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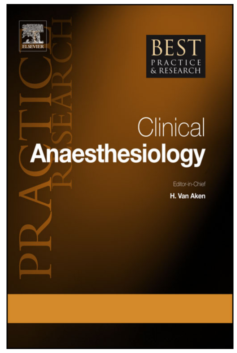

Modes of Mechanical Ventilation for the Operating Room

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Modes of Mechanical Ventilation for the Operating Room

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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.

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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_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 cmH_2O 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 cmH_2O PSV and 6 cmH_2O PEEP to conventional pre-oxygenation in 28 morbidly obese patients[32], and found 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 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 cmH_2O PSV and 5 cmH_2O 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 FiO_2 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 Reflector, 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 $C_{rs} = V_T/(P_{peak}\text{-PEEP})$; 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_{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, 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_{lim} or P_{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_{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 Crs 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 Crs 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 intermitted 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_{plat} and intrinsic PEEP ($PEEP_i$). 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_2O, 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_2O, until a plateau pressure of 30 or 40 cmH_2O is achieved. Subsequently, PEEP can be decreased in steps of 2 cmH_2O 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_2O, 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_2O, 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_2O might be inadequate in order to fully recruit the lung: pressures up to 60 cmH_2O 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

Manufacturer	Model	Ventilator type	Modes of ventilation	Optional modes of ventilation	Tidal volume (mL)	Respiratory rate (breaths/min)	Inspiratory flow (L/m)	Pressure limit (cmH2O)	PEEP (cmH2O)
Drager 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 to 2000	3 to 100	0 to 180	7 to 80	Off, 2 to 35
Drager Medical	Apollo	Piston	Manual/spontaneous, VC-CMV, PC-CMV	PS, VC-CMV/AF	20 to 1400	3 to 100	0 to 150	up to 70	0 to 20
GE Healthcare	Aisys CS2	Ascending bellows	VC-CMV	PC-CMV, PCV-VG, VC/PC/VG-SIMV, CPAP/PS	20 to 1500	4 to 100	0 to 120	12 to 100	Off, 4 to 30
MEDEC	Saturn Evo	Horizontal bag-in-bottle bellows	VC-CMV, VC-SIMV, PC-CMV, PC-SIMV	PS	10 to 1600	4 to 80	Not specified	7 to 99	0 to 20
Spacelabs Healthcare	Blease e900	Ascending bellows	VC-CMV, PC-CMV, SIMV	PS	20 to 1500	2 to 99	up to 100	10 to 70	3 to 20
Maquet	FLOW-i	Volume Reflector	Manual/spontaneous, VC-CMV, PC-CMV	PS, PRVC, SIMV	20 to 2000	4 to 100	0 to 200	0 to 120	0 to 50

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.

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 having a residual respiratory drive, or during emergence 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.

Table 2. Main ventilation modes used in the operating room (readapted from Principles and Practice of Mechanical Ventilation, 3rd edition)[35].

Study	Number	Patients	Laparoscopic	Surgery	Airway	Ppeak	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	Gynecologic surgery	Tracheal Tube	↓	↑	=	N/A
Jeon 2011[46]	60	Women	Yes	Gynecologic 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

Table 3. Studies comparing VCV and PCV during general anaesthesia. Outcomes are reported as PCV vs. 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

			Control group		Intervention group		Intraoperative outcomes	Post-operatory outcomes
Study	Number	Patients	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 to 10	5 and 10	8 to 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 cholecystecto my	0	8	5 10+R	8	Improved oxygenation, compliance	Improved oxygenation, reduced atelectasis
Futier 2013[11]	400	Abdominal surgery	0	10 to 12	6 to 8 + R	6 to 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

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

Conflict of interest statement

None.

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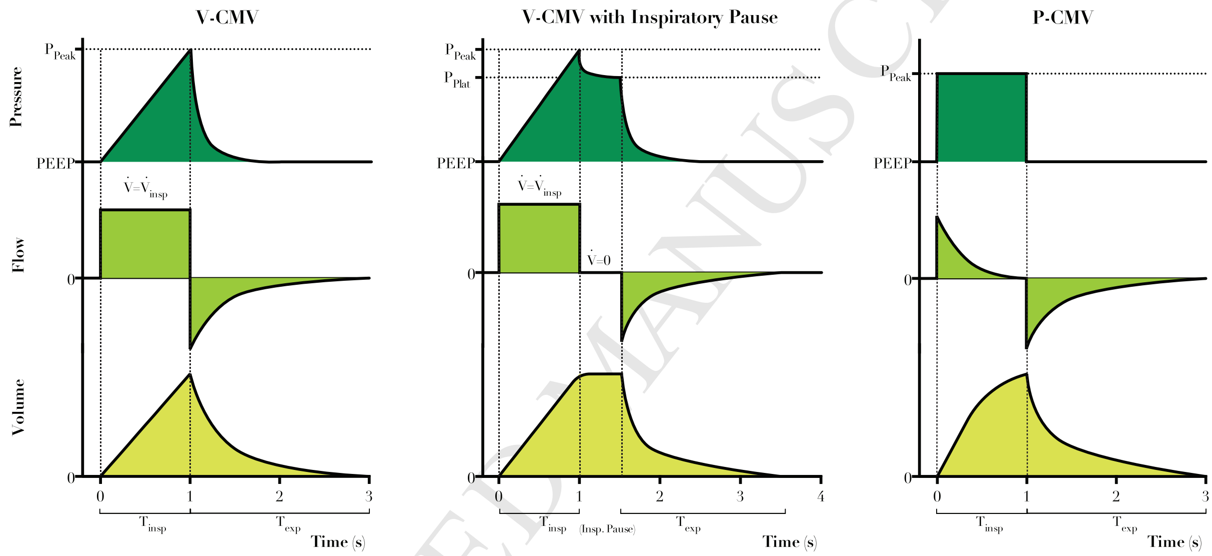

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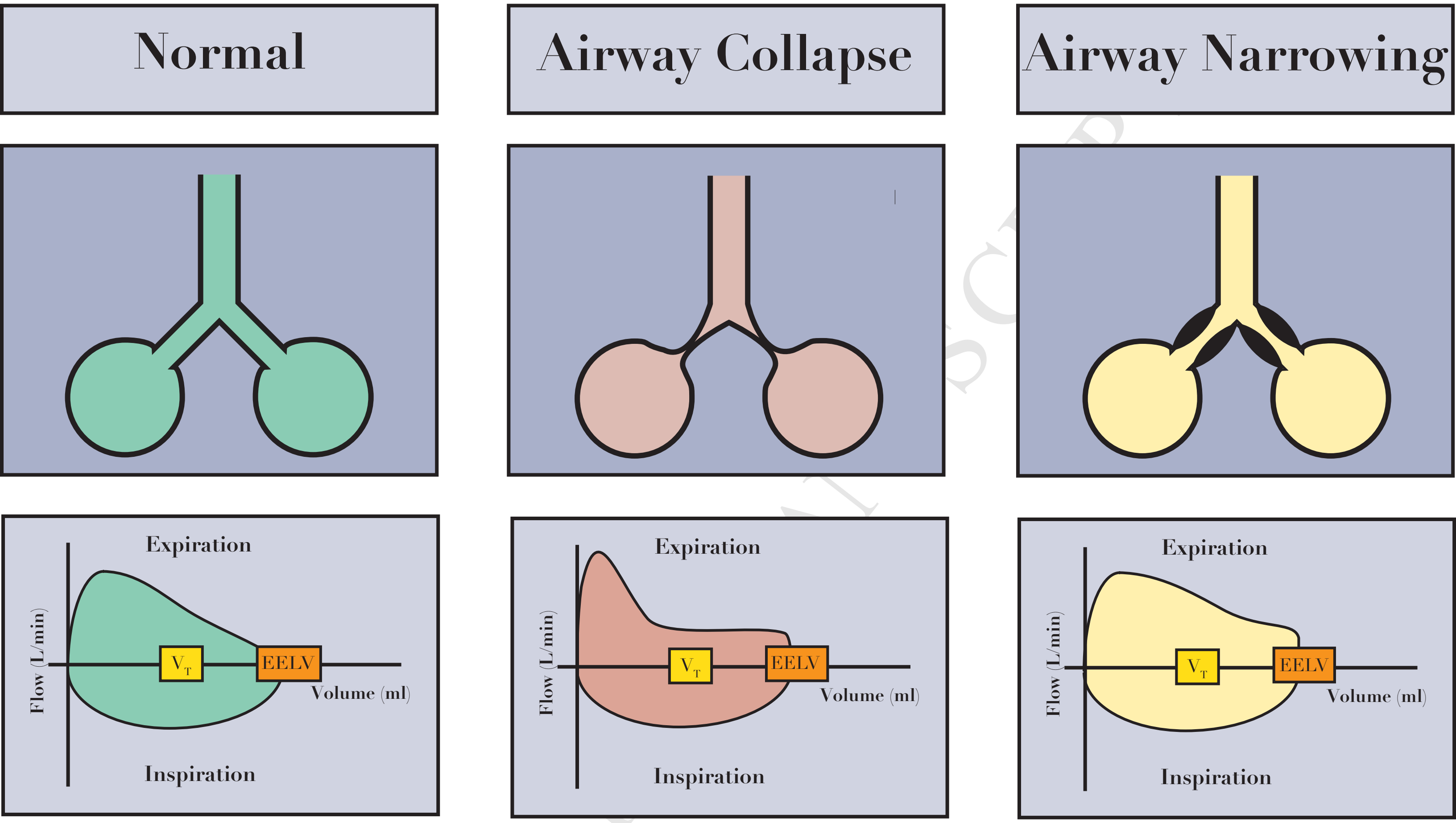
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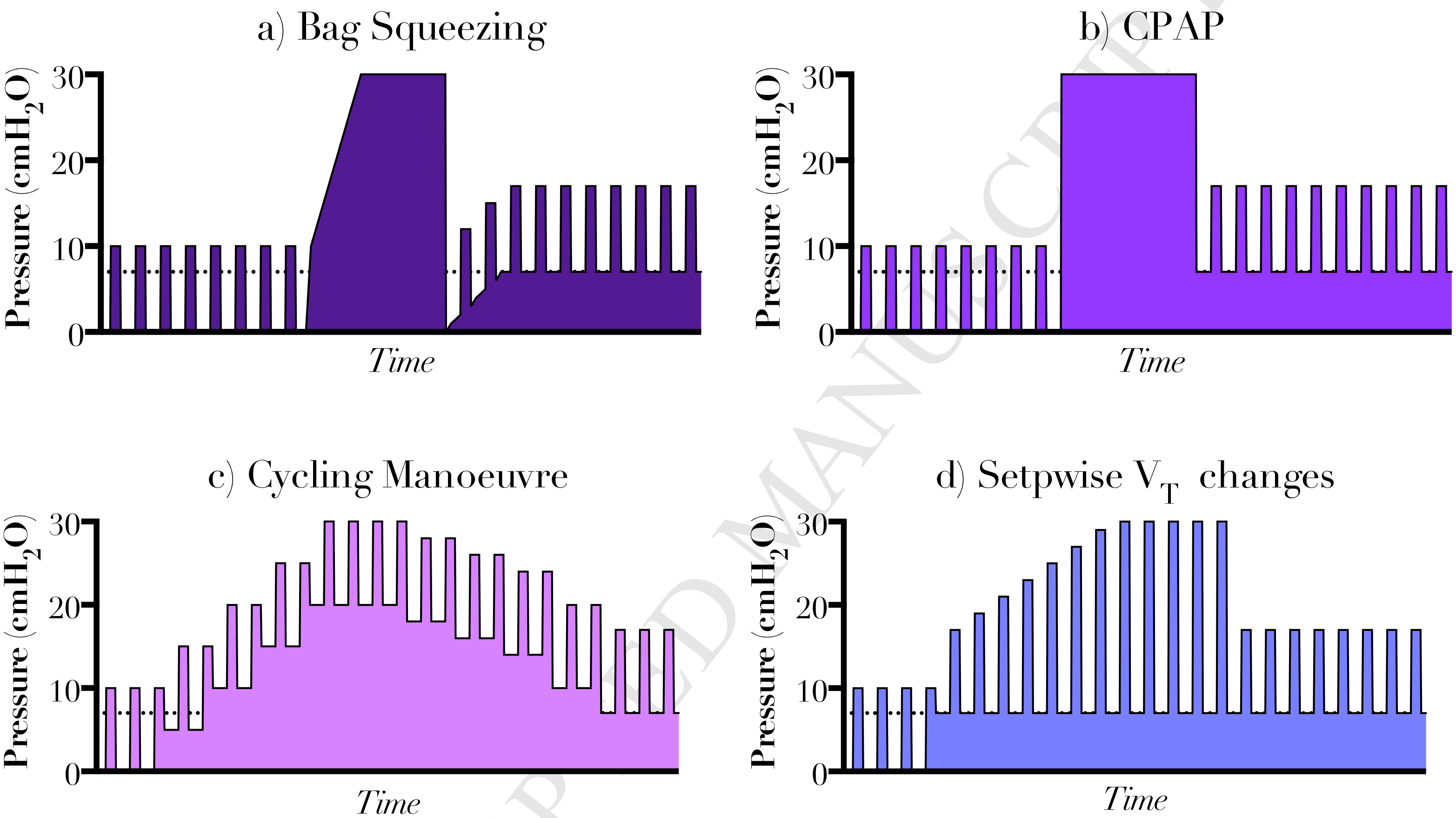
a) Bag Squeezing
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