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2

# Modes of mechanical ventilation for the operating room

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Most patients undergoing surgical procedures need to be mechanically ventilated, because of the impact of several drugs administered at induction and during maintenance of general anaesthesia on respiratory function. Optimization of intraoperative mechanical ventilation can reduce the incidence of post-operative pulmonary complications and improve the patient's outcome. Preoxygenation at induction of general anaesthesia prolongs the time window for safe intubation, reducing the risk of hypoxia and overweighs the potential risk of reabsorption atelectasis. Non-invasive positive pressure ventilation delivered through different interfaces should be considered at the induction of anaesthesia morbidly obese patients. Anaesthesia ventilators are becoming increasingly sophisticated, integrating many functions that were once exclusive to intensive care. Modern anaesthesia machines provide high performances in delivering the desired volumes and pressures accurately and precisely, including assisted ventilation modes. Therefore, the physicians should be familiar with the potential and pitfalls of the most commonly used intraoperative ventilation modes: volume-controlled, pressure-controlled, dual-controlled and assisted ventilation. Although there is no clear evidence to support the advantage of any one of these ventilation modes over the others, protective mechanical ventilation with low tidal volume and low levels of positive end-expiratory pressure (PEEP) should be considered in patients undergoing surgery. The target tidal volume should be calculated based on the predicted or

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ideal body weight rather than on the actual body weight. To optimize ventilation monitoring, anaesthesia machines should include end-inspiratory and end-expiratory pause as well as flow-volume loop curves. The routine administration of high PEEP levels should be avoided, as this may lead to haemodynamic impairment and fluid overload. Higher PEEP might be considered during surgery longer than 3 h, laparoscopy in the Trendelenburg position and in patients with body mass index >35 kg/m$^2$. Large randomized trials are warranted to identify subgroups of patients and the type of surgery that can potentially benefit from specific ventilation modes or ventilation settings.



## Introduction

Patients undergoing surgical procedures often require general anaesthesia. Most of the drugs used during induction and maintenance of general anaesthesia have important effects on patient's respiratory function [1], mainly causing a depression in alveolar ventilation, as well as modifications in the activity of respiratory muscles [2] and the distribution of ventilation and perfusion within the lungs [3]. As a result, >230 million patients receiving a surgical intervention need to be mechanically ventilated each year [4]. During the last decades, great insight into mechanical ventilation of the critically ill patient with lung injury modified the way clinicians support the respiratory function. Mechanical ventilation itself can worsen [5] or even initiate [6] lung injury: physicians developed a series of strategies referred to as ‘protective ventilation’. More recently, these changes are under extensive investigation for the non-injured lung as well, in an effort to bring the advances made in intensive care to a wider population [7]. Post-operative pulmonary complications (PPCs) are a major determinant of post-operative morbidity, mortality, length of hospital stay and health-care-associated social costs [8,9]. It was suggested that intraoperative protective ventilation, namely low tidal volume and moderate levels of positive end-expiratory pressure (PEEP), could improve post-operative pulmonary function [10,11]. More recent evidence shows that low tidal volume plays a major role in reducing PPCs [12,13], at least in non-obese patients undergoing abdominal surgery. Nevertheless, moderate PEEP might be considered during surgery longer than 3 h, laparoscopy in the Trendelenburg position and in patients with body mass index (BMI) > 35 kg/m$^2$. Ventilators used in the operating room were developed according to the specific requirements of the surgical scenario. With the evolution of technology, these became intrinsically different from their counterparts used in the intensive care unit (ICU). The classical anaesthesia machine delivers gases to the patient through a closed-circuit system, using a bellows system. In the last years, most of the manufacturers began implementing technologies derived from the ICU ventilators in the anaesthesia machine, introducing modes of ventilation once exclusively available in the ICU. Some manufacturers are also replacing bellows-based designs with turbine- or motor-driven piston systems, especially on flagship machines [14]. The impact of the availability of these high-quality ventilators in the operating theatre and different ventilation modes on patient outcome has to be determined. In the present article, ventilation strategies at the induction of general anaesthesia and during surgery are discussed.

## Ventilatory strategies at the induction of general anaesthesia

### *Preoxygenation*

At the induction of general anaesthesia, a high dose of sedatives and analgesics as well as muscle relaxants is often administered, frequently resulting in complete apnoea. During both planned and emergency intubations, there is a non-negligible risk of developing hypoxia [15]. Difficult intubation may lead to unexpected peripheral oxygen desaturation [15,16]. In addition, clinicians must be aware that certain subgroups of patients may have a reduced tolerance to systemic hypoxia, such as those suffering from cerebrovascular disease, epilepsy and coronary artery disease. In addition, the clinicians should consider that certain subgroups of patients may have a reduced tolerance to systemic hypoxia, such as those suffering from cerebrovascular disease, epilepsy and coronary artery disease. In the supine position, the functional residual capacity (FRC) is reduced, via multiple mechanisms, mainly the dorsal displacement of mediastinal organs and the cephalad shift of the diaphragm, spurred by the abdominal content. Therefore, obese and pregnant patients show a higher reduction in FRC and are more prone to desaturation at the induction of general anaesthesia [17]. In obese patients, respiratory volumes decrease inversely with the increase in BMI: in the morbidly obese, the FRC can be as low as 75% of that of a healthy subject [18,19]. The risk of oxygen desaturation after a standard 3-min preoxygenation with 100% oxygen delivered through a face mask is low, unless the patient has an elevated metabolic demand, pulmonary pathology or specific predisposing factors [17]. Standard preoxygenation can be inadequate for specific subgroups of patients. Factors predicting the inadequacy of preoxygenation were essentially those previously described as risk factors for difficult mask ventilation: bearded male (odds ratio (OR) 9.1), beardless male (OR 2.4), American Society of Anesthesiologists (ASA) score of 4 (OR 9.1), ASA score of 2–3 (OR 2.4), lack of teeth (OR 2.4) and age >55 years (OR 1.8) [20]. Furthermore, it has been reported that 37% of the claims due to death or brain damage linked to difficult intubation concerned obese patients [21]. Several techniques such as the head-up position at 25° [22], the ramped position [23], fibre-optic intubation, or intubation through a laryngeal mask or with a video laryngoscope [24] have been proposed to overcome difficult intubation and increase the pre-intubation arterial oxygen tension, as well as the safety margin for airway control in the obese patient. Preoxygenation with high-flow humidified nasal cannulae has been described [25]; however, in a randomized open-label trial, this device was not superior to a high-flow facial mask in reducing the lowest level of desaturation at induction in hypoxaemic patients [26]. In patients with abdominal sepsis, showing an intrinsically higher oxygen demand, pre-induction incentive spirometry performed within 1 h from induction reduced apnoea time and increased oxygenation in a randomized trial conducted on 66 patients [27]. Researchers have long discussed how preoxygenation with high $FiO_2$ can induce denitrogenation and therefore reabsorption-related atelectasis after surgery, but a recent randomized trial on a small number of patients showed that this does not influence post-operative FRC [28]. Nevertheless, the benefits of achieving good oxygenation at induction, prolonging the time window for a safe intubation, outweigh this risk [17].

*Perioperative non-invasive positive pressure ventilation*

Non-invasive positive pressure ventilation (NPPV) can be delivered through several interfaces, including different types of masks, and combining pressure support ventilation (PSV) and PEEP. Many of the modern commercially available operating room ventilators can deliver NPPV, as shown in Table 1. NPPV increases the FRC by recruiting collapsed respiratory units, therefore increasing the oxygen reserve within the lungs. The role of NPPV at induction of general anaesthesia has been evaluated in several studies, with particular reference to morbidly obese patients. In 2001, Cressey and colleagues tested the effectiveness of 7.5 cm $H_2O$ continuous positive airway pressure (CPAP) alone versus conventional preoxygenation through a Mapleson type A circuit, in 20 consecutive morbidly obese women. They concluded that no clinical advantage in terms of reduction of time to desaturation could be achieved with such an approach alone [29]. In morbidly obese patients, low-pressure CPAP combined with low-pressure PSV during preoxygenation resulted in better oxygenation, compared with neutral-pressure breathing, and prevented desaturation episodes [30,31]. Delay et al. compared NPPV with 8 cm $H_2O$ PSV and 6 cm $H_2O$ PEEP to conventional preoxygenation in 28 morbidly obese patients [32], finding a higher end-tidal $O_2$ concentration in the NPPV group. Futier et al. studied 66 consecutive obese patients in a randomized trial comparing spontaneous breathing with NPPV alone and NPPV plus preoperative recruitment manoeuvre (RM). They showed that NPP alone and in combination with RM improved both gas exchange and FRC compared with standard preoxygenation [33]. More recently, a study on 44 adults scheduled for laparoscopic bariatric surgery found that even low-pressure NPPV (5 cm $H_2O$ PSV and 5 cm $H_2O$ PEEP) was better than neutral-pressure breathing for preventing oxygen

**Table 1**
Some of the commercially available mechanical ventilators for the operating room. PC: Pressure Controlled, VC: Volume Controlled, CMV: Continuous Mandatory Ventilation, SIMV: Synchronized Intermittent Mandatory Ventilation, BIPAP: Bilevel Positive Airway Pressure, AF: AutoFlow, CPAP: Continuous Positive Airway Pressure, APRV: Airways Pressure Release Ventilation, PS: Pressure Support, VG: Volume Guaranteed, PRVC: Pressure-Regulated Volume Control. Technical parameters were retrieved from the manufacturers' website in April 2015.

| Manufacturer | Model | Ventilator type | Modes of ventilation | Optional modes of ventilation | Tidal volume (mL) | Respiratory rate (breaths/min) | Inspiratory flow (L/m) | Pressure limit (cm $H_2O$) | PEEP (cm $H_2O$) |
|---|---|---|---|---|---|---|---|---|---|
| Dräger Medical | Perseus A500 | Turbine | Manual/spontaneous, PC-CMV, PC-BIPAP, VC-CMV, VC-CMV/AF, VC-SIMV/AF | CPAP/PS, PC-BIPAP/PS, VC-SIMV/AF/PS, PC-APRV | 20–2000 | 3–100 | 0–180 | 7–80 | Off, 2–35 |
| Dräger Medical | Apollo | Piston | Manual/spontaneous, VC-CMV, PC-CMV | PS, VC-CMV/AF | 20–1400 | 3–100 | 0–150 | Up to 70 | 0–20 |
| GE Healthcare | Aisys CS2 | Ascending bellows | VC-CMV | PC-CMV, PCV-VG, VC/PC/VG-SIMV, CPAP/PS | 20–1500 | 4–100 | 0–120 | 12–100 | Off, 4–30 |
| MEDEC | Saturn Evo | Horizontal bag-in-bottle bellows | VC-CMV, VC-SIMV, PC-CMV, PC-SIMV | PS | 10–1600 | 4–80 | Not specified | 7–99 | 0–20 |
| Spacelabs Healthcare | Blease e900 | Ascending bellows | VC-CMV, PC-CMV, SIMV | PS | 20–1500 | 2–99 | up to 100 | 10–70 | 3–20 |
| Maquet | FLOW-i | Volume Reflector | Manual/spontaneous, VC-CMV, PC-CMV | PS, PRVC, SIMV | 20–2000 | 4–100 | 0–200 | 0–120 | 0–50 |

desaturation episodes at induction [30]. A retrospective study in ICU patients showed that a previous failed attempt of NPPV is associated with a twofold increase in a composite intubation risk complication (desaturation, hypotension and aspiration) [34]. In conclusion, preoxygenation can be considered a safe practice, outweighing the risks of potential post-operative atelectasis. We suggest that a routine preoxygenation at an $FiO_2 \leq 0.8$ should be used, except in cases of difficult intubation. NPPV should be considered for obese patients.

## Intraoperative mechanical ventilation

Modern anaesthesia ventilators are becoming increasingly sophisticated, integrating many functions that were once exclusive to ICU ventilators [35]. Table 1 presents the characteristics of some of the new commercially available anaesthesia machines, including the supported ventilatory modes. The potential indications of different ventilation modes during anaesthesia are illustrated in Table 2. Modern ventilators used in the operating room allow accurate control of the volume and pressure delivered to the patient, through mechanisms of compliance compensation [14,35]. The most widespread ventilator type is still the bellows-in-bottle type, but several manufacturers are switching to alternative designs derived from technologies previously used in ICU ventilators, especially in flagship machines. Alternative designs already available on the market include electronically controlled piston pump ventilators (e.g., Dräger Apollo), turbine ventilators (e.g., Dräger Perseus) and proprietary gas-driven rigid reservoir system ventilators (Maquet Volume Reflector, available on FLOW-I series). Piston ventilators allow a tight control of the delivered volume, allowing a steeper increase in flow than traditional bellows systems, as required by pressure-controlled ventilation modes. Turbine anaesthesia ventilators can optimize closed-circuit ventilation systems, minimizing the use of inhaled agents [36]. Bench studies have shown high volume and pressure delivery accuracy performances, comparable to those of more expensive ICU ventilators [37]. Neuromuscular blockade to allow orotracheal intubation and/or to facilitate surgery is a common practice. However, muscle paralysis may lead to post-operative residual curarization, associated with higher morbidity [38]. Nevertheless, several surgical interventions can be performed without complete curarization: the anaesthesiologist should be able to support the respiratory pump partially, using assisted ventilation in place of controlled ventilation [35,39]. All the modern anaesthesia machines include, at least as an option, assisted ventilation modes (Table 1).

In all cases, tidal volume should be calculated on the predicted body weight and not on the actual patient weight.

### *Volume-controlled ventilation*

Volume-controlled continuous mandatory ventilation (V-CMV or VCV) is a time-cycled, volume-targeted ventilation mode available on all modern ventilators. As shown in Fig. 1 in the left panel, VCV delivers a desired tidal volume ($V_T$) by means of a constant flow with a square waveform: as a result, as the time integral of flow, the volume increases linearly until $V_T$ is achieved, within an allowed inspiratory time. Concerning airway pressure, during inspiration, a quasilinear increase can be seen, until a peak is reached ($P_{peak}$). The relationship between $V_T$ and $P_{peak}$ is a result of the complex interaction between the dynamic airway resistance to flow and the respiratory system compliance. In conventional VCV ventilation, the expiratory valve is opened immediately after $V_T$ is delivered, allowing passive expiration through the expiratory limb of the respiratory circuit. Anaesthesia machines can estimate the compliance of the respiratory system ($C_{rs}$) with the formula $C_{rs} = V_T/(P_{peak} - \text{PEEP})$. As $C_{rs}$ is biased by the contribution of airway flow resistance in this case, this measurement is referred to as *dynamic* compliance, which underestimates actual compliance. Modern ventilators allow the operator to set an end-inspiratory pause (Fig. 1, central panel), usually set as a percentage of the inspiration time (15–25%). In this case, after $P_{peak}$ is reached and $V_T$ fully delivered, the ventilator sets the inspiratory flow to zero without opening the expiratory valve, eliminating the contribution to pressure due to the airway resistance to flow: a rapid decrease in airway pressure can be seen, until a stable plateau pressure ($P_{plat}$) is achieved. Therefore, respiratory system compliance can be calculated as $C_{rs} = V_T/(P_{plat} - \text{PEEP})$, providing a more reliable quasi-static estimation of compliance. An advantage of VCV,

**Table 2**
Main ventilation modes used in the operating room (readapted from *Principles and Practice of Mechanical Ventilation, third edition*) [35].

| Mode | Type | Details | Use in anaesthesia |
|---|---|---|---|
| V-CMV (volume continuous mandatory ventilation), VCV (volume-controlled ventilation) | Mandatory | Controlled ventilation, targeted on tidal volume, time-cycled | Most common mode of ventilation, provides good control of tidal volume, especially with modern anaesthesia machines that provide compliance compensation. |
| P-CMV (pressure continuous mandatory ventilation), PCV (pressure-controlled ventilation) | Mandatory | Controlled ventilation, targeted on airway pressure, time-cycled | Common mode of ventilation, provides best control of inspiratory peak pressure, useful for compensating air loss in uncuffed tubes and decrease gastric insufflation in combination with laryngeal masks and other supraglottic devices. Often used in one-lung ventilation. |
| VCV/V-CMV with VG (pressure guaranteed), AF (autoflow) or PRVC (pressure-regulated, volume-controlled) | Mandatory | Controlled ventilation, targeted on tidal volume, time-cycled, pressure-limited. This mode has different names and proprietary algorithms on different ventilator manufacturers, aimed at delivering the desired volume with the lowest possible inspiratory pressure. | Increasingly available in anaesthesia machines, combines advantages of VCV and PCV, allowing a tight control on tidal volume, with a better compromise towards peak inspiratory pressure. |
| V or P-ACV (volume or pressure assisted controlled ventilation | Mandatory/ Assisted | Delivers the desired volume or pressure target both automatically or upon patient's inspiratory effort. | Can be used in patients with residual respiratory drive to assist spontaneous breathing without risking apnoea. |
| V or P-SIMV (volume- or pressure-synchronized intermittent mandatory ventilation) | Mandatory/ Assisted | Delivers the desired mandatory volume or pressure, plus an assisted volume or pressure when an inspiratory effort is detected within a sensing window. | Similar to V/P-ACV, can be used in patients with a residual respiratory drive, or when emerging from general anaesthesia. |
| PSV (pressure support ventilation) | Assisted | Delivers a target pressure when an inspiratory effort is detected. | In patients with a respiratory drive, in presence of restrictive lung disease, induction of general anaesthesia, neuromuscular disease, weaning from controlled ventilation. |
| CPAP | Assisted | Increases mean airway pressure in spontaneously breathing patients | At induction, to avoid excessive loss of FRC/EELV, can decrease inspiratory effort in intubated patients, before extubation. |

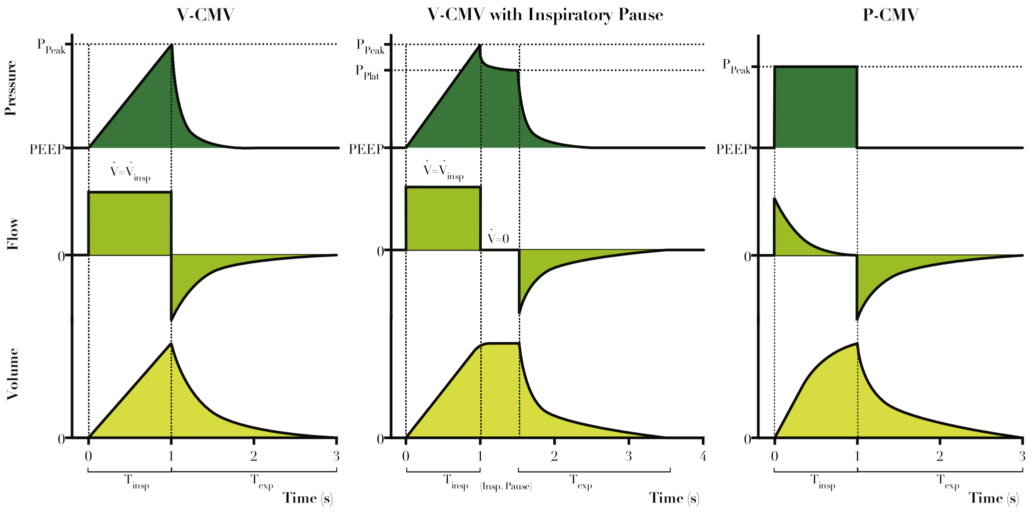


**Figure 1.** Flow, pressure and volume curves for the three most commonly used controlled ventilation modes in the operating room.

which makes it the first choice of many anaesthesiologists during general anaesthesia, is the guarantee of minute ventilation. This ensures adequate gas exchange, especially $CO_2$ elimination, regardless of changes in compliance due to patient positioning, variation in depth of neuromuscular blockade, surgical procedure or other factors. Nevertheless, during VCV, airway pressure is not controlled, but it is a direct consequence of the interaction between airway resistance and respiratory system compliance: delivering a desired $V_T$ when a sudden decrease in $C_{rs}$ occurs results in high airway pressures. The clinician sets a clinically acceptable pressure range for the specific patient; the anaesthesia machine generates an alarm when this range is exceeded, to alert the operator to modify ventilation settings. As an additional safety measure, ventilators have a pressure limit ($P_{lim}$ or $P_{max}$) that, once reached, stops inspiratory flow. Newer ventilators implement compliance compensation systems that guarantee the accuracy of the delivered $V_T$ also for small volumes and at low lung compliance, more efficiently than ventilators that only rely on inspiratory flow sensors [40]. When monitoring patients undergoing VCV, an increase in $P_{peak}$ can be due to a reduction in $C_{rs}$ or an increase in airway resistance to flow. In order to discriminate between the two conditions, setting an end-expiratory pause is strongly advised (Fig. 1).

*Pressure-controlled ventilation*

Pressure-controlled continuous mandatory ventilation (P-CMV or PCV) is a widely available, time-cycled form of pressure-targeted ventilation. In this ventilation mode, the clinician sets a desired inspiratory pressure level; the machine initiates inspiration delivering a high flow until the desired level is reached. The pressure increase rate can be set in most ventilators. As shown in Fig. 1 (right panel), after a short initial phase of high flow, the alveolar pressure starts to equilibrate with the pressure inside the inspiratory limb of the respiratory circuit. Therefore, the gas flow needed to maintain the desired inspiratory pressure decreases throughout the inspiration, resulting in a characteristic decelerating pattern in the flow–time waveform, whereas the pressure–time curve is ideally a square waveform. As the flow is not constant, the ascending limb of the volume–time curve is not linear; rather, it increases at a slower rate in the late inspiration phase. Symmetrically to what happens in VCV, in PCV, the pressure is set and $V_T$ is the result of the interaction between inspiratory pressure, airway resistance and respiratory system compliance. While tight control of inspiratory peak pressure is easily achieved in PCV, minute ventilation is not guaranteed. The perioperative period is potentially characterized by steep changes of $C_{rs}$: this is observed in, for instance, the rapid modifications in diaphragm distension or relaxation caused by induction or resolution of the pneumoperitoneum during laparoscopic abdominal surgery. When these modifications occur during PCV, the variations in $V_T$ are sufficient to cause hypoventilation or delivery of inappropriately high, and thus potentially harmful [5], tidal volumes. For this reason, the clinician must set an acceptable $V_T$ alarm range for the patient and closely monitor the changes in $C_{rs}$ and the resulting variations in $V_T$, adjusting the inspiratory pressure in order to achieve acceptable volumes. PCV can be beneficial when supraglottic airways or uncuffed tubes are used, for its ability to reduce gas leaks and gastric insufflation [41]. As shown in Table 3, several small-sampled randomized controlled trials investigated the impact of PCV on respiratory mechanics, haemodynamics and gas exchange, in comparison with VCV. These studies focused on specific populations: obese patients undergoing bariatric surgery [42]; laparoscopic bariatric surgery [43,44]; women undergoing laparoscopic gynaecologic surgery [45,46]; and children [47], obese adults [48] and non-obese adults [49,50] undergoing laparoscopic cholecystectomy. The results are contradictory; no strong evidence for PCV or VCV in obese patients exists presently [51] In PCV, both reduction in compliance and increase in flow resistance always result in a reduction in tidal volume, making it more difficult to discriminate the cause leading to $V_T$ reduction.

*Dual-controlled ventilation*

Recently, the advances in technology made new ventilation modes available in some new anaesthesia machines, with the aim of combining the advantages of both PCV and VCV, the so-called dual-controlled ventilation modes. These ventilation modes are referred to with different proprietary names, depending on the vendor (see Table 1): volume mode with autoflow (Dräger), pressure-controlled ventilation with volume guaranteed (PCV-VG, General Electric) and pressure-regulated volume control (PRVC, Maquet). These ventilation modes are structurally very similar, aimed at delivering the desired $V_T$ at the lowest possible inspiratory pressure. To achieve this goal, the ventilator uses a decelerating inspiratory flow pattern, similar to that of PCV (Fig. 1, right panel); calculates $C_{rs}$ at each breath cycle; and readapts the inspiratory pressure to obtain the $V_T$ set by the clinician. All the algorithms deliver a first volume-controlled breath at a constant inspiratory flow to make an initial estimation of $C_{rs}$ and the pressure needed to reach the volume target. These ventilation modes have only recently been made widely available in anaesthesia machines, and very few studies have investigated their potential advantages, especially in one-lung ventilation, which mandates a tight control on both pressure and volume [52]. Even if the actual impact of dual-controlled ventilation on clinical outcomes is still to be determined, there is an undoubted clinical advantage to using a PCV mode that does not need frequent manual adjustments of inspiratory pressure during the course of surgery.

*Assisted ventilation and other ventilation modes*

Many patients undergoing minor surgical procedures can be maintained in spontaneous breathing or be assisted at different degrees by the clinician. General anaesthesia itself does not necessarily imply controlled mechanical ventilation [35,39]. New ventilators offer several assisted or assisted–controlled ventilation modes (see Table 1). Synchronized intermittent mandatory ventilation (SIMV) is a hybrid ventilation mode that can be either pressure or volume controlled; further, this mode can play a role in the operating room as it can guarantee minute ventilation, and thus gas exchange, while allowing the patient to trigger assisted breaths. With SIMV, when the respiratory rate falls below a set value, the anaesthesia machine delivers mandatory breaths, providing a safety measure for patients whose ability to trigger spontaneous breaths could deteriorate during the surgical procedure. This method can be considered in patients with a residual ventilatory drive. The machine attempts to synchronize the respiratory efforts of the patient with the time-cycled mandatory breaths, and the clinician must set a trigger window, as a percentage of the expiratory time, during which the flow trigger senses for inspiratory effort. In addition to the role always described for preoxygenation, PSV is now available in many commercially available anaesthesia machines. It can be used, for instance, in patients undergoing minor surgery, or in patients deeply sedated after loco-regional anaesthesia or while emerging from general anaesthesia. Ventilators designed for the operating room often offer PSV with safety backup ventilation, to provide the patient with mandatory ventilation in the case of suppression of the

**Table 3**
Studies comparing VCV and PCV during general anaesthesia. Outcomes are reported as PCV versus VCV with VCV as control group. $PaCO_2$ arterial carbon dioxide pressure, $PaO_2$ arterial oxygen pressure, PAO2 alveolar oxygen pressure, BMI body mass index, N/A not assessed.

| Study | Number | Patients | Laparoscopic | Surgery | Airway | $P_{peak}$ | Compliance | Haemodynamics | Gas exchange |
|---|---|---|---|---|---|---|---|---|---|
| De Baerdemaeker 2008 [43] | 24 | Morbidly obese | Yes | Gastric banding | Tracheal tube | = | = | = | ↑$PaCO_2$ |
| Hans 2008 [42] | 40 | Morbidly obese | No | Gastric bypass | Tracheal tube | ↓ | = | = | = |
| Cadi 2008 [44] | 36 | BMI > 35 kg/m$^2$ | Yes | Gastric banding | Tracheal tube | = | = | = | ↑$PaO_2$ ↓$PCO_2$ |
| Oğurlu 2010 [45] | 60 | Women, ASA I and II | Yes | Gynaecologic surgery | Tracheal tube | ↓ | ↑ | = | N/A |
| Jeon 2011 [46] | 60 | Women | Yes | Gynaecologic surgery | Laryngeal mask | ↓ | = | = | ↓$PaCO_2$ |
| Tyagi 2011 [49] | 42 | BMI<30 kg/m$^2$ | Yes | Cholecystectomy | Tracheal tube | ↓ | ↑ | = | = |
| Kim 2011 [47] | 34 | Children | Yes | Appendicectomy | Tracheal tube | ↓ | ↑ | = | N/A |
| Gupta 2012 [48] | 102 | ASA I and II, Obese (BMI 30–40 kg/m$^2$) | Yes | Cholecystectomy | Tracheal tube | ↓ | N/A | = | ↑$PaO_2$ |
| Aydin 2014 [50] | 70 | ASA I and II | Yes | Cholecystectomy | Tracheal tube | = | = | = | ↓$PAO_2$-$PaO_2$ |

respiratory drive, as observed after deepening of sedation or an opioid bolus. In a recent study on 36 patients scheduled for knee arthroscopic surgery under general anaesthesia with a laryngeal mask, PSV reduced emergence time, propofol consumption and air leaks compared with VCV [53]. The use of CPAP during recovery from general anaesthesia has also been proposed in a pilot study to reduce the incidence of post-operative atelectasis [54]. Newer high-level ventilators also offer increasingly sophisticated ventilation modes, derived from ICU ventilators (Table 2). These modes can be used in surgeries of critically ill patients requiring protective ventilation, especially in the case of injured lungs.

*Monitoring ventilation in the anaesthetized patient*

An adequate monitoring of ventilation is mandatory [55]. An ideal anaesthesia machine should be able to set end-inspiratory and end-expiratory pause, in order to measure $P_{plat}$ and intrinsic PEEP ($PEEP_i$). Especially in cases where an end-expiratory pause cannot be set, useful information can be obtained by interpreting the flow-volume loop. As illustrated in Fig. 2, the flow-volume loop, also available on older ventilators, can help the clinician distinguish flow limitations due to airway collapse, which might benefit from higher PEEP levels, from conditions of airway thickening, where higher PEEP might be counterproductive.

*The role of tidal volume, PEEP and RMs*

The last years were characterized by an increasing tendency to translate advances in the mechanical ventilation of the injured lung in the ICU to the operating room. The role of protective ventilation in the operating room is still to be conclusively determined. As illustrated in Table 4, most of the randomized controlled trials did not investigate single aspects of the ventilation settings, but rather intervention bundles: in most of the cases, lower tidal volume as millilitres per predicted body weight, higher PEEP and RMs were used in the intervention group, compared with conventional ventilation. These studies were focused mainly on laparoscopic surgery only [56–60] and laparoscopic or open major abdominal surgery [10,11,13,61]. The results are conflicting: in several small studies, a strategy combining lower tidal volume, higher PEEP and RMs improved intraoperative gas exchange [56–60] and respiratory mechanics [10,57,59,61]; however, only some studies showed improved post-operative outcomes

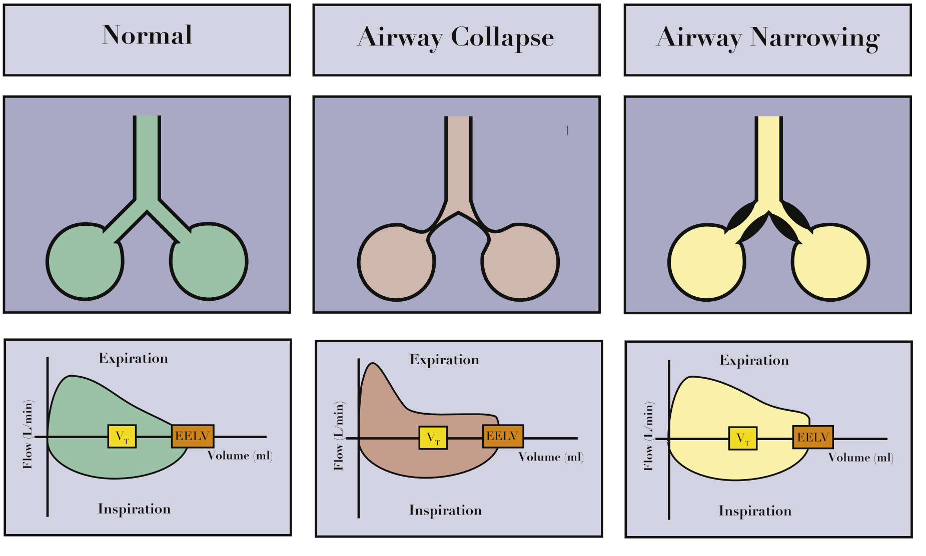


**Figure 2.** Flow-volume loop of a healthy subject (left), with flow resistance due to airway collapse (centre) and airway narrowing (right). Readapted from Ball et al. [55].

**Table 4**

Recent RCTs investigating the effect of PEEP, recruitment manoeuvres and tidal volume on clinical outcomes. R: recruitment manoeuvres, PPC post-operative pulmonary complications, PBW predicted body weight, N/A not assessed, PFT pulmonary functional tests, CXR chest X-ray.

| Study | Number | Patients | Control group | | Intervention group | | Intraoperative outcomes | Post-operative outcomes |
|---|---|---|---|---|---|---|---|---|
| | | | PEEP | $V_T$ mL/kg PBW | PEEP | $V_T$ mL/kg PBW | | |
| Meininger 2005 [56] | 20 | Laparoscopic surgery | 0 | / | 5 | / | Improved oxygenation | N/A |
| Whalen 2006 [57] | 20 | Laparoscopic bariatric surgery | 4 | 8 | 12 + R | 8 | Improved oxygenation, compliance | No effect |
| Talab 2009 [58] | 66 | Laparoscopic bariatric surgery | 0 | 8–10 | 5 and 10 | 8–10 | Improved oxygenation only with PEEP 10 | Improved oxygenation, reduced atelectasis, PPC, LOS |
| Reinus 2009 [61] | 30 | Bariatric surgery | 0 + R | 10 | 10 + R | 10 | Improved compliance | No effect |
| Kim 2010 [59] | 30 | Laparoscopic cholecystectomy | 0 | 8 | 5<br>10 + R | 8 | Improved oxygenation, compliance | Improved oxygenation, reduced atelectasis |
| Futier 2013 [11] | 400 | Abdominal surgery | 0 | 10–12 | 6–8 + R | 6–8 | Reduced peak pressure, improved compliance | Reduced major complications within 7 days from surgery |
| Severgnini 2013 [10] | 56 | Abdominal surgery | 0 | 9 | 10 + R | 7 | Reduced plateau pressure | Improved PFT, CXR |
| Hemmes 2014 [13] | 900 | Abdominal surgery | 2 | / | 12 + R | / | Increased incidence of hypotension | No effect on PPC incidence |
| Baki 2014 [60] | 60 | Laparoscopic surgery | 0 | 10 | 5 | 6 | Improved gas exchange | N/A |

[10,58,59], whereas others did not find differences [57,61] or did not investigate the patients post-operatively [56,60]. A large retrospective analysis on 29,343 patients found that the use of lower intraoperative tidal volume increased from 2008 to 2011, and that the use of a low $T_V$ (6–8 mL/kg PBW) and minimal PEEP seem to be associated with a higher risk of 30-day mortality [62]. The retrospective design of this study limits the interpretation of these results. In a large RCT on 400 patients undergoing abdominal surgery, Futier et al. found that a ventilatory strategy including low $V_T$, routine use of PEEP and RMs improved the composite outcome of pulmonary and extra-pulmonary post-operative complications [11]. In another large RCT conducted by the PROVE Network Investigators for the Clinical Trial Network of the European Society of Anaesthesiology on 900 surgical patients, the role of low PEEP alone versus high PEEP plus RMs alone was investigated, maintaining the same $V_T$ in the two arms, concluding that the latter strategy increased intraoperative hypotension and use of vasoactive drugs, without any modification of the incidence of PPCs [13].

*RM techniques*

RMs can be performed in several ways, as illustrated in Fig. 2. Most clinicians perform recruitment with the 'bag-squeezing' technique: the ventilator is switched in the manual mode, the adjustable pressure limiting (APL) valve set to 30 or 40 cm $H_2O$ and the patient kept at a constant pressure manually and then switched back to mechanical ventilation (Fig. 3a). This method has potential limitations. First, it is difficult to maintain the patient at a constant pressure with a manual bag; even more importantly, when the ventilator is switched back from manual to mechanical ventilation, a loss of pressure occurs in the respiratory circuit, potentially leading to lung de-recruitment. Moreover, many ventilators require several cycles before reaching the desired new PEEP level. This could be avoided using CPAP instead of manual bag squeezing (Fig. 3b); unfortunately, most of the anaesthesia machines do not have CPAP or is only available as an option (Table 1). Relying on ventilatory settings and avoiding switching to manual ventilation can give more reproducible and effective results. One strategy involves increasing the PEEP during VCV without modifying $V_T$, in steps of 5 cm $H_2O$, until a plateau pressure of 30 or 40 cm $H_2O$ is achieved. Subsequently, PEEP can be decreased in steps of 2 cm $H_2O$ in a decremental PEEP trial or cycling manoeuvre [63] (Fig. 3c). If the clinician wants to set PEEP at the level providing the optimal $C_{rs}$, a second RM must be performed after the stepwise decrease. A potential

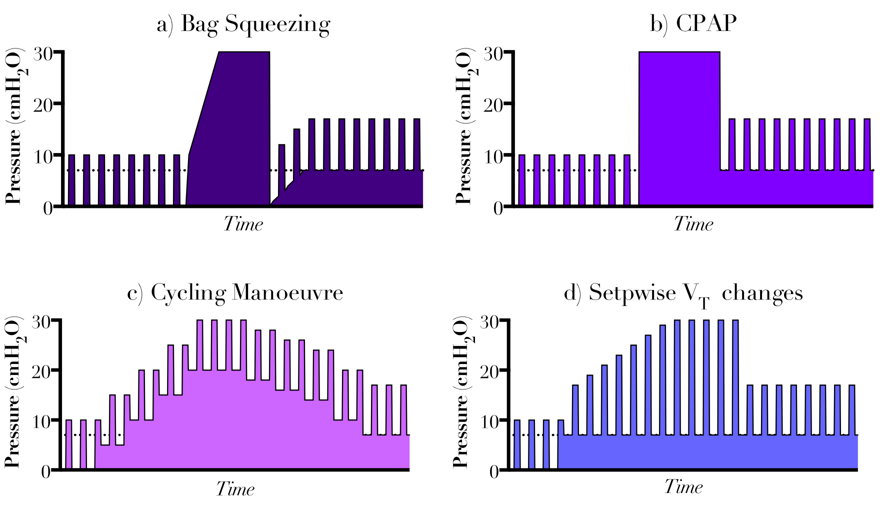


**Figure 3.** Pressure–time curves for three techniques of performing recruitment manoeuvres. Left panel: manual recruitment with bag squeezing or CPAP (dotted line), central panel: cycling manoeuvre with decremental PEEP trial, right panel: stepwise tidal volume adjustment.

limitation of this technique is that some new anaesthesia machine (Table 1) limits the maximum PEEP to 20 cm $H_2O$, which makes it difficult for some patients to reach the desired plateau pressure.

Recently, a manoeuvre based on changes in tidal volume was used in a randomized trial [13] (Fig. 3d). In this technique, PEEP is increased to the desired level, with $V_T$ being increased until a plateau pressure of 30 or 40 cm $H_2O$, held for few respiratory cycles and then set again to the desired volume. Some new anaesthesia machines implement automated cycling RMs. The clinician should be aware that, in morbidly obese patients, the conventional recruitment pressure of 30–40 cm $H_2O$ might be inadequate for fully recruiting the lung: pressures up to 60 cm $H_2O$ might be required [61].

## Summary

Mechanical ventilation for patients undergoing general anaesthesia is an increasingly complex yet safe procedure. Many improvements have been introduced in the last decades due to advances in both technology and knowledge. The impact of the intraoperative ventilation setting on clinical outcome has been recently proven. Given the high number of surgical interventions performed across the world currently, even small improvements in post-operative complications due to better ventilatory strategies may affect a high number of patients, reduce health-care costs and contribute to a better clinical outcome.

**Practice points**

- Mechanical ventilation during general anaesthesia is a safe practice, but ventilatory settings alone have an impact on the clinical outcome
- Tidal volume should be set according to the predicted or ideal body weight
- Preoxygenation is a safe practice, and NPPV preoxygenation can be considered in obese patients
- The clinician should be familiar with the potential and pitfalls of the most commonly used intraoperative ventilation modes
- The routine administration of high PEEP levels should be avoided
- Intraoperative recruitment manoeuvres should be considered in selected patients, and more standardized techniques should substitute the classical bag squeezing

**Research agenda**

- Large RCTs defining the impact on clinical outcome of emerging ventilations modes are warranted
- Future studies should identify subgroups of patients who might benefit from routine PEEP administration and recruitment manoeuvres

## Conflict of interest

None.

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