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Special Article

RESPIRATION AND THE AIRWAY

Lung-protective ventilation for the surgical patient: international expert panel-based consensus recommendations

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Summary

Postoperative pulmonary complications (PPCs) occur frequently and are associated with substantial morbidity and mortality. Evidence suggests that reduction of PPCs can be accomplished by using lung-protective ventilation strategies intraoperatively, but a consensus on perioperative management has not been established. We sought to determine recommendations for lung protection for the surgical patient at an international consensus development conference. Seven experts produced 24 questions concerning preoperative assessment and intraoperative mechanical ventilation for patients at risk of developing PPCs. Six researchers assessed the literature using questions as a framework for their review. The modified Delphi method was utilised by a team of experts to produce recommendations and statements from study questions. An expert consensus was reached for 22 recommendations and four statements. The following are the highlights: (i) a dedicated score should be used for preoperative pulmonary risk evaluation; and (ii) an individualised mechanical ventilation may improve the mechanics of breathing and respiratory function, and prevent PPCs. The ventilator should initially be set to a tidal volume of 6–8 ml kg^{-1} predicted body weight and positive end-expiratory pressure (PEEP) 5 cm H_2O. PEEP should be individualised thereafter. When recruitment manoeuvres are performed, the lowest effective pressure and shortest effective time or fewest number of breaths should be used.

Keywords: adverse effects; lung injury; perioperative; positive end-expiratory pressure; positive-pressure respiration; postoperative pulmonary complications; tidal volume

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Editor's key points

- Expert consensus-based recommendations were produced to reduce pulmonary complications after surgery.
- Low tidal ventilation (6–8 ml kg^{-1}) and PEEP (5 cm H_2O) should be used initially.
- Alveolar recruitment manoeuvres are beneficial in reopening collapsed alveoli and improving lung mechanics.

Postoperative pulmonary complications (PPCs) account for substantial morbidity and mortality. The incidence of PPCs varies according to definition and type of surgery, and has been reported to range from 5% to 33%.[1,2] The 30 day mortality rate for patients who develop PPCs can be as high as 20%.[1] Recent reviews have highlighted the growing evidence that lung-protective ventilation, consisting of low tidal volumes (V_T), application of PEEP, and use of alveolar recruitment manoeuvres (ARMs), can reduce PPCs.[3,4] More recently, high ventilator driving pressure (ΔP=plateau pressure [P_{plat}]−PEEP) has been recognised as a significant determinant of lung injury[5] and is linked to PPCs.[6] Despite evidence of harm, a large proportion of patients continue to receive high V_T mechanical ventilation with a wide range of PEEP and frequently elevated ΔP.[7,8]

Many factors may play a role in lung-protective ventilation, yet a consensus in the literature concerning the key clinical question of how to best provide lung protection during mechanical ventilation in surgical patients is lacking. For this reason, a multidisciplinary panel with expertise in perioperative care of mechanically ventilated patients was convened with the aim of developing consensus-based recommendations. As the practice of intraoperative mechanical ventilation varies widely in the published literature and amongst practitioners, a consensus-building approach from experts representing six countries in both Europe and North America was thought to best identify areas of agreement. The panel sought to first produce questions regarding preoperative pulmonary risk assessment and characteristics of intraoperative lung-protective ventilation. The current literature was then reviewed to provide evidence-based guidance in response to the identified questions and, in the absence of sufficient clinical data, an expert opinion was solicited. Subsequently, the panel convened and established consensus-based recommendations using the modified Delphi method. The Delphi method is a consensus-building method that is based upon a structured, iterative communication amongst content experts. The modified method allows for an expert discussion during the final round. Their combined contributions can help resolve complex clinical issues. It was used as a decision tool to efficiently identify best practices in protective lung ventilation whilst allowing for the experts to contribute their distinct perspectives.

Methods

Research/expert teams and main topics

The president of the coordinating team (CCY) discussed the development of lung-protective-ventilation practice recommendations with the meeting sponsor (GE Healthcare). The meeting sponsor agreed to assist with establishing a consensus conference. The president and sponsor identified individuals who were subsequently invited to participate in the consensus meeting. The selection criteria for the experts included previous publications in the field of intraoperative ventilation, demonstrated knowledge and interest in lung-protective strategies, and ability to participate in all pre-meeting teleconferences and a 1 day face-to-face meeting.

Seven experts (MGA, EF, MG, EMH, JPM, PP, and JS) from six countries agreed to serve on the panel for this consensus meeting. It has been suggested that between 5 and 10 experts are required for content validation,[9] and that a 'suitable minimum size' for an expert panel is seven.[10]

The coordinating team (CCY and CV) and experts generated, reviewed, and approved 24 questions on perioperative mechanical ventilation (Supplementary Table S1). A content-validity universal agreement was not directly measured. However, the use of participants who have knowledge and interest in the topic increases the content validity of the Delphi method, and the use of successive rounds in the development of the questionnaire likewise improves validity.[11]

A team of six researchers (SB, BB, RRDE, JM, CR, and BT) evaluated the existing literature for each question. A literature search was conducted in order to identify any additional topics of interest.

Processing literature

Research questions were used as guidance for literature searches conducted by a research librarian (AW). The search strategy combined subject headings and keywords for anaesthesia, surgery or perioperative care, and lung-protective ventilation in adults. A systematic literature search on each subject was performed by searching PubMed, Embase, and the Cochrane Central Register of Controlled Trials from inception to July 18, 2018 (Supplementary Table S2). Observational and experimental studies, and also literature reviews, systematic reviews, and meta-analyses written in English were included. The authors chose to include a clinically important, late-breaking randomised trial in the discussion even though it was not published until June 2019.[12]

All articles were screened and reviewed by teams of two for eligibility based on title and abstract (Fig. 1). Rayyan software (https://rayyan.qcri.org) was used as a screening tool to facilitate blind screening within the teams.[13] Every citation was reviewed by two members of the research team using the same inclusion criteria. Any conflicts in including or excluding articles were resolved through a discussion within the research teams.

Eligible full-text articles were obtained and categorised according to sub-questions developed for each topic. They were summarised and evaluated according to the Grading of Recommendations Assessment, Development and Evaluation (GRADE) system,[14] which systematically evaluates the available literature and focuses on the level of evidence based upon the types of studies included.

Each research team worked with one of the experts to formulate recommendations for their sub-questions based on the available literature and the input of their assigned expert. The quality of the evidence was evaluated according to the GRADE system, and assigned as 'high' (⊠⊠⊠⊠), 'moderate' (⊠⊠⊠), 'low' (⊠⊠), or 'very low' (⊠). The strength of the recommendation was based on judgement of the level of evidence, and reported as weak or strong. Expert and researcher teams produced recommendations for presentation at the face-to-face meeting. When the literature was insufficient to

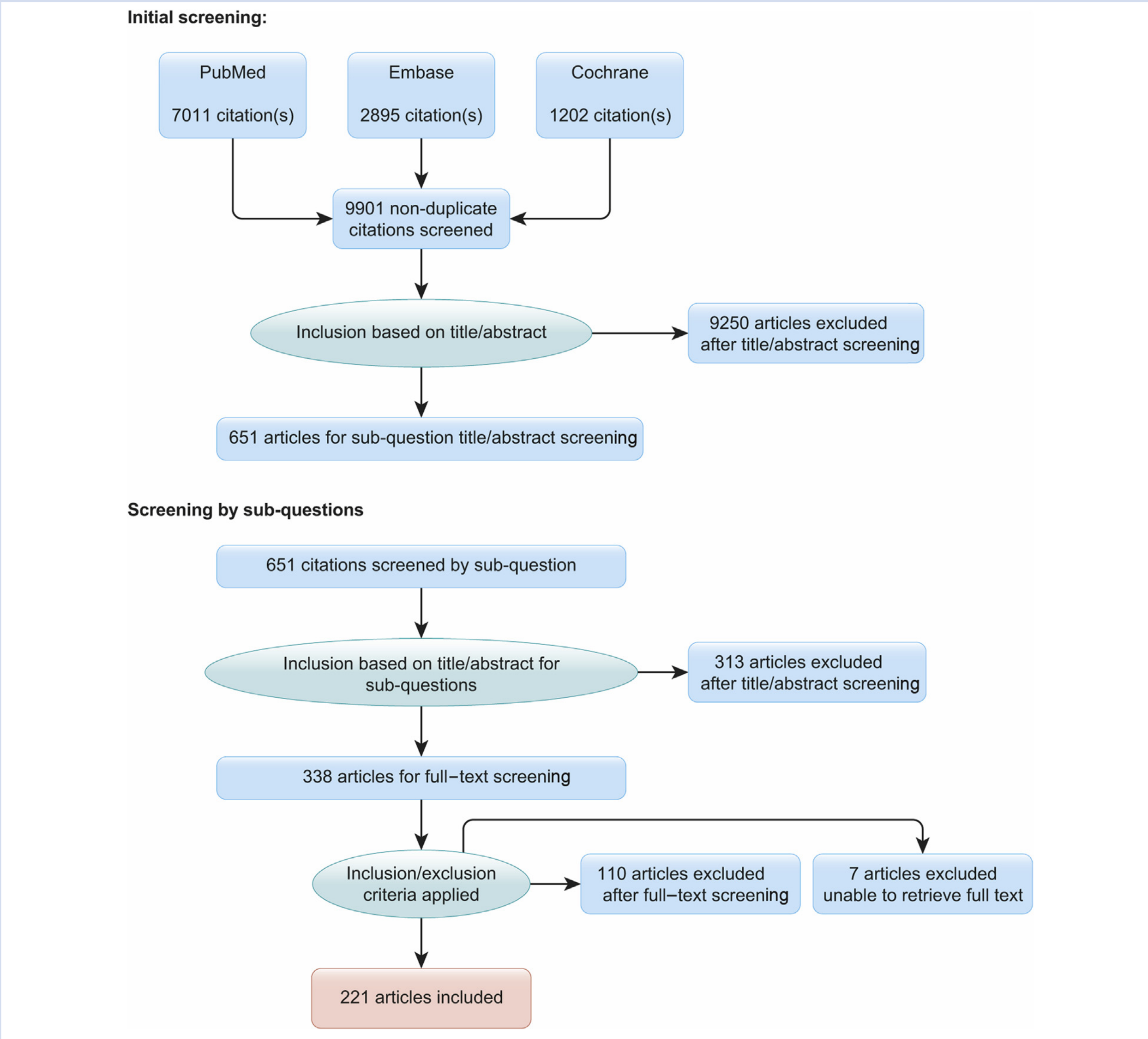

Fig 1. PRISMA flow diagram. Each search term underwent a systematic review using PubMed, Embase, and the Cochrane Central Register of Controlled Trials from inception to July 18, 2018. Then, 651 eligible full-text articles were obtained and categorised. After question development for each topic, the relevant full-text articles were summarised and evaluated according to the GRADE system; 221 articles were included in the final development of the lung-protective ventilation recommendations. PRISMA, preferred reporting items for systematic reviews and meta-analyses.

provide a recommendation, the expert was asked to provide an opinion (Fig. 2).

Throughout the article, recommendations or statements are referred to by their main topic and sub-question. For example, Topic 1 (pulmonary risk assessment) and Question 1 (factors that increase risk of PPCs) are denoted as (Q1.1). The results of every question are displayed in Tables 1–3.

Consensus meeting

The consensus meeting, held in Frankfurt, Germany on October 1, 2018, was organised according to a modified Delphi methodology referred to as the 'Amsterdam Delphi method'.[15] The key components of the Delphi method include iteration (two rounds), controlled acquisition of feedback, and aggregation of responses. The modified Delphi method was chosen because it allowed for expert interaction in the final round. This allowed members of the panel to provide further clarification on some matters and present arguments in order to justify their viewpoints. Anonymity, which is a component of the original Delphi method, was not feasible in this setting, and hence the 'modified' method was implemented. After displaying the recommendations, the experts voted their agreement or disagreement. Refraining from voting was not allowed. No discussion was allowed between the experts at this point. If 100% consensus was reached during the first round of voting, the recommendation was accepted without further voting or discussion. When the experts were not in full

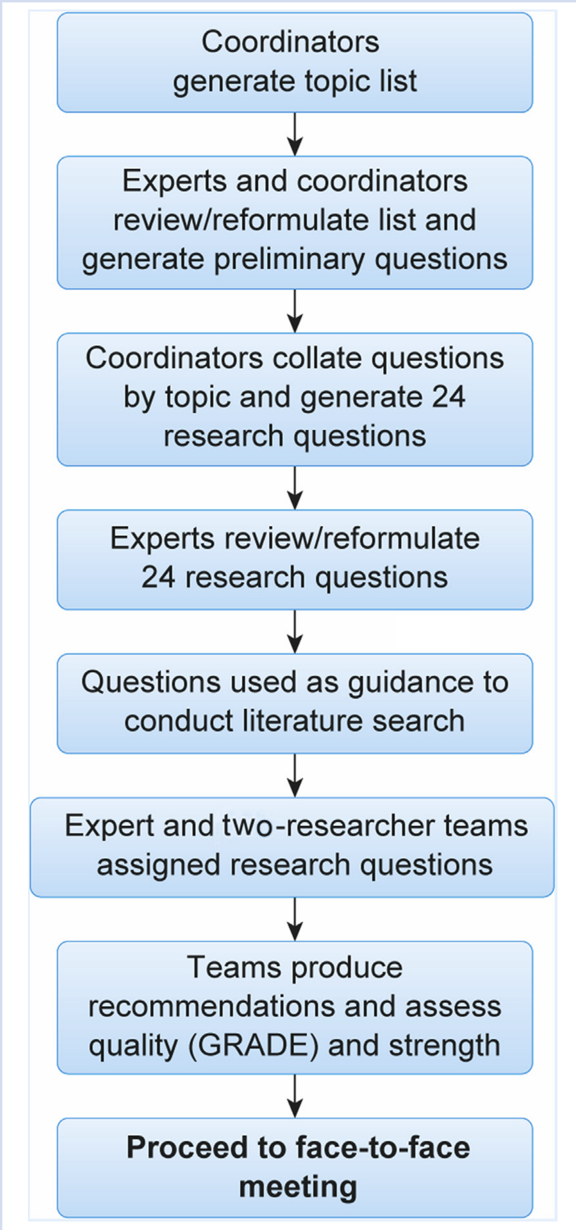

Fig 2. Initial development of recommendations flow chart. Experts developed preliminary questions and expert/researcher teams produced recommendations based upon literature review and quality assessment using the Grading of Recommendations Assessment, Development and Evaluation (GRADE) approach. The resulting recommendations were used as the basis of discussion at the face-to-face modified Delphi meeting.

agreement, the research team was given 2 min to present the underlying considerations. After this, 5 min of discussion amongst the experts was allowed and the recommendation could be reformulated. A given question could result in a statement rather than a recommendation at the discretion of the expert panel. A final round of voting was conducted using the revised recommendation or statement (Fig. 3). The 'consensus' level during the second round of voting was set at 70% agreement amongst experts. This level of agreement was validated and accepted at previous guideline development conferences, including the 2015 European Association for Endoscopic Surgery consensus meeting on appendicitis[16] and the 2016 American Society for Metabolic and Bariatric Surgery consensus meeting on perioperative management of obstructive sleep apnoea in bariatric surgery.[15]

Results

Preoperative risk assessment

Preoperative assessment should include a dedicated score for pulmonary risk evaluation in order to identify patients with greater risk for PPCs (Table 1; Q1.1). Many scoring systems exist to quantify PPC risk, but most are too complex to be clinically useful or lack external validation confirming the accuracy of the score. Although the definition of PPCs was revisited recently with the goal of standardising the criteria, the consensus achieved in that publication does not differ substantially from previous ones.[17] Despite the lack of evidence for the use of a specific prediction score, the patient factors and perioperative characteristics associated with increased PPC risk are well established. The panel agreed that the intraoperative ventilation strategy should be guided by an awareness of the factors that pose the greatest risk: age >50 yr, BMI >40 kg m^{-2}, ASA physical status >2, obstructive sleep apnoea, preoperative anaemia, preoperative hypoxaemia, emergency or urgent surgery, and ventilation duration >2 h (Table 1; Q1.1).

Intraoperative atelectasis, related changes in lung mechanics, and postoperative pulmonary complications

Atelectasis occurs in roughly 90% of all patients undergoing general anaesthesia and can persist for weeks after operation.[18,19] Intraoperative atelectasis results in decreased functional residual capacity (FRC), increased heterogeneity of lung expansion, cyclic lung overstress, and increased ΔP. ΔP is the pressure difference that generates V_T, and can be expressed as the ratio between V_T and respiratory system compliance (C_{RS}).[20] Lower intraoperative ΔP values have been associated with a reduction in PPCs,[21,22] and high ΔP is considered a key mediator of lung injury during positive-pressure ventilation.[23] Therefore, intraoperative ventilation that avoids derecruitment without causing over-distension of alveoli may decrease postoperative pulmonary risk by improving perioperative oxygenation and respiratory mechanics,[3,24,25] and reducing oxidative stress, inflammatory response, and lung injury.[26,27]

Induction of anaesthesia

Patient positioning

Supine positioning during induction of anaesthesia causes cephalad displacement of abdominal contents, thereby forcing the diaphragm upwards and compressing dependent lung regions. These changes are attenuated by placing patients in a head-up or ramped position (Table 1; Q3.1). During induction of anaesthesia, particularly in obese individuals, the head-up method produces a longer non-hypoxic apnoea time compared with supine, allowing more time for laryngoscopy.[28,29] The supine position should be avoided during

Table 1 Recommendations and statements concerning pulmonary risk assessment, case set-up, and ventilation management during anaesthesia induction. CPAP, continuous positive airway pressure; F_IO_2, fraction of inspired oxygen; HOB, head of bed; I:E, inspiratory:expiratory; NIPPV, non-invasive positive-pressure ventilation; OSA, obstructive sleep apnoea; PBW, predicted body weight; PPC, postoperative pulmonary complication; P_{plat}, plateau pressure; SpO_2, peripheral oxygen saturation; V_T, tidal volume; ZEEP, zero end-expiratory pressure.

Question	Statement/recommendation	Consensus (%)	Quality of evidence	Strength of recommendation
1.1	A dedicated score should be used for risk evaluation.	100	☒☒☐☐	Strong
	The greatest risk factors for PPCs include age >50 yr, BMI >40 kg m^{-2}, ASA >2, OSA, preoperative anaemia, preoperative hypoxaemia, emergency or urgent surgery, ventilation duration >2 h, and intraoperative factors (such as haemodynamic impairment and low oxyhaemoglobin saturation).	100	☒☒☐☐	Statement
1.2	Use a low-tidal-volume protective-ventilation strategy (6–8 ml kg^{-1} PBW). ZEEP is not recommended. Appropriate PEEP and recruitment manoeuvres may improve intraoperative respiratory function and prevent PPCs.	86	☒☒☒☐	Strong
1.3	The formation of perioperative clinically significant atelectasis may be an important risk factor for the development of PPCs.	100	☒☒☒☒	Statement
2.1	Individualised mechanical ventilation should be used and may improve intraoperative respiratory function, but the beneficial effects are likely to disappear after extubation.	100	☒☒☐☐	Strong
2.2	The ventilator should initially be set to deliver $V_T \leq$6–8 ml kg^{-1} PBW and PEEP=5 cm H_2O. Evidence regarding I:E ratio settings is lacking.	86	☒☒☒☐	Strong
2.3	PEEP should be individualised to the patient in order to avoid increases in driving pressure (P_{plat}–PEEP) whilst maintaining a low V_T. To optimise intraoperative respiratory function in obese patients, during pneumoperitoneum insufflation, and during prone or Trendelenburg positioning, PEEP adjustment may be required.	100	☒☒☐☐	Strong
3.1	Before induction of anaesthesia, position the patient with the HOB elevated ≥ 30 deg (i.e. ‘beach chair’); avoid flat supine position. If not contraindicated, before the loss of spontaneous ventilation, use NIPPV or CPAP to attenuate anaesthesia-induced respiratory changes.	100	☒☒☒☐	Strong
3.2	During induction, monitor for an obstructive breathing pattern and use a combination of appropriate techniques, including positioning, application of NIPPV or CPAP, or placement of a nasopharyngeal airway to avoid upper airway obstruction.	100	☒☐☐☐	Strong
3.3	After intubation, F_IO_2 should be set to ≤0.4. Thereafter, use the lowest possible F_IO_2 to achieve SpO_2 ≥94%.	100	☒☐☐☐	Weak
3.4	No specific mode of controlled mechanical ventilation is recommended.	100	☒☐☐☐	Statement

anaesthesia induction, as 30 degree head-up and reverse Trendelenburg position is associated with less reduction of FRC.[30]

Non-invasive ventilation during induction

Non-invasive positive-pressure ventilation (NIPPV) or continuous positive airway pressure (CPAP) should be considered as useful adjuncts during anaesthesia induction. Contraindications, such as altered mental status, certain procedures (face/nose/oesophageal resection), or emergency procedures, should be considered before applying NIPPV or CPAP (Table 1; Q3.1). Head-up positioning combined with NIPPV/CPAP[30] further attenuates FRC decrease with anaesthesia induction. Using NIPPV/CPAP during induction increases P_aO_2 and duration of non-hypoxic apnoea.[29,31–33] Two meta-analyses of obese patients corroborated the finding that NIPPV/CPAP during induction improved duration of non-hypoxic apnea[34] and improved oxygenation.[35] A single study failed to demonstrate positive effects of NIPPV/CPAP on non-hypoxic apnoeic time.[36] NIPPV/CPAP was also noted to decrease venous admixture when compared with spontaneous breathing.[31] Other methods, including monitoring of obstructive breathing, head positioning, and naso- or oropharyngeal airway insertion should be used to avoid upper airway obstruction during induction (Table 1; Q3.2).

Optimal intraoperative ventilator settings

Tidal volume

Low V_T ventilation, 6–8 ml kg^{-1} predicted body weight (PBW), is a fundamental component of lung-protective ventilation (Table 1; Q1.2). Multiple studies have demonstrated a significant reduction in PPCs associated with low (<8 ml kg^{-1}) *vs* high

Table 2 Recommendations and statements concerning respiratory system monitoring and ventilation management during anaesthesia maintenance/surgery. ESA, European Society of Anaesthesiology; P_{plat}, plateau pressure; F_IO_2, fraction of inspired oxygen.

Question	Statement/recommendation	Consensus (%)	Quality of evidence	Strength of recommendation
4.1	In addition to standard monitoring (ASA/ESA), dynamic compliance, driving pressure (P_{plat}−PEEP), and P_{plat} should be monitored on all controlled mechanically ventilated patients.	100	☒☒☒☐	Strong
4.2	Decreasing compliance caused by surgical/anaesthesia factors (i.e. pneumoperitoneum, positioning, and circuit disconnect) should be treated by appropriate interventions. Individualised PEEP can prevent progressive alveolar collapse. Recruitment manoeuvres can reverse alveolar collapse, but have limited benefit without sufficient PEEP. Statement: Increasing F_IO_2 may be effective in increasing the oxygenation, but is not an effective intervention to improve dynamic compliance of the respiratory system.	86	☒☒☒☒	Strong
4.3	The effectiveness of interventions aimed at optimising respiratory system mechanics should be evaluated by measuring an improvement of the respiratory system compliance under a constant tidal volume.	100	☒☒☐☐	Strong

Table 3 Recommendations and statements concerning recruitment manoeuvres and ventilation management during anaesthesia emergence. ARM, alveolar recruitment manoeuvre; CPAP, continuous positive airway pressure; F_IO_2, fraction of inspired oxygen; HOB, head of bed; NIPPV, non-invasive positive-pressure ventilation; P_{plat}, plateau pressure; SpO_2, peripheral oxygen saturation; ZEEP, zero end-expiratory pressure. *Consensus level <70%.

Question	Statement/recommendation	Consensus (%)	Quality of evidence	Strength of recommendation
5.1	High-quality supportive evidence is lacking to recommend a routine ARM for all patients after tracheal intubation. However, an ARM may be considered according to an individual risk−benefit assessment.	57*	☒☐☐☐	Weak
5.2	The bag-squeezing ARM should be avoided in favour of a ventilator-driven ARM.	100	☒☐☐☐	Weak
5.3	ARMs should be performed using the lowest effective P_{plat} (30−40 cm H_2O in non-obese; 40−50 cm H_2O in obese) and shortest effective time or fewest number of breaths.	100	☒☒☐☐	Weak
5.4	Continuous haemodynamic and oxygen saturation monitoring is recommended before and during an ARM. Ensure adequate haemodynamic stability before performing an ARM. Avoid ARMs when contraindicated.	100	☒☒☒☒	Strong
5.5	PEEP should be individualised after an ARM to avoid both alveolar overdistention and collapse.	71	☒☒☐☐	Weak
6.1	Optimise patient positioning and avoid ZEEP during emergence. Avoid tracheal tube suctioning immediately before tracheal extubation.	100	☒☐☐☐	Weak
6.2	Avoid apnoea with ZEEP before extubation.	100	☒☐☐☐	Weak
6.3	In the appropriate clinical scenario, the use of low F_IO_2 (<0.4) during emergence from general anaesthesia can improve pulmonary function in the postoperative period.	71	☒☐☐☐	Weak
6.4	When high F_IO_2 (>0.8) is used during emergence, the use of low F_IO_2 (<0.3) CPAP immediately after tracheal extubation may reduce the risk of resorption atelectasis.	29*	☒☐☐☐	Weak
6.5	Administration of postoperative supplemental oxygen is recommended when room air SpO_2 decreases below 94%. Avoid routine application of supplemental oxygen without investigating and treating the underlying cause.	100	☒☐☐☐	Weak
6.6	Prophylactic NIPPV/CPAP should be considered after operation for patients with prior routine use of NIPPV/CPAP.	100	☒☒☐☐	Strong

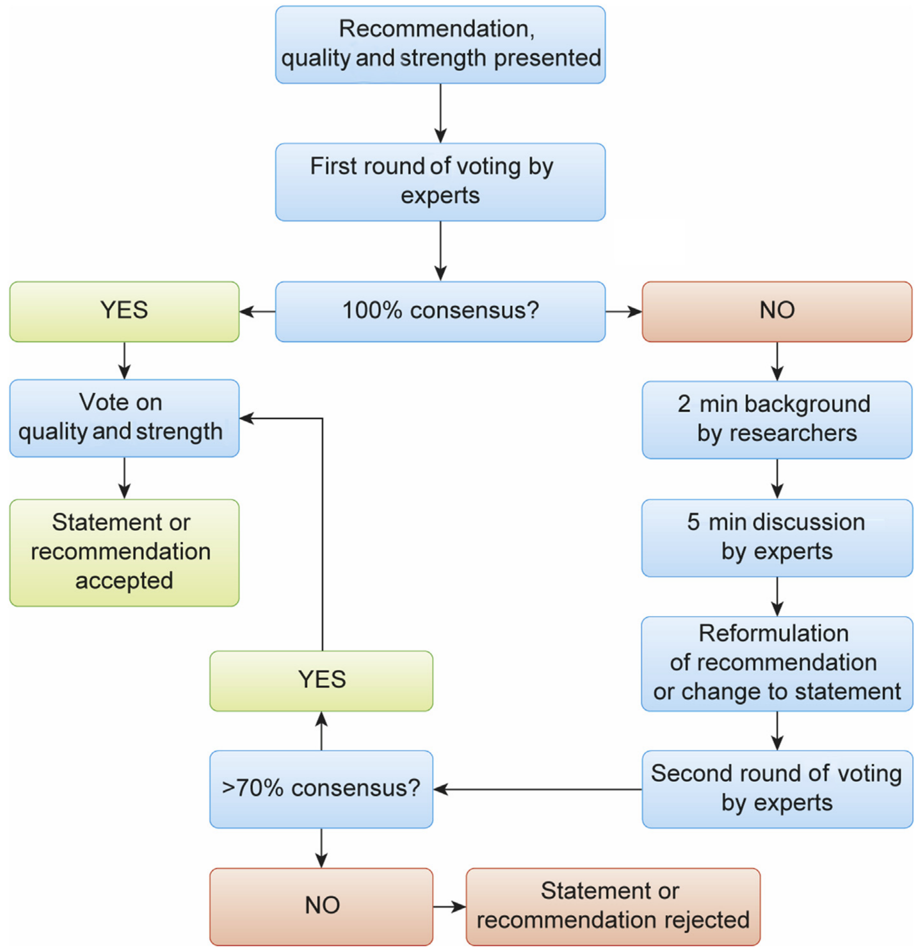

Fig 3. Modified Delphi process flow chart. After the development of recommendations, the experts met in a face-to-face meeting to develop a consensus. All recommendations and statements underwent two rounds of voting as no recommendation achieved 100% consensus during the first round. The final round of voting was conducted using the revised recommendation or statement.

(>8 ml kg^{-1}) V_T ventilation.[26,37,38] However, the use of a low V_T without adequate PEEP may increase the risk of atelectrauma as a result of cyclic lung de-recruitment.[37,39]

End-expiratory pressure

A number of studies have suggested the negative effects associated with mechanical ventilation with zero end-expiratory pressure (ZEEP).[4,40–43] These effects include a profound reduction in end-expiratory lung volume (EELV) after anaesthesia induction and an increased area of atelectasis. Loss of EELV and atelectasis contribute to decreased C_{RS} in de-recruited areas, and increase the propensity for overinflation of aerated lung tissue (volutrauma).[40,41] Therefore, allowing airway/alveolar pressure to achieve ZEEP is not recommended (Table 1; Q1.2).

Individualised PEEP improves oxygenation, EELV, and respiratory system mechanics during ventilation; however, these improvements may disappear soon after extubation.[44–51] Whilst the panel noted that many measurable effects of lung-protective ventilation may dissipate after extubation, they agreed that mechanical ventilation should be targeted to optimise the respiratory function (Table 1; Q2.1), and that more studies are needed to quantify whether these positive intraoperative effects on ventilatory mechanics have a clinically meaningful impact on postoperative respiratory outcomes.

Although several studies of low V_T (6–8 ml kg^{-1}) have consistently shown improvement in pulmonary function and reduction of PPCs, the optimal level of PEEP remains a matter of debate.[4,25,52,53] The panel agreed that lung-protective ventilation requires a combination of low V_T and some degree of PEEP (Table 1; Q2.2). Multiple studies demonstrate that the use of PEEP improves EELV; increases oxygenation; and improves dependent lung ventilation, C_{RS}, and postoperative pulmonary function when compared with ZEEP.[39,54–58] Moreover, several large RCTs showed that intraoperative ventilation with reduced V_T (6–8 ml kg^{-1}) and increased levels of PEEP (6–10 cm H_2O) prevents PPCs[38,59,60]; reduces atelectasis and recruitment/de-recruitment injury; and improves C_{RS}, EELV, PaO_2, and dependent lung ventilation with little-to-no overdistension.[43,57] However, one large trial protective ventilation during general anesthesia for open abdominal surgery: high versus low positive end-expiratory pressure (PROVHILO) showed no difference in the development of PPCs with low V_T and either high or low levels of PEEP ($\leq$2 cm H_2O *vs* 12 cm H_2O).[61] Whilst ZEEP is not recommended, the precise level of PEEP remains controversial.[42,43,57,58,61–67]

Individualised PEEP has demonstrated many benefits to pulmonary function, and is especially important in obese patients, during abdominal insufflation, and during prone or Trendelenburg positioning (Table 1; Q2.2). One RCT of obese patients (BMI >35 kg m^{-2}) undergoing laparoscopic surgery found that the average calculated individualised PEEP was 18.5 cm H_2O.[45] This trial also found that individualised PEEP decreased ΔP and increased PaO_2/F_IO_2 ratios, EELV, C_{RS}, and ventilation to dependent lung regions. A recent large international trial, however, showed that, although higher PEEP with recruitment manoeuvres results in improved pulmonary function intraoperatively compared with a low PEEP without recruitment manoeuvres, it does not reduce the incidence of PPCs in obese surgical patients.[12]

The importance of individualised PEEP was further highlighted in a meta-analysis of individual patient data from RCTs comparing intraoperative protective ventilation with conventional ventilation, which found that the benefits of protective ventilation were related to reductions in ΔP rather than to changes in V_T or level of PEEP.[6] The authors reported that only C_{RS} and ΔP were significantly associated with PPCs, and that their incidence was not affected by the level of PEEP unless it resulted in an increase in ΔP. Therefore, the panel recommends an initial PEEP setting of 5 cm H_2O and thereafter PEEP levels should be individualised (Table 1; Q2.2 and 2.3).

Inspiratory/expiratory ratio

Several studies have compared prolonged inspiratory-to-expiratory (I:E) ratios to the 1:2 ratio commonly used during mechanical ventilation. An I:E ratio of 1:1, which has been characterised as providing a 'balanced stress to time product',[4] was associated with attenuation of lung damage. Prolonged I:E ratio increases mean airway pressure and concomitantly reduces peak airway pressure. Studies using prolonged inspiratory times have described beneficial effects, including increased C_{RS} and PaO_2, lower alveolar–arterial gradient, and reduced inflammatory markers.[6,67–72] Given the lack of evidence for a clear benefit of a specific I:E ratio, no recommendation was offered by the panel (Table 1; Q2.2). However, the panel noted that optimisation of inspiratory time for individual patients can be achieved by monitoring parameters, such as oxygenation, C_{RS}, and ΔP.

Intraoperative F_IO_2

Increased F_IO_2 during mechanical ventilation is administered to prevent or correct hypoxaemia, but may result in hyperoxia.[73,74] The negative effects of hyperoxia are not clear, but it has been suggested that it may increase oxidative stress, peripheral vascular and coronary artery vasoconstriction, decrease cardiac output, increase resorption atelectasis, and increase the rate of PPCs.[75–81]

Recommendations for optimal use of oxygen and current evidence regarding the association between hyperoxaemia and clinically relevant outcomes during intraoperative mechanical ventilation are lacking. Few studies have revealed a protective effect of hyperoxaemia,[82] some report an association with mortality,[83] whilst others show no association with clinically relevant outcomes.[83] Therefore, in the absence of evidence, the most prudent course of action during mechanical ventilation is to maintain normoxaemia. SpO_2 monitoring can assist in the detection of hypoxaemia, but during oxygen therapy SpO_2 cannot detect hyperoxia.[84] Whilst SpO_2 monitoring reduces the incidence of hypoxaemia, it does not improve the overall patient outcomes and does not reduce morbidity and mortality.[85] Therefore, once the airway is secured, F_IO_2 should be set to $\leq$0.4 with the goal of using the lowest possible F_IO_2 to achieve normoxia (or SpO_2 $\geq$94%) (Table 1; Q3.3). Unnecessarily high F_IO_2 should be avoided. Administering lower F_IO_2 will not only decrease the risk of hyperoxia, but will also reduce the masking effect of oxygen therapy and allow for earlier diagnosis of gas-exchange impairment.[84]

Modes of mechanical ventilation

A number of studies explored whether one mode of mechanical ventilation is better than others at reducing PPCs. When assessing pressure-controlled ventilation (PCV) *vs* volume-controlled ventilation (VCV), the results are mixed. VCV was associated with lower maximal plateau pressures, greater V_T, and less dead-space ventilation.[86] In an observational study, the risk of PPC was higher in patients who received PCV compared with VCV, particularly with PEEP <5 cm H_2O.[87] A meta-analysis regarding intraoperative ventilation mode in obese patients found VCV to be superior to PCV.[88]

Pressure-controlled ventilation was superior to VCV on the basis of lower peak inspiratory pressure (PIP) or improved arterial blood gas (ABG) results in several studies. Four studies showed lower PIP with no change in arterial oxygenation.[89–92] Another demonstrated improved ABG results in patients ventilated with PCV compared with VCV, with no change in airway pressures.[93] No significant differences between PCV and VCV were found in one randomised trial when assessing airway pressures, ABG results, or oxygenation.[94] VCV with an inspiratory pause does allow for measurement of P_{plat}, therefore allowing for a more accurate determination of ΔP. Given the heterogeneity of the published trials, no specific mode of controlled mechanical ventilation is recommended (Table 1; Q3.4).

Alveolar recruitment manoeuvres

General anaesthesia promotes the formation of atelectasis, which negatively impacts respiratory function and may be associated with subsequent PPCs.[18,44] ARMs are beneficial in reopening collapsed alveoli and improving lung mechanics, suggesting that performing an ARM after intubation can combat anaesthesia-induced FRC changes.[45,95–100] Even after an ARM, normal alveoli filled with 100% oxygen have a rapid tendency to collapse and form shunt.[101] Therefore, resorption atelectasis can be attenuated with an ARM performed with F_IO_2 <1.0.[18] After an ARM, C_{RS} and PaO_2 improved.[24,60,102–104] ARMs are effective when applied after intubation and during any episodes of oxyhaemoglobin desaturations or release of positive pressure from the breathing circuit.

The period immediately after induction can often be a time of haemodynamic instability caused by medication and positive-pressure ventilation effects. Whilst ARMs are considered safe and effective,[105] some patients, such as those with hypovolaemia, severe emphysema, or chronic obstructive lung disease, may be prone to hypotension during an ARM; therefore, the risk to benefit ratio of ARMs should be carefully considered. High-quality supportive evidence is lacking to recommend a routine ARM for all patients after tracheal intubation. However, an ARM may be considered according to an individual risk–benefit assessment (Table 3; Q5.1). Further research is needed to identify which patients would benefit from an ARM immediately after induction.

ARMs should be performed after a disconnection from the circuit and whenever the patient's SpO_2 is consistently ≤94%. The two primary methods are manual ARM and ventilator-driven ARM.

Manual alveolar recruitment manoeuvres

A manual ARM is performed by sustained lung inflation using the reservoir bag on the anaesthesia machine with the adjustable pressure-limiting valve set to the desired inflation pressure. The manual ARM can lead to brief loss of positive pressure when switching back to the ventilator circuit, which results in recollapse of alveoli. For this reason, the ventilator-driven ARM is favoured (Table 3; Q5.2).

Ventilator-driven alveolar recruitment manoeuvres

Ventilator-driven ARMs can be divided into three types: vital capacity, pressure-controlled, or volume-controlled cycling manoeuvres. The vital-capacity ARM resembles the manual ARM except that the V_T is delivered through the ventilator circuit. This requires a ventilator capable of providing CPAP or an inspiratory hold of 7–8 s.[106] The panel concurs that 7–8 s is an appropriate inspiratory time in patients with healthy lungs, but that individual patient characteristics (elevated BMI, Trendelenburg position, and abdominal insufflation) may require longer times and higher PIP. Studies that have evaluated intraoperative alveolar collapse have found that, in healthy patients with BMIs <35 kg m^{-2}, a PIP hold of 40 cm H_2O is required to improve PaO_2 and lung compliance.[107] For patients with BMIs >35 kg m^{-2}, pressures of up to 50 cm H_2O or multiple, successive ARMs have been recommended.[51,62,90,102,108–113] The recently published effect of intraoperative high positive end-expiratory pressure (PEEP) with recruitment maneuvers vs low PEEP on postoperative pulmonary complications in obese patients (PROBESE) trial showed no reduction of PPCs when an ARM was performed after intubation and each hour afterwards as part of a non-individualised ventilator protocol in obese surgical patients.[12]

In pressure-controlled-mode ARM, recruitment airway pressure should be based upon patient BMI, as discussed previously, and this 'opening' pressure should be maintained for 10 breaths.[21,45,114–118] The panel was unanimous in urging caution when using PIP >50 cm H_2O. When using volume-controlled mode for ARM,[60] one should start with a V_T of 6–8 ml kg^{-1} PBW and I:E ratio of 1:1, and increase the V_T by 4 ml kg^{-1} every three to six breaths until P_{plat} of 30–40 cm H_2O is reached. After an additional three to six breaths at this level, sufficient recruitment occurs and V_T settings can be reduced. PEEP adjustment after an ARM may be required to maintain alveolar recruitment. The panel further recommends that one should evaluate change in C_{RS} and ΔP after an ARM, and repeat the ARM with a longer inspiratory hold or higher pressure if recruitment is assessed as ineffective.

The panel recommends using the lowest F_IO_2 during ARMs to aid in identifying the patient's opening and closing pressures, and sustain recruited alveoli by reducing the occurrence of resorption atelectasis.[119,120] They also state that the method used to produce an ARM through the ventilator circuit is not as important as avoiding the use of manual ARMs. ARMs should be performed using the lowest effective PIP and shortest effective time or fewest number of breaths (Table 3; Q5.3). ARM effectiveness can be measured by improved oxygenation, C_{RS}, or ΔP. Further research is required, as there is currently little evidence linking ARMs to pulmonary outcomes.

Complications related to alveolar recruitment manoeuvres

Hypoxaemia and haemodynamic instability are reported complications of ARMs. No adverse effects of performing an ARM were found in 26 of 33 studies.[24,51,57,59,60,62,65,95–100,102,104,108,111–114,116–118,121–123] Six studies identified transient haemodynamic instability requiring vasopressor treatment during ARMs.[21,45,46,52,61,103] One study found more oxyhaemoglobin desaturation in the ARM group.[124] The panellists recommend continuous haemodynamic and SpO_2 monitoring before and during the ARM.[125] It is essential to ensure adequate haemodynamic stability before performing an ARM and avoid ARMs when contraindicated (Table 3; Q5.4).

Intraoperative monitoring of lung mechanics and oxygenation

Because the lung is a dynamic system, altered by both anaesthesia and surgery, the components of the mechanical breath should be continuously evaluated.[20] C_{RS}, ΔP, and P_{plat} should be monitored on all mechanically ventilated patients (Table 2; Q4.1), and interventions aimed at optimising respiratory system mechanics should be evaluated by measuring C_{RS} under constant V_T[6] (Table 2; Q4.3).

Current monitoring standards focus primarily on detecting hypoxaemia using SpO_2. Interventions tend to focus more on improving SpO_2, often by increasing F_IO_2, rather than improving the underlying pulmonary system derangement. Whilst increasing F_IO_2 may be effective in increasing oxygenation, it does not improve the underlying ventilation–perfusion mismatch (Table 2; Q4.2).

To minimise the risk associated with mechanical ventilation, the ventilator should be set to maintain the ΔP as low as possible.[6] Appropriately set PEEP can maintain FRC without causing gross over-distension, and is evidenced by the lowest ΔP that achieves the desired V_T.[126] Surgical or anaesthesia factors that cause changes in C_{RS} or ΔP should be treated by interventions that restore physiological lung volume whilst avoiding both over- and under-distention (Table 2; Q4.2). During controlled mechanical ventilation, if the circuit is disconnected or switched from the ventilator to the manual mode, loss of lung volume will occur immediately, accompanied by a decrease in C_{RS} and an increase in ΔP.[127] In order to restore C_{RS} and prevent lung over-distension, FRC must be re-established by an increase in pressure sufficient to overcome the degree of lung collapse.[50,127]

The FRC is maintained, not restored, by PEEP. Therefore, in order to prevent lung over-distension related to PEEP, FRC should be restored with an ARM before any increase in the level of set PEEP.[127] Likewise, ARMs can reverse alveolar collapse, but the benefit will be of short duration without sufficient PEEP (Table 2; Q4.2). PEEP should be individualised after an ARM to avoid alveolar over-distension or collapse (Table 3; Q. 5.5).

Emergence from anaesthesia

Consideration should be given to avoiding conditions during emergence that negate the intraoperative efforts to recruit and maintain an open lung. Recommendations similar to those applied during induction include optimising patient positioning (head elevated ≥30 deg) and avoiding ZEEP (Table 3; Q6.1). Reduction of lung volume by routine suctioning of the tracheal tube just before extubation should be avoided. Other interventions likely beneficial include prevention of coughing and bucking on the tracheal tube, and avoiding upper airway obstruction after extubation. The common practice of turning off the ventilator allowing carbon dioxide to accumulate to stimulate spontaneous ventilation should also be avoided, as the period of apnoea is associated with ZEEP and collapse of alveoli (Table 3; Q6.2). Atelectasis that develops during general anaesthesia persists into the postoperative period. This finding argues for some methods of keeping recruited alveoli open, such as application of CPAP during the transition between mechanical ventilation and spontaneous breathing. However, applying an ARM followed by PEEP, and then maintaining positive airway pressure using CPAP from return of spontaneous breathing until extubation did not improve postoperative oxygenation.[122]

F_IO_2 during emergence

F_IO_2 >0.8 during emergence significantly increases atelectasis formation.[128–131] If clinically appropriate, F_IO_2 ≤0.4 during emergence may be used to reduce atelectasis. Lower F_IO_2 during emergence can improve postoperative pulmonary function[130] (Table 3; Q6.3). CPAP with low F_IO_2 (<0.3) after extubation may decrease the area of atelectasis.[31,123,130,132] However, current evidence regarding efficacy of this technique is lacking and cannot presently be universally recommended (Table 3; Q6.4). After extubation, supplemental oxygen should be administered for SpO_2 <94%; however, the underlying cause should be investigated and appropriate interventions should be used (Table 3; Q6.5).

Non-invasive ventilator support

A systematic review of CPAP administered after a major abdominal surgery found weak evidence that CPAP may reduce atelectasis, the rate of pneumonia, and the frequency of reintubation.[133] Prophylactic postoperative CPAP reduced the incidence of PPCs in patients undergoing abdominal surgery; however, the authors noted that the optimum CPAP in this setting is unknown and the administration of CPAP should be individualised.[134] Postoperative CPAP of 7.5 cm H_2O *vs* 6 L min^{-1} flow of 50% oxygen by the Venturi mask may reduce reintubation rate, pneumonia, infection, and sepsis after a major abdominal surgery.[135] CPAP of 10 cm H_2O after thoracoabdominal surgery reduced PPCs and decreased the duration of ICU and hospital stay.[136]

Administration of CPAP immediately post-extubation in the obese population has been shown to reduce atelectasis, improve oxygenation and pulmonary function, and may minimise the risk of developing PPCs.[66,137] The early postoperative use of NIPPV in obese patients promoted a more rapid recovery of lung function and improved oxygenation when compared with a 6 L min^{-1} flow of 50% oxygen via Venturi mask.[138] In addition, the PaO_2 and PaO_2/F_IO_2 ratio were significantly improved up to 24 h after operation when CPAP was applied immediately upon extubation in obese patients.[139] In obese patients undergoing laparoscopic surgery, NIPPV administration post-extubation improved pulmonary function and reduced the risk of respiratory complications; however, it did not reduce the risk of reintubation or unplanned ICU admission.[35]

The postoperative prophylactic use of NIPPV or CPAP should be considered for patients who use these modalities to maintain adequate ventilation before operation (Table 3; Q6.6).

Discussion

A panel of experts produced consensus recommendations for intraoperative protective ventilation for the surgical patient. Those statements and recommendations that were of moderate to high quality and received strong support from the expert panel are presented in Table 4. We need to reiterate that two study questions did not achieve the consensus level of 70%. First, high-quality supportive evidence is lacking to recommend a routine ARM for all patients after tracheal intubation; however, 57% agreement was achieved that an ARM may be considered according to an individual risk–benefit assessment. Second, only 29% agreement was achieved that low F_IO_2 (<0.3) with CPAP immediately after tracheal extubation may reduce the risk of resorption atelectasis. In both cases, published evidence was weak or nonexistent, and the non-agreeing experts expressed concern about supporting potentially harmful interactions without more robust evidence.

Whilst these are the first published recommendations for the management of intraoperative mechanical ventilation, practice guidelines for mechanical ventilation in adult patients with acute respiratory distress syndrome (ARDS) strongly support the use of low V_T ventilation (4–8 ml kg^{-1} PBW) and limiting P_{plat} to less than 30 cm H_2O.[140] The recommendations presented here are similar except for the use of ΔP instead of P_{plat}, as this appears better correlated with outcomes.[5,6] In surgical patients, PEEP titration in conjunction with ARM is likely to be beneficial particularly during times when C_{RS} changes rapidly, such as during insufflation and steep Trendelenburg positioning. The use of higher levels of PEEP and ARM is only conditionally recommended in ARDS patients.[140] These differences likely reflect the different underlying pathophysiologies occurring in ARDS (inflammatory pulmonary oedema and cellular debris accumulation in alveoli) *vs* in the operating room (healthy lungs with a high degree of atelectasis). Whilst atelectatic alveoli during surgery can be reopened with ARM and incremental PEEP, the ‘baby lung’ of ARDS may not have a similar recruitable alveolar volume, and therefore, may not respond as favourably to ARM and PEEP.[141]

The modified Delphi method is recommended to determine a consensus for a defined clinical problem in the healthcare setting, and is an effective process for determining expert group consensus where there is little or no definitive evidence,

Table 4 Recommendations and statements with moderate-to high-quality and strong expert support. ARM, alveolar recruitment manoeuvre; CPAP, continuous positive airway pressure; ESA, European Society of Anaesthesiology; F_IO_2, fraction of inspired oxygen; HOB, head of bed; I:E, inspiratory-to-expiratory ratio; NIPPV, non-invasive positive-pressure ventilation; PBW, predicted body weight; PPC, postoperative pulmonary complication; P_{plat}, plateau pressure; V_T, tidal volume; ZEEP, zero end-expiratory pressure.

Moderate- to high-quality recommendations with strong expert support:

- The ventilator should initially be set to deliver $V_T \leq 6-8$ ml kg^{-1} PBW and PEEP=5 cm H_2O. ZEEP is not recommended.
- Appropriate PEEP and recruitment manoeuvres may improve intraoperative respiratory function and prevent PPCs.
- Before the induction of anaesthesia, position the patient with the HOB elevated ≥30 deg (i.e. 'beach chair'); avoid flat supine position. If not contraindicated, before the loss of spontaneous ventilation, use NIPPV or CPAP to attenuate anaesthesia-induced respiratory changes.
- In addition to standard monitoring (ASA/ESA), dynamic compliance, driving pressure (P_{plat}−PEEP), and P_{plat} should be monitored on all controlled mechanically ventilated patients.
- Continuous haemodynamic and oxygen saturation monitoring is recommended before and during an ARM. Ensure adequate haemodynamic stability before performing an ARM. Avoid ARMs when contraindicated.

Moderate- to high-quality statements with strong expert support:

- The formation of perioperative clinically significant atelectasis may be an important risk factor for the development of PPCs.
- Decreasing compliance caused by surgical/anaesthesia factors (i.e. pneumoperitoneum, positioning, and circuit disconnect) should be treated by appropriate interventions.
- Individualised PEEP can prevent progressive alveolar collapse. Recruitment manoeuvres can reverse alveolar collapse, but have limited benefit without sufficient PEEP.
- Increasing F_IO_2 may be effective in increasing the oxygenation, but is not an effective intervention to improve dynamic compliance of the respiratory system.

and where opinion is important.[11] The strengths of this method include the ability to bring a geographically dispersed and diverse group of expert panellists together, having an organised communication process in place, refining the content through repeated review, and the ability to condense expert opinion into clearly defined practice recommendations. Recognised limitations include the time required for expert participation and lack of anonymity during the face-to-face meeting. A limitation of our recommendations is that most of the literature focuses on surrogate endpoints, such as oxygenation or respiratory mechanics, and that relatively little published data support improvements in morbidity or mortality. By the same token, the recommendations are independent from the recently revised definition of PPCs.[17] Interventions with associated costs or potential complications with no proven benefit in hard endpoints could not be recommended. Whilst the focus of this consensus conference was specifically to provide guidance for preoperative risk assessment and intraoperative mechanical ventilation for patients undergoing surgery, other factors not addressed in our review that may contribute to PPCs, such as incomplete reversal of neuromuscular block, postoperative opioid use, and surgical inflammation suppression, deserve further investigation. Future studies should continue to evaluate the roles of PEEP and ARM in the surgical patient. New imaging modalities, such as ultrasound and electrical impedance tomography, may help further elucidate their roles. Good-quality data on lung de-recruitment during emergence and possible mitigating methods are also needed. Finally, the role of F_IO_2 in the development of PPCs requires further study.

Conclusion

In conclusion, this consensus meeting resulted in 26 recommendations and statements concerning the use of lung-protective ventilation in patients undergoing mechanical ventilation in the operating theatre. As the basic and clinical research focused on the application of mechanical ventilation in the surgical setting continues to emerge, it is likely that best practices to reduce or eliminate PPCs will likewise evolve. The panel urges continued investigations and the adoption of proven interventions that will help optimise the perioperative care and safety of surgical patients. Further studies are needed to definitively confirm the beneficial effects of these interventions and manoeuvres on meaningful clinical outcomes.

Authors' contributions

Study design: CCY, EMH, CV
Literature search: AW
Literature review/compilation: SB, BB, RRDE, JM, CR, BT
Review of studies with research team: MGA, MG, EF, JPM, PP, JS, EMH
Writing of first draft: CCY, EMH, CV
Formatting of references: AW
Revising of final draft: all authors
CCY was the consensus conference president (coordinating team). CV was the consensus conference moderator (coordinating team). EMH, MGA, MG, EF, JPM, PP, and JS were the consensus conference experts. SB, BB, RRDE, JM, CR, and BT were the consensus conference participants.

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Declarations of interest

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Appendix A. Supplementary data

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