Positive end-expiratory pressure during mechanical ventilation and respiratory support in newborns and children

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ABSTRACT

Positive end-expiratory pressure (PEEP) is used during non-invasive and invasive ventilation of newborns, infants and children. PEEP improves gas exchange by increasing the functional residual capacity, reducing respiratory effort, lowering requirements for respiratory mixture oxygen, and enabling a decrease in the peak inspiratory pressure (PIP) without decreasing the mean airway pressure. Its effects on the cardiovascular system appear to be insignificant, particularly in patients with severe respiratory failure that is not accompanied by circulatory insufficiency. The use of PEEP to provide the optimal conditions for improvement of gas exchange should be tailored individually for each patient under control of blood gas analysis, PIP and FiO\textsubscript{2}. This strategy minimises ventilator-induced lung injury and prevents the development of circulatory failure associated with ventilation. Nasal continuous positive airway pressure (NCPAP), used with various PEEP values, is a recognised treatment method of respiratory failure in newborns, especially in preterm infants.

Key words: mechanical ventilation, positive end-expiratory pressure, newborns, children

Mechanical lung ventilation is applied to treat respiratory failure and to provide proper gas exchange. Extreme caution should be exercised during its use in newborns and children to minimise lung injuries and to reduce ventilation-associated inflammatory reactions.

Positive end-expiratory pressure (PEEP), i.e., distending pressure, prevents excessive air escape from the lungs during expiration and is a part of conventional mechanical ventilation, nasal non-invasive ventilation and respiratory support using continuous positive airway pressure (CPAP). The CPAP method is used to prevent and treat atelectasis and obstructive apnoea. The method was introduced by G. Gregory as a form of “improved” expiratory groaning of newborns [1]. The method is widely applied in cases of respiratory distress syndrome (RDS). The CPAP value is practically comparable to PEEP and mean airway pressure (MAP) during spontaneous breathing supported with this technique. The pre-set PEEP value used during nasal continuous positive airway pressure (NCPAP) and non-invasive ventilation can be substantially different from the actual values in the respiratory system. The value changes depending on whether the patient inspires or expires and whether the respiratory system is tight or there is no air escape, e.g., through the open mouth. The PEEP fluctuations associated with changes in air flow during different respiratory phases can be minimised due to the variable flow CPAP system, e.g., the Infant Flow SiPAP (Carefusion, San Diego, USA). CPAP/PEEP fluctuations are minimised during the entire respiratory cycle because the air flowing from the child changes the direction of gas inflow in a specially designed head and the expiratory resistance is not increased.

Patients breathing completely spontaneously also generate positive end-expiratory pressure, called “auto-PEEP”. This pressure is elevated in patients with airway obstruction and leads to increased resistances during both inspiration and expiration. Patients with respiratory failure and audible expiratory groaning generate “auto-PEEP”. Gas that remains in the alveoli prevents their collapse during expiration, enables maintenance of FRC and reduces respiratory effort. However, this gas decreases the pressure gradient between the true glottis and pulmonary alveoli.

Proper gas exchange depends on the respiration rate, tidal volume and FRC, i.e., the air that stays in the lungs after
normal expiration. In ventilated patients, FRC is dependent on MAP, which in turn is associated with PIP, PEEP, time of inspiration and respiration rate. PEEP is the lowest value of positive airway pressure upon completion of expiration but before the subsequent mechanical inspiration.

The values of PEEP used during mechanical ventilation are usually precisely pre-set and measured using a ventilator. In some cases, auto-PEEP (unintended by the operator) may additionally superimpose onto PEEP values. This process is not always clearly visible. The modern ventilators show the real and set values of this parameter in the numerical or respiratory curve form. Positive end-expiratory pressure is essential for the treatment of patients with atelectasis. PEEP is involved in the “opening” of atelectatic lung areas and improving improper ventilation/perfusion ratio, thus improving gas exchange as primarily evidenced by increased oxygen pressure. This effect is better visible when the patient’s position is changed. The patient should be placed in the lateral recumbent position with the worse aerated lung directed upward. In this position, the lung is better ventilated, which reduces the affected areas [2].

The question arises as to whether a gradual increase in PEEP to improve oxygenation of arterial blood is a more beneficial solution than increases in PIP or TV and whether this management is safe and provides better protection against ventilator-induced lung injury, particularly in the youngest patients.

Positive end-expiratory pressure affects not only gas exchange but also the cardiovascular system. It has been demonstrated that PEEP increased > 10 cm H₂O (0.98 kPa) over a short period (30 minutes) resulted in the reduced value of cardiac index (CI), although circulatory failure had not been observed earlier [3]. The higher the MAP values, the bigger the CI decrease.

In children with severe respiratory failure without circulatory insufficiency, no correlations between PEEP in the range of 0–15 cm H₂O (0–1.47 kPa) and the mean cardiac index, pulse rate, arterial pressure, peripheral vascular resistance, or right ventricular afterload have been observed [4–7].

When high PEEP values are used, changes in cardiac index also depend on the circulating blood volume and vascular bed volume [8, 9]. In patients with hypovolaemia and low vascular resistance, e.g., in septic shock, rapid decreases in CI should be expected at high PEEP values, especially when PIP values are also high. In patients whose vascular bed was filled with massive fluid infusions, high ventilation parameters are often necessary due to the development of pneumothorax. Otherwise, in patients with unstable circulation, high PEEP values should be used with caution to avoid additionally aggravating circulatory insufficiency. PEEP of 15 cm H₂O (1.47 kPa) and more can cause excessive lung distension and adversely affect the elimination of carbon dioxide or even blood oxygenation [10].

There are only a few papers analysing the effects of PEEP values on haemodynamics in newborns. According to the available findings, cardiac output changes in pre-term infants with a birth body weight < 1500 g who are undergoing nasal CPAP of 4.4 ± 0.9 cm H₂O (0.43 ± 0.09 kPa) [11].

Positive end-expiratory pressure should be used in all newborns and infants who require mechanical lung ventilation. The values of PEEP are adjusted individually. To determine its optimal value during mechanical lung ventilation, PEEP should be gradually increased by 2 cm H₂O (0.2 kPa), starting with 5 cm H₂O (0.49 kPa). The choice of optimal PEEP values should be based on the change in PEEP required to provide proper blood oxygenation and changes in PaCO₂ or EtCO₂. The simplest way is to determine PEEP at the level of one-tenth of the patient’s oxygen requirements in percent (e.g., PEEP = 8 cm H₂O (0.78 kPa) at FIO₂ = 0.8).

In children undergoing general anaesthesia, particularly when high oxygen concentration in the respiratory mixture is necessary, the use of PEEP is essential, as it prevents decreases in FRC. Decreased values of FRC and formation of atelectatic areas are associated with the increased speed of oxygen resorption in the alveoli; thus, during ventilation with high oxygen concentrations, the pulmonary shunt gradually increases and may lead to the risk of desaturation. The atelectatic areas are well visible on thorax CT scans. During anaesthesia of patients at FIO₂ = 1.0, this phenomenon is prevented by using PEEP of 6 cm H₂O (0.59 kPa), as opposed to PEEP of 3 cm H₂O (0.29 kPa). PEEP = 5 cm H₂O (0.49 kPa) is sufficient at FIO₂ = 0.4 in the inspiratory mixture, whereas PEEP = 3 cm H₂O (0.29 kPa) at FIO₂ = 0.3 [12].

The optimal PEEP values can also be determined using the curve of pressure and volume, which is plotted by some ventilators. On the descending part of this curve, the pressure below which alveoli collapse is read. Minimal PEEP should not be below this point. However, this method is not useful in everyday clinical practice. The other methods to optimise PEEP values include forced oscillation and electrical impedance tomography. The former method involves the connection of a special speaker to the inspiratory part of a ventilator and measurements of oscillatory compliance at the generated sound of 5 Hz [13]. The impedance tomography method is performed using a non-invasive, portable, bedside device for monitoring and visualisation of ventilation and perfusion of various pulmonary parts [14, 15].

Saharan and co-workers [16] describe the strategy of lung ventilation in children with ARDS based on incremental increases in PEEP by 2–3 cm H₂O (0.2–0.29 kPa) from 5 cm H₂O (0.49 kPa) to 20 cm H₂O (1.96 kPa). The strategy aims at the provision of proper blood oxygenation and SpO₂ increase to 90–95% using FIO₂ < 0.6, TV ≤ 6 mL kg⁻¹ and PIP < 30 cm H₂O.
Moreover, CPAP improves the translocation of alveolar fluid referential centres [20]. However, the biggest advantage of nasal CPAP is that it reduces the surfactant requirement of respiratory failure after extubation and treatment of respiratory insufficiency during RDS, prevention of respiratory failure after extubation and treatment of apnoea of prematurity. CPAP reduces the surfactant requirements and frequency of transferring patients to higher referential centres [20]. However, the biggest advantage of its use is decreased incidence of severe BPD [21, 22]. Moreover, CPAP improves the translocation of alveolar fluid produced during the foetal life from the alveolar lumen to interalveolar spaces; therefore, nasal CPAP is also applied to treat transient tachypnoea in full-term newborns.

Studies comparing various methods of nasal CPAP (from the conventional ventilator, using the Infant Flow system or bubble CPAP) have not demonstrated the superiority of any of them. Some papers suggest that a particularly effective method of NCPAP in pre-term babies is bubble CPAP, in which the air movement during water bubbling of 15–30 Hz frequency superimposes onto the positive PEEP, as in the resonance box, thereby improving lung compliance and ventilation [22].

The use of NCPAP with PEEP = 5 cm H\(_2\)O (0.49 kPa) immediately after extubation in pre-term newborns reduces the frequency of possible future respiratory failure, re-intubation and BPD [22]. Two short tubes placed in the nasal passages are more effective than one nasopharyngeal tube [23].

The size of PEEP during CPAP remains an open issue. In the COIN study with pre-term newborns delivered in Australia between 25-28 gestational weeks who showed the features of respiratory insufficiency, nasal CPAP with PEEP of 8 cm H\(_2\)O (0.78 kPa) was used in the delivery room. The incidence of pneumothorax amongst these patients was significantly higher compared with the group treated with a ventilator, yet the total frequency of deaths and BPD, defined as the oxygen requirement on day 28, was found to be lower [24]. Therefore, it seems that PEEP values in pre-term newborns should not exceed 7 cm H\(_2\)O (0.07 kPa). In Great Britain, the recommended PEEP used immediately after delivery of pre-term babies with respiratory insufficiency is 4–9 cm H\(_2\)O (0.39–0.88 kPa), even if nasal ventilation is applied [22]. Another study demonstrated lower incidence of intubation, shortened time of mechanical ventilation and NCPAP, and reduced incidence of pneumothorax and BPD in pre-term newborns with NCPAP of 20 cm H\(_2\)O (1.96 kPa) applied through the nasopharyngeal tube immediately after delivery for 10 s when compared with the group subjected to AMBU ventilation [25].

The European guidelines regarding treatment of RDS and the guidelines of the European Resuscitation Council recommend the use of a PEEP valve for ventilation using an AMBU bag and Neopuff device during resuscitation in the delivery room. Optimal PEEP values range from 5 to 7 cm H\(_2\)O (0.49–0.69 kPa) [21, 22]. Moreover, ventilation of pre-term newborns with 100% oxygen, compared with air ventilation, reduced the cerebral flow by 20% and oxygen gradient between the pulmonary alveolus and the artery. Therefore, it is recommended to start the resuscitation of full-term babies with 21% oxygen and pre-term newborns with 30% oxygen.

An interesting variant of CPAP is a continuous flow of the mixture of oxygen and air at the maximum speed of...
2 L min⁻¹ (high-flow) via two short nasal cannulae, 3 mm in diameter, which generates the mean PEEP of 9.8 cm H₂O (0.96 kPa) [26]. However, the safety of this method has not been fully confirmed [26, 27].

In conclusion, PEEP is an intrinsic element of ventilation used during resuscitation, non-invasive respiratory support and non-invasive and invasive ventilation in children, including newborns and pre-term infants. The value of PEEP should not be lower than 5 cm H₂O (0.05 kPa). The optimal PEEP should be tailored individually for each patient considering the severity of lung pathology and circulatory efficiency [28]. To reduce the risk of complications, PEEP values ought to be continuously measured.

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