recruitment manoeuvres for OES vs CES.

Table 1. ARDSnet Protocol for Lower PEEP Titration[10]

Lower PEEP/FiO$_2$ Table														
FiO$_2$	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 (cm H_2O)	5	5	8	8	10	10	10	12	14	14	14	16	18	18-24

Table 2. ARDSnet Protocol for Higher PEEP Titration

Higher PEEP/FiO$_2$ Table														
FiO$_2$	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	1.0
PEEP (cm H_2O)	5	8	10	12	14	14	16	16	18	20	22	22	22	24

Note: Stepwise changes are recommended, and the plateau pressure should remain less than 30 cm H2O.

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