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Modes of Mechanical Ventilation for the Operating Room

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Keywords: general anaesthesia, mechanical ventilation, pressure controlled ventilation, volume controlled ventilation, volume guaranteed, non-invasive positive pressure ventilation, induction, pre-oxygenation
Abstract

Most of the patients undergoing surgical procedures need to be mechanically ventilated, because of the impact on respiratory function of several drugs administered at induction and during maintenance of general anaesthesia. Optimization of intraoperative mechanical ventilation can reduce the incidence of postoperative pulmonary complications, and improve patient’s outcome. Pre-oxygenation at induction of general anaesthesia prolongs the time window for safe intubation, reducing the risk of hypoxia and overcoming the potential risk of reabsorption atelectasis. Non-invasive positive pressure ventilation delivered through different interfaces should be considered for morbidly obese patients. Anaesthesia ventilators are becoming increasingly sophisticated, integrating many functions that were once prerogative of those used in intensive care. Modern anaesthesia machines provide high performances in delivering accurately and precisely the desired volumes and pressures, including assisted ventilation modes. The physicians should therefore 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 single 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 ideal body weight rather 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 since may lead to hemodynamic impairment and fluid overload. Higher PEEP might be considered during surgery longer than 3 hours, laparoscopy in Trendelenburg position and in patients with Body Mass Index higher than 35
Kg/m\(^2\). Large randomized trials are warranted to identify subgroups of patients and 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 on respiratory muscles activity[2] and the distribution of ventilation and perfusion within the lungs[3]. As a result, more than 230 million of patients receiving a surgical intervention need to be mechanically ventilated each year[4]. During the last decades, a huge increase in knowledge on 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 also for the non-injured lung, in an effort aimed at translating to the wider population the advances made in the Intensive Care[7]. Postoperative pulmonary complications (PPCs) are a major determinant of postoperative morbidity, mortality, length of hospital stay and healthcare 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 postoperative 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 hours, laparoscopy in Trendelenburg position and in patients with Body Mass Index higher than 35 Kg/m$^2$. Ventilators used in the operating room were developed according to the specific requirements of the surgical scenario, thus technology evolved making them 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 started to implement 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 on patient outcome of the availability of these high quality ventilators in the operating theatre and different ventilation modes has to be determined. In the present article we will discuss ventilation strategies at the induction of general anaesthesia and during surgery.

Ventilatory Strategies at the Induction of General Anaesthesia

Pre-oxygenation

At the induction of general anaesthesia, high dose of sedatives and analgesics as well as muscle relaxants are often administered, frequently resulting in complete apnoea. Both during 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 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 the supine position the functional residual capacity (FRC) is reduced, through 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 have a higher reduction in FRC and tend to be more prone to desaturation at the induction of general anaesthesia[17]. In obese patients, respiratory volumes decrease inversely to the increase in body mass index (BMI): in 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-minute
preoxygenation with 100% oxygen delivered through facemask is low, unless the patient has an
elevated metabolic demand, pulmonary pathology or specific predisposing factors [17]. Standard
pre-oxygenation can be inadequate for specific subgroups of patients. Factors predicting
inadequateness of pre-oxygenation were essentially those previously described as risk factors for
difficult mask ventilation: bearded male (OR 9.1), beardless male (OR 2.4), ASA score of 4 (OR 9.1),
ASA score of 2-3 (OR 2.4), lack of teeth (OR 2.4) 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 like the head-up positioning at 25 degrees[22],
ramped position[23], fiberoptic intubation, intubation through laryngeal mask or with a video
laryngoscope[24], have been proposed to overcome difficult intubation, increase the pre-
intubation arterial oxygen tension, as well as the safety margin for airway control in the obese
patient. Pre-oxygenation with high flow humidified nasal cannulae has been described[25], but in
a randomized open label trial this device was not superior to high flow facial mask in reducing the
lowest level of desaturation at induction in hypoxemic patients[26]. In patients with abdominal
sepsis, showing an intrinsically higher oxygen demand, pre-induction incentive spirometry
performed within one hour from induction reduced apnoea time and increased oxygenation in a
randomized trial conducted on 66 patients[27]. For long time the researchers discussed how
preoxygenation with high FiO\textsubscript{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]; nonetheless, the benefits of achieving a good
oxygenation at induction, prolonging the time window for a safe intubation, overwhelm 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 cmH₂O Continuous Positive Airway Pressure (CPAP) alone versus conventional pre-oxygenation through Mapleson type A circuit, in 20 consecutive morbidly obese women, concluding that no clinical advantage in terms of reduction of time-to-desaturation could be achieved with such approach alone[29]. In morbidly obese patients, low-pressure CPAP combined with low-pressure PSV during pre-oxygenation resulted in better oxygenation, compared with neutral-pressure breathing, and prevented desaturation episodes[30, 31]. Delay et al. compared NPPV with 8 cmH₂O PSV and 6 cmH₂O PEEP to conventional pre-oxygenation in 28 morbidly obese patients[32], and found a higher end-tidal O₂ concentration in the NPPV group. Futier et al. studied 66 consecutive obese patients in a randomized trial comparing spontaneous breathing to NPPV alone and NPPV plus preoperative recruitment manoeuvre (RM), showing that NPP alone and with RM improved both gas exchange and FRC compared to standard preoxygenation[33]. More recently, a study on 44 adults scheduled for laparoscopic bariatric surgery found that even low-pressure NPPV (5 cmH₂O PSV and 5 cmH₂O PEEP) was better than neutral-pressure breathing for prevention of oxygen 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, aspiration)[34]. In conclusion, pre-oxygenation can
be considered a safe practice, overwhelming the risks of potential post-operative atelectasis. We suggest that a routine pre-oxygenation at a FiO₂ lower or equal to 0.8 should be used unless a difficult intubation is expected. NPPV should be considered for obese patients.

**Intraoperative Mechanical Ventilation**

Modern anaesthesia ventilators are becoming increasingly sophisticated, integrating many functions that were once prerogative of the ICU ventilators[35]. Table 1 resumes the characteristics of some of the new commercially available anaesthesia machines, including the supported ventilatory modes. Potential indications during anaesthesia of different ventilation modes are illustrated in Table 2. Modern ventilators used in the operating room provide an accurate control on 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 on 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 Reflect, available on FLOW-I series). Piston ventilators allow a tight control on delivered volume, allowing a steeper increase in flow compared to traditional bellows systems, as required by pressure-controlled ventilation modes. Turbine anaesthesia ventilators can optimize closed-circuit ventilation systems, minimizing usage of inhaled agents[36], and bench studies showed 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 postoperative residual curarization, associated with higher
morbidity[38]. Despite this, several surgical interventions can be performed without a complete curarization: the anaesthesiologist should be able to support also partially the respiratory pump in cases in which assisted ventilation can be used 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 Figure 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, being volume the time integral of flow, volume increases linearly until the $V_T$ is achieved, within an allowed inspiratory time. Concerning airway pressure, during inspiration a quasi-linear increase can be seen, until a peak is reached ($P_{peak}$). The relationship between $V_T$ and $P_{peak}$ is the result of the complex interaction between the dynamic airways 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 $C_{rs} = V_T/(P_{peak}-PEEP)$; since in this case $C_{rs}$ is biased by the contribution of airway flow resistance, this measurement is referred to as *dynamic* compliance, and underestimates actual compliance. Modern ventilators allow the operator to set an end-inspiratory pause (Figure 1, central panel), usually set as 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 airways resistance to flow: a rapid decrease in airway pressure can be seen, until a stable
plateau pressure ($P_{\text{plat}}$) is achieved. Therefore, respiratory system compliance can be calculated as

$$C_{rs} = V_T / (P_{\text{plat}} - \text{PEEP})$$

providing a more reliable quasi-static estimation of compliance. An advantage of VCV, making it the first choice of many anaesthesiologists during general anaesthesia, is the fact that minute ventilation is guaranteed. This ensures an 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 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 such range is exceeded, to recall the operator’s attention to possibly modify ventilation settings. As an additional safety measure, ventilators have a pressure limit ($P_{\text{lim}}$ or $P_{\text{max}}$) that stops inspiratory flow once reached. Newer ventilators implement compliance compensation systems that guarantee accuracy of the delivered $V_T$ also for small volumes and at low lung compliance, more efficiently than ventilators only relying on inspiratory flow sensors[40]. Concerning monitoring of patients undergoing VCV, an increase in $P_{\text{peak}}$ can be due to a reduction in $C_{rs}$ or to an increase in airway resistance to flow. In order to discriminate between the two conditions setting an end-expiratory pause is strongly advised (Figure 1).

**Pressure Controlled Ventilation**

Pressure controlled continuous mandatory ventilation (P-CMV or PCV) is widely available, time-cycled, 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 Figure 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, while the pressure-time curve is ideally a square waveform. Since the flow is not constant, the ascending limb of the volume-time curve is not linear, but rather increases slower in the late inspiration phase. Symmetrically to what happens in VCV, in PCV pressure is set and $V_T$ is the result of the interaction between inspiratory pressure, airway resistance and respiratory system compliance. While in PCV a tight control of inspiratory peak pressure is easily achieved, minute ventilation is not guaranteed. The perioperative period is potentially characterized by steep changes of $C_{rs}$: this is the case, for instance, of the rapid modifications in diaphragm distension or relaxation caused by induction or resolution of pneumoperitoneum during laparoscopic abdominal surgery. When these modifications occur during PCV, the variations in $V_T$ can be enough to cause hypoventilation or delivery of inappropriately high, thus potentially harmful[5], tidal volumes. For this reason the clinician must set an acceptable $V_T$ alarm range for the patient, and monitor tightly 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 the gas leaks and gastric insufflation[41]. As shown in Table 3, several small-sampled randomized controlled trials studied the impact of PCV on respiratory mechanics, haemodynamics and gas exchange, as compared to 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], children[47], adult obese[48] and non-obese[49, 50] undergoing laparoscopic cholecystectomy. Results are contradictory, and for obese patients at the moment no strong evidence suggests PCV or VCV[51]. In PCV, both
reduction in compliance and increase in flow resistance always result in a reduction in tidal volume, making more difficult to discriminate the cause leading to $V_T$ reduction.

**Dual Controlled Ventilation**

Recently, the advances in technology made available on some new anaesthesia machines new ventilation modes, trying to combine 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), pressure regulated volume control (PRVC, Maquet). These ventilation modes are structurally very similar, and 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 (Figure 1, right panel), calculates $C_{rs}$ at each breath cycle and readapts inspiratory pressure in order to obtain the $V_T$ set by the clinician. All the algorithms deliver a first volume-controlled breath at a constant inspiratory flow in order to make an initial estimation of $C_{rs}$ and the pressure needed to reach the volume target. These ventilation modes are only recently made widely available on anaesthesia machines, and very few studies investigated their potential advantages, especially in one-lung ventilation, where a tight control on both pressure and volume is mandatory[52]. Even if the actual impact of dual-controlled ventilation on clinical outcomes is still to be determined, there is an undoubted clinical advantage in having the ability to use 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 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 intermittently mandatory ventilation (SIMV) is a hybrid ventilation mode, it can be either pressure or volume controlled, and can play a role in the operating room as it can guarantee the minute ventilation, thus gas exchange, while allowing the patient to trigger assisted breaths. With SIMV, when 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 could be considered for patients with a residual ventilatory drive. The machine tries to synchronize the respiratory efforts of the patient with the time-cycled mandatory breaths, and the clinician has to set a trigger window, as percentage of the expiratory time, during which the flow trigger senses for inspiratory effort. In addition to the role always described for pre-oxygenation, Pressure Support Ventilation (PSV) is now available in many commercially available anaesthesia machines, and can be used, for instance, for patients undergoing minor surgery, patients deeply sedated after loco-regional anaesthesia or at the emergence from general anaesthesia. Ventilators designed for the operating room, often offer PSV with safety backup ventilation, in order to provide the patient with mandatory ventilation in case of suppression of the respiratory drive, as occurs after a deepening of sedation or an opioid bolus. In a recent study on 36 patients scheduled for knee arthroscopic surgery under general anaesthesia with laryngeal mask, PSV reduced emergence time, propofol consumption and air leaks compared to VCV[53]. The use of CPAP at recovery from general anaesthesia has also been proposed in a pilot study to reduce the incidence of postoperative atelectasis[54]. Newer high-level ventilators also offer even more sophisticated ventilation modes, derived from ICU ventilators (Table 2). These modes can be used for the surgery of the critically ill patient requiring protective ventilation, especially in 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 $P_{\text{plat}}$ and intrinsic PEEP ($\text{PEEP}_i$). Especially in cases where an end-expiratory pause cannot be set, precious information can be derived from the interpretation of the flow-volume loop. As illustrated in Figure 2, the flow-volume loop, available also on older ventilators, can help the clinician to distinguish flow limitations due to airway collapse, that might benefit from higher PEEP levels, from conditions of airway thickening, where higher PEEP might be counterproductive.

The Role of Tidal Volume, PEEP and Recruitment Manoeuvres

The last years were characterized by the increasing tendency to translate to the operating room the advances in the mechanical ventilation of the injured lung in the ICU. A role of protective ventilation in the operating room is still to be definitely 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 recruitment manoeuvres were used in the intervention group and compared to conventional ventilation. These studies were focused mainly in laparoscopic only [56-60] and laparoscopic or open major abdominal surgery[10, 11, 13, 61]. Results are conflicting: in several small studies a strategy combining lower tidal volume, higher PEEP and recruitment manoeuvres improved intraoperative gas exchange[56-60], respiratory mechanics[10, 57, 59, 61], but improved postoperative outcomes only in some studies[10, 58, 59], while others did not find differences[57, 61] or did not investigate the patients postoperatively[56, 60]. A large retrospective analysis on 29343 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 seems to be associated with a higher risk of 30-day mortality[62]. The retrospective design of this
study limits the interpretation of these results. Futier et al., in a large RCT on 400 patients undergoing abdominal surgery, found that a ventilatory strategy including low $V_T$, routine use of PEEP and recruitment manoeuvres improved a composite outcome of pulmonary and extra-pulmonary postoperative complications[11]. In another large RCT carried out by the PROVE Network Investigators for the Clinical Trial Network of the European Society of Anaesthesiology on 900 surgical patients, investigated the role of low PEEP alone versus high PEEP plus recruitment manoeuvres alone, maintaining the same $V_T$ in the two arms, concluding that the latter strategy increased intraoperative hypotension, use of vasoactive drugs, without any modification of the incidence of PPCs[13].

**Recruitment Manoeuvres Techniques**

Recruitment manoeuvres can be performed in several ways, as illustrated in Figure 2. Most clinicians perform recruitment with the “bag squeezing” technique: the ventilator is switched in manual mode, the adjustable pressure limiting (APL) valve set to 30 or 40 cmH$_2$O, the patient kept at a constant pressure manually then switched back to mechanical ventilation (Figure 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 (Figure 3b), but unfortunately most of the anaesthesia machines do not have CPAP or is only available as option (Table 1). Relying on ventilatory settings, avoiding switching to manual ventilation, can give more reproducible and effective results. One strategy can be increasing PEEP during VCV without modifying $V_T$, in steps of 5 cmH$_2$O, until a plateau pressure of 30 or 40 cmH$_2$O is achieved. Subsequently, PEEP can be decreased in steps of 2 cmH$_2$O in a decremental PEEP trial or cycling
manoeuvre[63] (Figure 3c). If the clinician wants to set PEEP at the level providing the optimal Crs, after the stepwise decrease a second recruitment manoeuvre must be performed. A potential limitation of this technique is that some new anaesthesia machine (Table 1) limits maximum PEEP to 20 cmH$_2$O, thus for some patients could be difficult to reach the desired plateau pressure.

Recently, a manoeuvre based on changes of tidal volume has been used in a randomized trial[13] (Figure 3d). In this technique, PEEP is increased to the desired level, and then $V_T$ increased until a plateau pressure of 30 or 40 cmH$_2$O, held for few respiratory cycles, and then set again to the desired volume. Some new anaesthesia machines implement automated cycling recruitment manoeuvres. The clinician should be aware that in morbidly obese patients, the conventional recruitment pressure of 30 to 40 cmH$_2$O might be inadequate in order to fully recruit the lung: pressures up to 60 cmH$_2$O might be required[61].

**Summary**

Mechanical ventilation for patients undergoing general anaesthesia is an increasingly complex and safe procedure. Many improvements have been introduced in the last decades due to the advances both in technology and knowledge. Intraoperative ventilation setting has been recently proved to impact on clinical outcome. Given the high number of surgical interventions made worldwide nowadays, even small improvements in postoperative complications due to better ventilatory strategies may affect a high number of patients, reduce healthcare costs and contribute to a better clinical outcome.
Practice Points

• Mechanical ventilation during general anaesthesia is a safe practice, but ventilatory settings alone has an impact on the clinical outcome
• Tidal volume should be set according to the predicted or ideal body weight
• Pre-oxygenation 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 impact on clinical outcome of emerging ventilations modes are warranted
• Future studies should identify subgroups of patients that might benefit from routine PEEP administration and recruitment manoeuvres

Figure Legends

Figure 1: Flow, Pressure and Volume curves for the three most commonly used controlled ventilation modes in the operating room.

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].
Figure 2: 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.
## Tables

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Model</th>
<th>Ventilator type</th>
<th>Modes of ventilation</th>
<th>Optional modes of ventilation</th>
<th>Tidal volume (mL)</th>
<th>Respiratory rate (breaths/min)</th>
<th>Inspiratory flow (L/m)</th>
<th>Pressure limit (cmH2O)</th>
<th>PEEP (cmH2O)</th>
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<tr>
<td>Drager Medical</td>
<td>Perseus A500</td>
<td>Turbine</td>
<td>Manual/spontaneous, PC-CMV, PC-BIPAP, VC-CMV, VC-CMV/AF, VC-SIMV/AF</td>
<td>CPAP/PS, PC-BIPAP/PS, VC-SIMV/AF/PS, PC-APRV</td>
<td>20 to 2000</td>
<td>3 to 100</td>
<td>0 to 180</td>
<td>7 to 80</td>
<td>Off, 2 to 35</td>
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<tr>
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<td>Apollo</td>
<td>Piston</td>
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<td>3 to 100</td>
<td>0 to 150</td>
<td>up to 70</td>
<td>0 to 20</td>
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<td>Ascending bellows</td>
<td>VC-CMV</td>
<td>PC-CMV, PCV-VG, VC/PC/VG/SIMV, CPAP/PS</td>
<td>20 to 1500</td>
<td>4 to 100</td>
<td>0 to 120</td>
<td>12 to 100</td>
<td>Off, 4 to 30</td>
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<td>Saturn Evo</td>
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<td>10 to 1600</td>
<td>4 to 80</td>
<td>Not specified</td>
<td>7 to 99</td>
<td>0 to 20</td>
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<tr>
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<td>Ascending bellows</td>
<td>VC-CMV, PC-CMV</td>
<td>PS</td>
<td>20 to 1500</td>
<td>2 to 99</td>
<td>up to 100</td>
<td>10 to 70</td>
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<tr>
<td>Maquet</td>
<td>FLOW-i Volume Reflector</td>
<td>Manual/spontaneous, VC-CMV, PC-CMV</td>
<td>PS, PRVC, SIMV</td>
<td>PS</td>
<td>20 to 2000</td>
<td>4 to 100</td>
<td>0 to 200</td>
<td>0 to 120</td>
<td>0 to 50</td>
</tr>
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</table>

**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 on the manufacturers’ website on April 2015.
<table>
<thead>
<tr>
<th>Mode</th>
<th>Type</th>
<th>Details</th>
<th>Use in anaesthesia</th>
</tr>
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<tbody>
<tr>
<td>V-CMV (volume continuous mandatory ventilation), VCV (volume controlled ventilation)</td>
<td>Mandatory</td>
<td>Controlled ventilation, targeted on tidal volume, time-cycled</td>
<td>Most common mode of ventilation, provides good control of tidal volume, especially with modern anaesthesia machines that provide compliance compensation.</td>
</tr>
<tr>
<td>P-CMV (pressure continuous mandatory ventilation), PCV (pressure controlled ventilation)</td>
<td>Mandatory</td>
<td>Controlled ventilation, targeted on airway pressure, time-cycled</td>
<td>Common mode of ventilation, provides better 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.</td>
</tr>
<tr>
<td>VCV/V-CMV with VG (pressure guaranteed), AF (autoflow) or PRVC (pressure regulated volume controlled)</td>
<td>Mandatory</td>
<td>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.</td>
<td>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.</td>
</tr>
<tr>
<td>V or P-ACV (volume or pressure assisted controlled ventilation)</td>
<td>Mandatory / Assisted</td>
<td>Delivers the desired volume or pressure target both automatically or upon patient’s inspiratory effort.</td>
<td>Can be used in patients with residual respiratory drive to assist spontaneous breathing without risking apnoea.</td>
</tr>
<tr>
<td>V or P-SIMV (volume or pressure synchronized intermittent mandatory ventilation)</td>
<td>Mandatory / Assisted</td>
<td>Delivers the desired mandatory volume or pressure, plus an assisted volume or pressure when an inspiratory effort is detected within a sensing window.</td>
<td>Similar to V/P-ACV, can be used in patients having a residual respiratory drive, or during emergence from general anaesthesia.</td>
</tr>
<tr>
<td>PSV (pressure support ventilation)</td>
<td>Assisted</td>
<td>Delivers a target pressure when an inspiratory effort is detected.</td>
<td>In patients with a respiratory drive, in presence of restrictive lung disease, induction of general anaesthesia, neuromuscular disease, weaning from controlled ventilation.</td>
</tr>
<tr>
<td>CPAP</td>
<td>Assisted</td>
<td>Increases mean airway pressure in spontaneously breathing patients</td>
<td>At induction, to avoid excessive loss of FRC / EELV, can decrease inspiratory effort in intubated patients, before extubation.</td>
</tr>
</tbody>
</table>

**Table 2.** Main ventilation modes used in the operating room (readapted from Principles and Practice of Mechanical Ventilation, 3rd edition)[35].
Table 3. Studies comparing VCV and PCV during general anaesthesia. Outcomes are reported as PCV vs. VCV with VCV as control group. PaCO₂ arterial carbon dioxide pressure, PaO₂ arterial oxygen pressure, PAO₂ alveolar oxygen pressure, BMI body mass index, N/A not assessed.

<table>
<thead>
<tr>
<th>Study</th>
<th>Number</th>
<th>Patients</th>
<th>Laparoscopic</th>
<th>Surgery</th>
<th>Airway</th>
<th>Ppeak</th>
<th>Compliance</th>
<th>Haemodynamics</th>
<th>Gas Exchange</th>
</tr>
</thead>
<tbody>
<tr>
<td>De Baerdemaeker 2008</td>
<td>24</td>
<td>Morbidly obese</td>
<td>Yes</td>
<td>Gastric banding</td>
<td>Tracheal Tube</td>
<td>=</td>
<td>=</td>
<td>=</td>
<td>↑PaCO₂</td>
</tr>
<tr>
<td>Hans 2008</td>
<td>40</td>
<td>Morbidly obese</td>
<td>No</td>
<td>Gastric bypass</td>
<td>Tracheal Tube</td>
<td>↓</td>
<td>=</td>
<td>=</td>
<td>=</td>
</tr>
<tr>
<td>Cadi 2008</td>
<td>36</td>
<td>BMI&gt;35 kg/m²</td>
<td>Yes</td>
<td>Gastric banding</td>
<td>Tracheal Tube</td>
<td>=</td>
<td>=</td>
<td>=</td>
<td>↑PaO₂ ↓PCO₂</td>
</tr>
<tr>
<td>Oğurlu 2010</td>
<td>60</td>
<td>Women, ASA I and II</td>
<td>Yes</td>
<td>Gynecologic surgery</td>
<td>Tracheal Tube</td>
<td>↓</td>
<td>↑</td>
<td>=</td>
<td>N/A</td>
</tr>
<tr>
<td>Jeon 2011</td>
<td>60</td>
<td>Women</td>
<td>Yes</td>
<td>Gynecologic surgery</td>
<td>Laryngeal Mask</td>
<td>↓</td>
<td>=</td>
<td>=</td>
<td>↓PaCO₂</td>
</tr>
<tr>
<td>Tyagi 2011</td>
<td>42</td>
<td>BMI&lt;30 kg/m²</td>
<td>Yes</td>
<td>Cholecystectomy</td>
<td>Tracheal Tube</td>
<td>↓</td>
<td>↑</td>
<td>=</td>
<td>=</td>
</tr>
<tr>
<td>Kim 2011</td>
<td>34</td>
<td>Children</td>
<td>Yes</td>
<td>Appendicectomy</td>
<td>Tracheal Tube</td>
<td>↓</td>
<td>↑</td>
<td>=</td>
<td>N/A</td>
</tr>
<tr>
<td>Gupta 2012</td>
<td>102</td>
<td>ASA I and II, Obese (BMI 30-40 kg/m²)</td>
<td>Yes</td>
<td>Cholecystectomy</td>
<td>Tracheal Tube</td>
<td>↓</td>
<td>N/A</td>
<td>=</td>
<td>↑PaO₂</td>
</tr>
<tr>
<td>Aydin 2014</td>
<td>70</td>
<td>ASA I and II</td>
<td>Yes</td>
<td>Cholecystectomy</td>
<td>Tracheal Tube</td>
<td>=</td>
<td>=</td>
<td>=</td>
<td>↓PAO₂-PaO₂</td>
</tr>
</tbody>
</table>

Table 3. Studies comparing VCV and PCV during general anaesthesia. Outcomes are reported as PCV vs. VCV with VCV as control group. PaCO₂ arterial carbon dioxide pressure, PaO₂ arterial oxygen pressure, PAO₂ alveolar oxygen pressure, BMI body mass index, N/A not assessed.
### Table 4. Recent RCTs investigating the effect of PEEP, Recruitment Manoeuvres and Tidal Volume on clinical outcomes.

<table>
<thead>
<tr>
<th>Study</th>
<th>Total</th>
<th>Procedure</th>
<th>Pressure</th>
<th>Recruitment</th>
<th>Tidal Volume</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reinus 2009[61]</td>
<td>30</td>
<td>Bariatric surgery</td>
<td>0+R</td>
<td>10</td>
<td>10+R</td>
<td>Improved compliance</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10</td>
<td></td>
<td>No effect</td>
</tr>
<tr>
<td>Kim 2010[59]</td>
<td>30</td>
<td>Laparoscopic cholecystectomy</td>
<td>0</td>
<td>8</td>
<td>5+R</td>
<td>Improved oxygenation, compliance</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8</td>
<td></td>
<td>Improved oxygenation, reduced atelectasis</td>
</tr>
<tr>
<td>Futier 2013[11]</td>
<td>400</td>
<td>Abdominal surgery</td>
<td>0</td>
<td>10 to 12</td>
<td>6 to 8+R</td>
<td>Reduced peak pressure, improved compliance</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6 to 8</td>
<td></td>
<td>Reduced major complications within 7 days from surgery</td>
</tr>
<tr>
<td>Severgnini 2013[10]</td>
<td>56</td>
<td>Abdominal surgery</td>
<td>0</td>
<td>9</td>
<td>10 + R</td>
<td>Reduced plateau pressure</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Improved PFT, CXR</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>No effect on PPC incidence</td>
</tr>
<tr>
<td>Baki 2014[60]</td>
<td>60</td>
<td>Laparoscopic surgery</td>
<td>0</td>
<td>10</td>
<td>5</td>
<td>Improved gas exchange</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6</td>
<td>N/A</td>
</tr>
</tbody>
</table>

manoeuvres, PPC post-operative pulmonary complications, PBW predicted body weight, N/A not assessed, PFT pulmonary functional tests, CXR chest X-ray
Conflict of interest statement

None.

References


22. Dixon BJ, Dixon JB, Carden JR et al. Preoxygenation is more effective in the 25 degrees head-up position than in the supine position in severely obese patients: a randomized controlled study. *Anesthesiology* 2005;102: 1110-5; discussion 5A.


63. Tusman G, Bohm SH, Suarez-Sipmann F et al. Lung recruitment and positive end-expiratory pressure have different effects on CO2 elimination in healthy and sick lungs. Anesth Analg 2010;111: 968-77.
Inspiration

Expiration

Flow (L/min)

Volume (ml)

Normal

Airway Collapse

Airway Narrowing

Inspiration

Expiration

Flow (L/min)

Volume (ml)

Normal Airway Collapse Airway Narrowing
a) Bag Squeezing

b) CPAP

c) Cycling Manoeuvre

d) Stepwise $V_T$ changes