24 Continuous Positive Airway Pressure in the Hypoxemic Patient

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24.1 Introduction

Continuous positive airway pressure (CPAP) is a ventilatory technique by which the patient breathes spontaneously with a constant level of positive pressure during both inspiration and expiration. A tracing showing airway pressure, esophageal pressure, airflow, and tidal volume recorded in a patient breathing in CPAP mode is given in Fig. 24.1. Airway pressure (P_{aw}) is maintained almost constant throughout the breathing cycle. This is an important characteristic and, ideally, the P_{aw} gradient between inspiration and expiration should be identical to that observed during normal spontaneous breathing, the only difference being that breathing occurs above the atmospheric pressure at a level determined by the preset positive end-expiratory pressure (PEEP).

CPAP has been widely used to treat hypoxemic patients who are able to breathe spontaneously. The beneficial effects of CPAP in hypoxemic patients are presumably due to the increase in functional residual capacity induced by PEEP.

The effectiveness of CPAP in improving hypoxemia of patients suffering from cardiac edema was first described in 1935 [1, 2]; however, its widespread use began after 1971, when Gregory et al. [3] reported that this technique was of value in reversing the hypoxemia associated with idiopathic respiratory distress syndrome of the newborn. CPAP was used in intubated adult patients with acute respiratory failure by Civetta et al. [4] in 1972. Shortly thereafter, its use became generalized in both intubated patients and nonintubated patients ventilated via face masks. Despite a large number of physiological studies, only very few randomized controlled trials have allowed precise determination of the indications for CPAP.

24.2 Working Principles

There are two basic CPAP systems: those with continuous-flow circuits (which may be "homemade" systems), and those with demand valves (the vast majority

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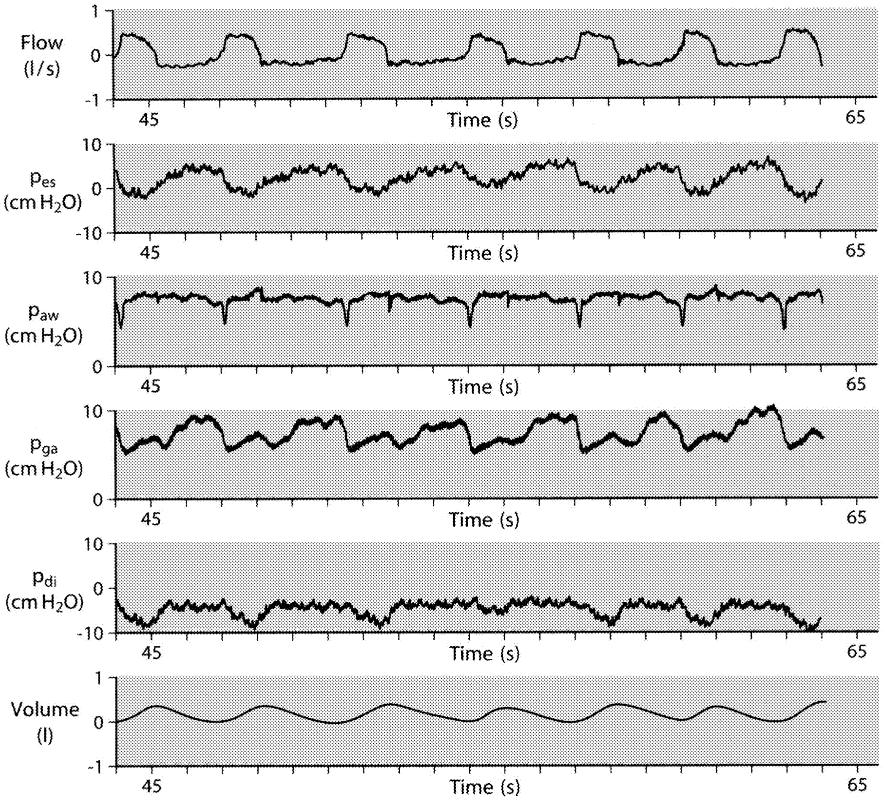

Fig. 24.1. From *top* to *bottom*: air flow (*flow*), esophageal pressure (P_{es}), airway pressure (P_{aw}), gastric pressure (P_{ga}), transdiaphragmatic pressure (P_{di}), and tidal volume (*volume*), obtained from a patient breathing in CPAP mode

of which are incorporated in intensive care mechanical ventilators). The two systems have different characteristics.

24.2.1 Continuous-Flow Circuits

Basically, continuous-flow circuits are built with an air-oxygen blender and a flowmeter, enabling delivery of an FiO_2 between 0.21 and 1 and a gas flow high enough to meet the patient's inspiratory demands. Inspired gases are heated and humidified adequately, usually by means of a cascade-type system. These systems should contain a manometer to control P_{aw}, positioned as close as possible to the patient's airway opening.

Various mechanisms are used to generate PEEP: underwater seal, threshold resistors, orificial resistances, etc. A common feature of these mechanisms is that many of them tend to increase PEEP when expiratory flow increases [5]. As valve resistance to air flow increases, higher fluctuations in P_{aw} are observed and the work of breathing is greater [6]. The ideal mechanism would be a pure nonresistive threshold valve, i.e., a determined threshold pressure that is maintained constant despite changes in expiratory airflow.

In a study in 1985, Marini and colleagues [5] showed that spring-loaded PEEP valves produce excessively high expiratory resistances in comparison with systems using a water column or an inflatable diaphragm. In the lung model study, most valves (spring-loaded or magnetic PEEP valves) used in a continuous-flow CPAP system were shown not only to impose high levels of inspiratory work, but also to induce active expiratory work. The high flow resistance of these valves probably explains the induction of a substantial amount of extra work despite the fact that the flow in the CPAP circuit consistently exceeded the flow demands of the model [7]. Some continuous-flow CPAP systems are built with spring-loaded PEEP valves and may induce an excessive effort in patients with acute respiratory failure and high minute ventilation. Moreover, the increase in expiratory resistance may also lead to an increase in the sensation of dyspnea. Because continuous-flow systems do not use valves, the inspired gas enters the patient's lungs directly, and any excess gas delivered to the lung is vented on the expiratory side.

24.2.2 Demand-Valve Systems

Demand-valve CPAP systems are usually built into artificial ventilators. Demand valves are mechanical devices that open when an inspiratory effort is detected. These valves may detect changes in airway pressure, or flow, or both. When a certain threshold level is reached (valve sensitivity), the gas is delivered to the patient's lungs.

The effort required of patients in order to reach a given level of valve sensitivity is variable and depends on the particular characteristics of each valve. In bench studies at least, the performance of pressure-triggered and flow-triggered systems has nowadays become quite similar [8, 9].

When demand-valve and continuous-flow systems are compared the former often exhibits a higher resistance to airflow as PEEP increases, a higher fluctuation between inspiratory and expiratory airway pressures, and also a greater time lag between inspiratory effort and the beginning of inspiratory flow [10].

24.2.3 Continuous-Flow Systems Incorporated in Ventilators

Many modern ventilators incorporate modified continuous-flow mechanisms. These mechanisms significantly reduce the inspiratory effort required to trigger a breath compared with conventional demand valves.

With the aim of improving the demand-valve mechanisms of artificial ventilators, a modified continuous-flow system, called "flow-by", was initially incorporated in the Puritan-Bennett 7200a ventilator [11] and later in other modern microprocessed ventilators. The "flow-by" mechanism consists in a constant and continuous basic flow of gas circulating within the inspiratory and expiratory circuit, with continuous measurement of flow on both the inspiratory and expiratory sides. When the patient is expiring, the total flow measured in the exhalation port becomes higher than the base flow. When inspiration begins, the flow measured in the exhalation port is lower than the base flow. When the difference between the base flow and the measured exhaled flow reaches a certain threshold level, called flow sensitivity, the inspiratory valve opens and delivers a predetermined gas flow to the circuit, in order to maintain the preset airway pressure.

24.3 Effects of the Different Systems on the Work of Breathing

24.3.1 Demand-Valve Versus Continuous-Flow CPAP

In intubated patients recovering from severe acute respiratory failure or from major surgical procedures, demand-valve CPAP systems have been shown to induce a higher work of breathing (WOB) than continuous-flow CPAP systems. This was considered to be related to the high circuit resistances in the former [12].

In a study of a group of intubated patients undergoing weaning from mechanical ventilation, Beydon et al. [13] reported that WOB was significantly lower when the patient was breathing through a continuous flow system than with the demand valves of several ventilators.

The main advantages of conventional demand valves over continuous-flow systems are the considerable gas savings, the possibility of using all the alarm and ventilatory parameter-monitoring capabilities offered by mechanical ventilators, and the availability of back-up ventilation if episodes of apnea ensue.

24.3.2 Effects of "Flow-by"

In COPD patients undergoing weaning from mechanical ventilation, Sassoon et al. [14] evaluated the effects of different CPAP systems on WOB. They found that during CPAP at 0 cmH_2O, there was a significant decrease in WOB (expressed as J/l of ventilation) when comparing CPAP demand-flow with CPAP "flow-by", but when WOB was expressed as J/min they did not detect any differences between the two CPAP systems. During CPAP 8 cm H_2O, WOB, expressed in either J/l or J/min, did not differ significantly between the two CPAP systems. In this study, the WOB during CPAP demand-flow decreased only when a pressure support level of 5 cmH_2O was added. Other authors, however, have reported that during weaning from mechanical ventilation using either CPAP, synchronized intermittent mandatory ventilation, or pressure-support ventilation, the "flow-by" mechanism significantly reduces the WOB and inspiratory effort of these patients, compared with the pressure-triggered demand-valve mechanism [15–19]. The difference, however, is of small magnitude [19]. Aslanian et al. showed, for instance, that no difference was found between the two types of triggering mechanism using assist-control ventilation [19]. The authors presumed this was due to an insufficient peak-flow setting during assist-control, counterbalancing any small difference in the effort to trigger the breath.

24.4 Indications for CPAP

24.4.1 Hypoxemic Respiratory Failure

Pathophysiological Findings

The improvement in oxygenation induced by CPAP presumably results from an increase in functional residual capacity and a decrease in intrapulmonary shunt induced by PEEP. In addition, compared with spontaneous nonassisted breathing, PEEP may improve lung compliance by recruiting alveoli, which decreases the elastic workload that the respiratory muscles must overcome. These effects have been demonstrated by Katz and Marks [20] in intubated patients recovering from acute respiratory failure. These authors found that CPAP increased lung compliance, decreased WOB, and also decreased the alveolar-to-arterial oxygen pressure difference compared with T-piece breathing. In addition, the lung volume increase induced by PEEP may reduce airway resistance, leading to a decrease in resistive WOB. A study by Sassoon et al. [21] of ten patients being weaned from mechanical ventilation showed that lung resistance was decreased during CPAP 5 cmH_2O, compared with T-piece breathing.

In patients with left heart failure, several important pathophysiological abnormalities concern lung function. These patients usually present with orthopnea, which is thought to reflect perivascular, peribronchiolar, and interstitial edema, which compress airways and also may stimulate lung receptors, thus provoking reflex bronchoconstriction (this is the notion of "cardiac asthma"). Interestingly, a recent investigation by Yap et al. indicates that patients with left heart failure have small lung volumes when seated (reduced TLC and similar FRC compared with control subjects) [22]. When subjects lie in the supine posture, those who have heart failure do not exhibit changes in FRC, whereas normals do so. Nevertheless, in supine, patients who have heart failure exhibit significant reductions in vital capacity, whereas this parameter is unchanged in controls. Additionally, the change in posture from seated to supine is associated with major increases in respiratory air flow resistance (Rrs) in patients with left heart failure, whereas normal controls do not exhibit any change in Rrs. The increase in Rrs was not reverted by inhaled ipratropium bromide.

Bradley and colleagues documented the hemodynamic changes that take place in patients with congestive heart failure when they are breathing with CPAP [23]. With CPAP [5], they observed significant increases in cardiac index and stroke volume only in those patients who had elevated pulmonary capillary wedge pressures (PCWP), whereas in patients with low PCWP the cardiac index significantly decreased.

Lenique et al. also studied the effects of CPAP in patients with an acute exacerbation of chronic left heart failure [24]. When comparing spontaneous unassisted breathing with CPAP 10 cmH_2O they observed a significant improvement in lung compliance, significant decreases in both the elastic and the resistive components of WOB, and significant reductions in inspiratory muscle effort. Arterial PO_2 significantly improved and breathing pattern remained essentially unchanged. Additionally, no major changes were seen in cardiac index or stroke volume, although transmural filling pressures decreased with CPAP, which was interpreted as better cardiac performance.

Clinical Findings

There have been numerous cohort studies dealing with the usefulness of CPAP in patients with acute respiratory failure of various etiologies: multiple trauma, ARDS, pneumonia, sepsis, acute pancreatitis, cardiogenic pulmonary edema and pneumonia due to *Pneumocystis carinii* in patients with human immunodeficiency virus infection [4, 25–34]. These investigations have included more than 250 patients and have shown that, in the vast majority of cases, CPAP tended to improve arterial PO_2, with no major changes in arterial PCO_2 and few alterations in cardiac output. A number of patients, however, fail to improve with CPAP for various reasons: no improvement in PaO_2 despite increasing PEEP levels, progressive CO_2 retention, uncooperativeness, fatigue, and other complications associated with the primary disease.

It must be stressed that these studies varied greatly concerning their design: Some authors used face masks and others used CPAP with continuous- or demand-flow systems in intubated patients; the PEEP levels used were not uniform; and etiologies of acute respiratory failure varied. These differences render comparison and interpretation of the studies difficult.

Cardiogenic Pulmonary Edema

The studies mentioned above did not have a controlled and/or randomized design, with the exception of three that were conducted in the setting of cardiogenic pulmonary edema [30, 32, 34].

The studies conducted by Räsänen et al. [32] and Lin et al. [34] had a specific design that essentially allowed evaluation of the effect of CPAP on arterial oxygenation, since:

- The CPAP duration was predetermined (3 h for Räsänen and 6 h for Lin).
- The primary end-point in both studies was treatment failure.

Failure criteria were defined mainly as predetermined level of hypoxemia, rise in arterial carbon dioxide tension, and respiratory rate. For instance, in the study by Räsänen et al. the intubation rate of control patients was very high (60%) and this could have been attributable to the low FiO_2 (28%–30%) used. This is important since the main cause of treatment failure was hypoxemia. In the study by Lin et al., the failure rate over 6 h was 24% (12/50) in the CPAP group and 50% (25/50) in the control group ($p<0.01$), but only 3/12 and 4/25 patients reaching these failure criteria eventually required intubation and mechanical ventilation during their ICU stay (not significant).

Bersten et al. [30] studied 39 patients with cardiogenic pulmonary edema presenting with hypoxemia (mean PaO_2/FiO_2 between 136 and 138 mmHg) and acute hypercapnia (mean $PaCO_2$ between 58 and 64 mmHg), and compared 10 cmH_2O

continuous-flow CPAP with a face mask with conventional therapy with oxygen given by mask. They found a significant improvement in PaO_2 and a significant decrease in $PaCO_2$ in patients treated with CPAP compared with those conventionally treated. Intubation and mechanical ventilation were needed for 35% of patients (7/20) in the conventional treatment group and occurred within 3 h of study entry (CPAP was administered for a total of 9.3±4.9 h). None of the 19 patients treated with CPAP needed intubation. The mortality was similar in both groups. Additionally, a recent study confirmed the benefit of CPAP in patients with severe hypercapnic cardiogenic pulmonary edema [35].

Acute Lung Injury

Delclaux et al. recently investigated whether CPAP delivered by a face mask had physiological benefit and would reduce the need for intubation and mechanical ventilation in patients suffering from permeability pulmonary edema [36]. One hundred and twenty-three patients with acute nonhypercapnic respiratory failure (PaO_2:FiO_2 ratio <300 mmHg) resulting from bilateral pulmonary edema were randomized to receive either oxygen alone (n=61) or oxygen plus CPAP (n=62). Randomization was stratified on the existence of an underlying cardiopathy. In other words, both groups included, in addition to patients with acute lung injury or the acute respiratory distress syndrome, patients with a superimposed noncardiac cause of pulmonary edema in the presence of underlying cardiac disease. After 1 h, both subjective response to treatment (dyspnea) and PaO_2:FiO_2 ratio showed a greater improvement with CPAP than with oxygen alone [203 mmHg (45–431) versus 151 (73–482), p<0.05]. No difference was found in the need for intubation and mechanical ventilation in the CPAP group versus the oxygen group (21/62 versus 24/61, p=0.53), or in in-hospital mortality or length of ICU stay. A higher number of complications occurred in the CPAP group (CPAP: 18 versus oxygen: 6, p=0.03, including four cardiac arrests in the CPAP group observed at the time of intubation or when removing the mask).

Therefore, despite early physiological improvement in oxygenation and in dyspnea obtained with CPAP, these results do not support the use of CPAP in the setting of acute lung injury as a means of avoiding endotracheal intubation. CPAP might thus be reserved for patients in whom distress can be rapidly improved by medications, such as fluid overload. In such patients frank ventilatory failure can be transiently avoided by CPAP, giving time for the medications to act.

24.4.2 Weaning

CPAP has been also proposed for hypoxemic patients being weaned from mechanical ventilation. In these patients, CPAP therapy may improve oxygenation and decrease WOB compared with the classic T-piece trial in patients with restrictive lung disease [21, 37]. Glottic function is suppressed by the presence of the endotracheal tube, and some authors proposed that this may constitute another mechanism to explain why CPAP may be useful during spontaneous breathing through an endotracheal tube [38]. The glottis normally acts as an expiratory brake, facilitates coughing, and helps maintain the intrapulmonary gas volume [37, 39].

Sassoon et al. [21] studied ten patients during weaning from mechanical ventilation and observed that during CPAP with 5 cmH_2O PEEP, oxygenation was not better than with a T-piece. However, the pressure-time product of the inspiratory muscles was significantly lower during CPAP than during T-piece breathing. These data were not confirmed in another study conducted by Polese et al. [16] of ten non-COPD patients during weaning. No difference between spontaneous breathing and 5 cmH_2O CPAP was detected in terms of work of breathing or the pressure-time product of the inspiratory muscles.

24.4.3 Atelectasis

Postoperative atelectasis has been considered a further indication for CPAP. Andersen et al. [40] have demonstrated radiologic and gas exchange improvements in patients treated after surgery with intermittent CPAP at 15 cmH_2O PEEP over 24 h, compared with the conventional treatment. These beneficial effects were attributed to an increase in collateral flow to the obstructed alveolar regions induced by CPAP, and to greater facility in the removal of secretions. However, other investigators [41] were unable to demonstrate that CPAP prevents pulmonary complications, improves gas exchange or vital capacity, or improves chest X-ray findings compared with spontaneous breathing without PEEP in patients undergoing elective abdominal surgery. These findings may be explained partially by the low level of PEEP (5–10 cmH_2O) used and the short duration (4 h) of CPAP therapy.

The incidence of postoperative atelectasis may be high [42, 43] after both abdominal (about 20%) and thoracic (about 30%) surgery. The best methods of preventing and treating postoperative atelectasis remain open to debate. Patients with an inspiratory capacity greater than 1 l rarely need additional treatment. In others, any maneuver increasing functional residual capacity and inspiratory capacity may constitute adequate treatment [42, 43].

A study by Stock and co-workers [44], compared the results obtained in a group of 65 postoperative patients (elective abdominal surgery) with incentive spirometry, with deep inspiration and coughing, and with intermittent 7.5 cmH_2O CPAP using a face mask and a continuous-flow system. The authors found a lower incidence of atelectasis during CPAP treatment (21%) compared with the other methods (41%). They concluded, however, that although the increment in functional residual capacity was higher and faster with CPAP, all the methods were satisfactory, because the overall incidence of major pulmonary complications in a population considered at high risk was very low in all groups (only two patients developed postoperative pneumonia). In a study [45] performed in 160 patients undergoing cardiac and pulmonary surgery the incidence of postoperative atelectasis was shown to be the same for the three different methods of face-mask physiotherapy: either CPAP, expiratory positive airway pressure (EPAP), or inspiratory resistance with EPAP. All these data suggest that nowadays (an era of better anesthesia and surgical techniques), and at least in postoperative low-risk patients, standard nursing care is as effective in preventing complications as CPAP or other physiotherapeutic techniques [46, 47].

24.5 Contraindications and Complications

When CPAP is delivered via a face mask, the patient's cooperation is important. The presence of fractures or facial anatomical abnormalities and laryngeal, tracheal, or esophageal lesions contraindicate the use of face-mask CPAP.

During face-mask CPAP, patients may complain of facial pain and discomfort and may present with gastric distension with an attendant risk of vomiting and aspiration of the gastric contents. In patients with mild acute respiratory failure, nasal-mask CPAP has been reported to be more comfortable than full face-mask CPAP [48]. In a study of normal subjects, the hemodynamic effects of CPAP were shown to be critically dependent on mouth position [49]. In subjects receiving nasal-mask CPAP (with the mouth closed) or facial-mask CPAP and subjective to progressive increments in PEEP from 0 to 20 cmH_2O, a significant decrease in cardiac output and a parallel and significant increase in end-expiratory esophageal pressure were observed. No hemodynamic or esophageal pressure changes were detected when the subjects received nasal-mask CPAP with the mouth open.

24.6 Summary and Recommendations

Hypoxemic patients with acute hypercapnic respiratory failure and low functional residual capacity due to severe cardiogenic pulmonary edema seem to benefit from CPAP treatment, because it usually improves oxygenation and may potentially eliminate the need for intubation and mechanical ventilation in very acute forms of the disease, usually associated with hypercapnia. On the other hand, the benefit of CPAP in noncardiogenic edema has never been clearly demonstrated and its systematic use to prevent intubation in acute lung injury cannot be supported; it can even be hazardous by unnecessarily delaying intubation. Although CPAP may offer some advantages over the T-piece during weaning from mechanical ventilation because it improves gas exchange and decreases the work of breathing, the clinical impact of such a technique has never been demonstrated. Finally, CPAP is also indicated in the treatment of postoperative atelectasis, especially after thoracic and abdominal surgery. However, conventional methods of active respiratory physiotherapy and routine nursing care are also useful in preventing postoperative pulmonary complications. If CPAP is indicated for such patients, the average PEEP levels used are about 10 cmH_2O in order to allow significant increments in transpulmonary pressure. It should be stressed, however, that despite the widespread use of CPAP in the ICU, there is a lack of controlled studies to demonstrate its clinical efficacy in most situations.

When the clinical decision to use CPAP is made, it is useful to increase the PEEP levels in serial increments of 5 cmH_2O so as to obtain a PEEP value with minimal expiratory air flow resistance. As regards the inspiratory circuit, continuous-flow systems are preferable to demand valves. In continuous-flow systems, it is very important that gas flow within the circuit be at least equal to the patient's spontaneous inspiratory peak flow.

Ideally, the instantaneous gas flow within the circuits should be about 4–5 times the patient's minute ventilation: In this way the WOB done to overcome the impedance of the CPAP system is minimal. A manometer to control the airway pressure may be useful as a help to adjust the PEEP level, and to minimize the fluctuations in airway pressure and the patient's breathing effort.

24.7 References

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