Obesity causes major alterations in pulmonary mechanics. Obese patients undergoing bariatric surgery present mechanical ventilation-related challenges that may lead to perioperative complications. Databases were systematically searched for clinical trials of ventilation maneuvers for obese patients and bariatric surgery. Thirteen randomized controlled trials were selected. The quality of the studies was evaluated with the Critical Appraisal Skills Programme tool, and a matrix was developed to present the essential components of the studies.

Eight strategies of ventilation maneuvers were identified. Recruitment maneuvers followed by positive end-expiratory pressure (PEEP) consistently demonstrated effectiveness in obese patients undergoing bariatric surgery. Pressure-controlled ventilation and volume-controlled ventilation did not differ significantly in their efficacy. Noninvasive positive pressure ventilation (NIPPV) during induction was effective in preventing atelectasis and increasing the duration of safe apnea. Equal ratio ventilation can be a useful ventilation strategy.

Recruitment maneuvers followed by PEEP are effective ventilation strategies for obese patients undergoing bariatric surgery. During induction, NIPPV provides further benefit. Future studies are needed to examine the postoperative effects of recruitment maneuvers with PEEP as well as the efficacy and safety of equal ratio ventilation.

Keywords: Bariatric surgery, noninvasive positive pressure ventilation, obesity, positive end-expiratory pressure, recruitment maneuver.
including the terms mechanical ventilation, bariatric surgery, gastric bypass, obesity, and morbid obesity. A total of 262 articles were generated. Filters such as human, adults (ages of 19 [years] or above), English, and clinical trial were employed. Overlapped articles were excluded. The abstracts of 24 articles were reviewed for inclusion. Thirteen randomized controlled trials (RCTs) investigating ventilation maneuvers for obese patients undergoing bariatric surgery were selected for the literature review. The selection process is summarized in the Figure.

The quality of the selected studies was analyzed using the Critical Appraisal Skills Programme (CASP) tool for RCTs\(^\text{11}\) and additional subject-appropriate items. The CASP tool for RCTs is a relatively commonly used quality assessment tool that provides a practical guideline to evaluate the internal and external validity of RCTs.\(^\text{11}\) The 3 screening questions were as follows: (1) Did the review address a clearly focused question? (2) Was the assignment of patients to treatments randomized? and (3) Were all the patients who entered the trial properly accounted for at its conclusion? Despite its usability, the CASP tool is not sufficient for all studies. In fact, most of the existing quality assessment tools for experimental studies lack rigor, and there is currently no gold standard.\(^\text{12}\) Therefore, additional criteria such as postoperative follow-up, use of high oxygen concentration, and carryover effects of crossover designs (Table 1) were used to generate a more rigorous and subject-specific assessment.

### Results

All 13 selected studies passed the 3 screening questions. The studies exhibited some limitations (see Table 1) when detailed questions of the CASP tool were exercised.

A matrix was developed, with similar studies grouped in chronological order (Table 2). The first 7 studies\(^\text{13-19}\) (the first shaded section of the table) in the matrix were focused on positive end-expiratory pressure (PEEP) and recruitment maneuver. Coussa et al\(^\text{20}\) and Futier et al\(^\text{21}\) (the first unshaded section) investigated the use of PEEP during induction to prevent atelectasis. Three studies\(^\text{22-24}\) (the second shaded section) compared pressure-controlled ventilation (PCV) and volume-controlled ventilation (VCV). The last study\(^\text{25}\) (last row, no shading) examined the efficacy of equal ratio ventilation in contrast to conventional 1:2 inspiratory:expiratory ratio ventilation. Altogether, 8 ventilation strategies were examined in the studies: recruitment maneuver alone,
<table>
<thead>
<tr>
<th>Study</th>
<th>Sample size/mean BMI kg/m²</th>
<th>Surgery type</th>
<th>Patient exclusion criteria</th>
<th>Ventilation strategies investigated</th>
<th>Measurements</th>
<th>Results</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whalen et al, 2006</td>
<td>20 / 51</td>
<td>Laparoscopic Roux-en-Y</td>
<td>Substantial pulmonary disease (FEV₁ &lt; 50% predicted; FVC &lt; 50% predicted; active asthma; home O₂ therapy)</td>
<td>RM group: PEEP is increased in stepwise fashion of 10-15-20 cm H₂O, not to exceed PAP of 50 cm H₂O; Control group: PEEP 4 cm H₂O</td>
<td>Pao₂, Pao₂/Fio₂, PEEP ramp minute ventilation, VT, C₉₅, R₉₅, driving pressure, HR, MAP, cardiac index</td>
<td>RM group had 1) significantly higher Pao₂/Fio₂ ratio and 2) significantly increased system dynamic compliance</td>
<td>One of the first studies investigating RM in obese patients undergoing bariatric surgery</td>
</tr>
<tr>
<td>Valenza et al, 2007</td>
<td>20 / 42</td>
<td>Laparoscopic gastric banding</td>
<td>Heart failure, CAD, documented obstructive disease</td>
<td>Group PEEP: 10 cm H₂O Group ZEEP: zero PEEP</td>
<td>IAP, EELV (with helium dilution), PAP, esophageal pressure, R₉₅, Eₑₓ, Eₑₕ, Pao₂, PaCO₂, MAP, HR, VD/Vt</td>
<td>1. Anesthesia and paralysis led to increased IAP, decreased EELV, and increased Eₑₓ and Eₑₕ. Pneumoperitoneum further worsened the parameters. 2. EELV and Eₑₓ improved significantly with beach chair position and PEEP of 10 cm H₂O, but R₉₅ and oxygenation did not change.</td>
<td>Examined individual and combined effects of positioning and ventilation strategy on respiratory parameters</td>
</tr>
<tr>
<td>Chalhoub, et al, 2007</td>
<td>54 / 45</td>
<td>Open bariatric surgeries</td>
<td>Cardiac, pulmonary, neurologic diseases</td>
<td>Group PEEP: 8 cm H₂O Group VC maneuver + PEEP: PAP 40 cm H₂O for 15 s + PEEP 8 cm H₂O</td>
<td>Sao₂, Pao₂, A-aDO₂, PaCO₂, HR, MAP</td>
<td>Group VC maneuver + PEEP had significantly greater S ao₂ and P ao₂, and smaller A-aDO₂ compared with group PEEP</td>
<td>Validated previous finding that RM + PEEP was more effective than PEEP alone</td>
</tr>
<tr>
<td>Almarakbi et al, 2009</td>
<td>60 / 33</td>
<td>Laparoscopic gastric banding</td>
<td>Asthma, COPD, restrictive lung disease, increased ICP, history of smoking</td>
<td>Group P: PEEP 10 cm H₂O Group R: recruitment with PIP 40 cm H₂O for 15 s Group RP: recruitment once + PEEP Group RRP: repeated recruitment + PEEP; recruitment every 10 minutes + PEEP</td>
<td>HR, MAP, Spo₂, PaO₂, C₉₅, Spo₂ (in PACU), chest x-ray (in PACU)</td>
<td>1. Group RRP had the greatest Pao₂, Spo₂, and C₉₅. 2. Group RP had the next best results, but the effects were not sustained. 3. Group R and Group P did not show improvement in those parameters. 4. Group RRP had the highest S ao₂ in the PACU and earlier discharge time from the hospital.</td>
<td>Compared repeated RM followed by single RM followed by PEEP, RM alone, and PEEP alone</td>
</tr>
<tr>
<td>Reinius et al, 2009</td>
<td>30 / 45</td>
<td>Gastric bypass surgery</td>
<td>Age &lt; 18 years, pregnancy, cardiac disease, obstructive lung disease (FEV₁ &lt; 80% of predicted value)</td>
<td>Group PEEP: PEEP of 10 cm H₂O Group RM + ZEEP: RM followed by ZEEP Group RM + PEEP: RM followed by PEEP of 10 cm H₂O (RM: PIP 55 cm H₂O for 10-second hold)</td>
<td>Spiral CT, single-section CT, Pao₂/Fio₂, PaCO₂, C₉₅, EELV, atelectasis, MAP, HR</td>
<td>1. Induction of anesthesia and paralysis dramatically reduced EELV, promoted atelectasis, and caused a marked fall in Pao₂. 2. RM followed by PEEP increased EELV, decreased atelectatic lung areas, increased compliance, and improved Pao₂.</td>
<td>Presented visual evidence via CT images to demonstrate the effects of anesthesia and paralysis, as well as the effects of PEEP alone, RM alone, and RM + PEEP on EELV and atelectasis</td>
</tr>
</tbody>
</table>

continues on page 38
<table>
<thead>
<tr>
<th>Study</th>
<th>Year</th>
<th>Procedure</th>
<th>Protocol Details</th>
<th>Outcomes</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Talab et al.</td>
<td>2009</td>
<td>Laparoscopic bariatric surgery</td>
<td>Hospitalization for &gt; 24 hours before surgery, heart or lung diseases</td>
<td>Group ZEEP: RM + ZEEP Group PEEP 5: RM + PEEP 5 cm H₂O Group PEEP 10: RM + PEEP 10 cm H₂O</td>
<td>A-aDO₂, preoperative CT, postoperative CT, atelectasis score, HR, MAP</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>PEEP 10 group had better oxygenation intraoperatively and postoperatively, lower atelectasis score, fewer postoperative pulmonary complications, and shorter hospital stay than other 2 groups</td>
<td>Demonstrated that RM was effective only when it was followed by an effective PEEP. PEEP at 10 cm H₂O was effective, while PEEP at 5 cm H₂O was not.</td>
</tr>
<tr>
<td>Defresne et al.</td>
<td>2014</td>
<td>Laparoscopic gastric bypass</td>
<td>Age &lt; 18 and &gt; 65 years, diagnosis of OSA, history of pneumothorax or right-sided heart failure, surgery scheduled to take place on a Friday</td>
<td>RM group: 40 cm H₂O for 40 s, once after creation of the pneumoperitoneum, once after the exsufflation; PEEP 10 cm H₂O was used. Control group: no RM; PEEP 10 cm H₂O was used. Preoperative and postoperative spirometry: FRC, FVC, FEV₁, and Cresp</td>
<td>1. Intraoperative RM significantly improved Cresp 2. No significant difference in FRC, FVC, and FEV₁ was found between the groups postoperatively.</td>
</tr>
<tr>
<td>Coussa et al.</td>
<td>2004</td>
<td>Bariatric surgery</td>
<td>Hospitalization &gt; 24 hours before surgery, history or clinical signs of heart or lung disease</td>
<td>Control group: no CPAP or PEEP before induction or before intubation Group PEEP: CPAP 10 cm H₂O before induction and PEEP of 10 cm H₂O after induction and before intubation</td>
<td>PaO₂, PaCO₂, CT before induction, CT after intubation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>PaO₂ was significantly higher in the PEEP group after intubation.</td>
<td>Significantly greater atelectasis developed in both groups after intubation but was more pronounced in the control group. 2. PaCO₂ was significantly higher in the PEEP group after intubation.</td>
</tr>
<tr>
<td>Futier et al.</td>
<td>2011</td>
<td>Laparoscopic sleeve gastrectomy or Roux-en-Y gastric bypass</td>
<td>Consent refusal, age &lt; 18 years, pregnancy, severe cardiac failure (NYHA class &gt; III), COPD (FEV₁ &lt; 80% of expected value)</td>
<td>Conventional preoxygenation group Group NIPPV: pressure support ventilation with PEEP of 6-8 cm H₂O and goal Vₚ of 8 mL/kg of predicted body weight Group NIPPV + RM: NIPPV followed by RM; RM was applied after intubation with 40 cm H₂O for 40 s</td>
<td>PaO₂, EELV, PaCO₂, arterial pH, MAP, HR, Pmax, Pplateau, Eresp</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>PaO₂, EELV, PaCO₂, arterial pH, MAP, HR, Pmax, Pplateau, Eresp</td>
<td>1. NIPPV resulted in better oxygenation compared with conventional preoxygenation during induction; 2. NIPPV + RM further optimized PaO₂ and EELV.</td>
</tr>
<tr>
<td>De Baerdemaeker et al.</td>
<td>2008</td>
<td>Laparoscopic gastric banding surgery</td>
<td>Cardiopulmonary disease, hepatorenal disease</td>
<td>Group VCV: Vt 10 mL/kg IBW; end-inspiratory pause of 10% of the inspiratory time Group PCV: Pressure set to achieve Vt 10 mL/kg IBW without exceeding pressure limit of 35 cm H₂O</td>
<td>HR, MAP, PaO₂, PaCO₂, PAP, Pplateau, Pmean, Cresp, Rresp, SaO₂, A-aDO₂</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>HR, MAP, PaO₂, PaCO₂, PAP, Pplateau, Pmean, Cresp, Rresp, SaO₂, A-aDO₂</td>
<td>1. VCV generated equal airway pressures and cardiovascular effects with a lower Paco₂ than PCV 2. There was no difference in oxygenation between the 2 groups.</td>
</tr>
</tbody>
</table>

Continued from page 37
Laparoscopic gastric banding surgery

Major obstructive or restrictive pulmonary disease (<70% of predicted values for PFT variables) PaCO₂ < 6 kPa

Group PVC: Pₚₚₐₜₑᵤₑ set so that VT = 8 mL/kg
Group VCV: VT = 8 mL/kg

Pao₂, Paco₂, Sao₂, Pao₂/Fio₂, peak inspiratory flow, PAP, Pₚₚₐₜₑᵤₑ

1. PCV group had significantly higher Pao₂, Sao₂, Pao₂/Fio₂ ratio than VCV group.
2. Paco₂, ETCO₂-Paco₂ gradient were lower in the PCV group than VCV group.

Authors suggested that PCV using decelerating inspiratory flow could allow alveolar recruitment without side effects.

---

Laparoscopic or open Roux-en-Y surgery

Not applicable

Group VCV: VT titrated to maintain ETCO₂ around 35 mm Hg
Group PCV: pressure was adjusted to provide the same VT as in VCV
Crossover: 30 minutes of VCV followed by 30 minutes of PCV, and vice versa

BP, HR, ETCO₂, Spo₂, PAP, Pₚₚₐₜₑᵤₑ Pₘₑᵃⁿ

Peak inspiratory airway pressures were significantly lower during PCV than during VCV. There was no difference in other respiratory parameters.

Crossover design of the study reduces the effect of intergroup heterogeneity, but the study did not report the absence of carryover effect.

---

Laparoscopic gastric band ligation

Substantial obstructive or restrictive pulmonary disease (<70% of predicted values for PFT variables or PaCO₂ > 45 mm Hg), active asthma, substantial cardiac dysfunction (LVEF ≤ 40 %)

Group 1: I:E = 1:1
Group 2: I:E = 1:2
Crossover: group 1: I:E = 1:2; group 2: I:E = 1:1

Pao₂, Paco₂, ETCO₂, PAP, Pₚₚₐₜₑᵤₑ, MAP, HR

1. Pao₂ and C₀₂₉ were significantly increased during ERV compared with conventional ventilation after the carryover effect was ruled out.
2. PAP was lower with ERV than conventional 1:2 ratio ventilation.

Study was the first to evaluate the effect of equal ratio ventilation in this patient population. It provides an alternative to RM.

### Table 2. Matrix of Randomized Clinical Trials Reviewed

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Year</th>
<th>Published</th>
<th>Procedure</th>
<th>Patients</th>
<th>Methods</th>
<th>Findings</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cadi et al, 23</td>
<td>2008</td>
<td>36 / 44</td>
<td>Laparoscopic gastric banding surgery</td>
<td>Major obstructive or restrictive pulmonary disease (&lt;70% of predicted values for PFT variables) PaCO₂ &lt; 6 kPa</td>
<td>Group PVC: Pₚₚₐₜₑᵤₑ set so that VT = 8 mL/kg Group VCV: VT = 8 mL/kg</td>
<td>Pao₂, Paco₂, Sao₂, Pao₂/Fio₂, peak inspiratory flow, PAP, Pₚₚₐₜₑᵤₑ</td>
<td>1. PCV group had significantly higher Pao₂, Sao₂, Pao₂/Fio₂ ratio than VCV group. 2. Paco₂, ETCO₂-Paco₂ gradient were lower in the PCV group than VCV group. Authors suggested that PCV using decelerating inspiratory flow could allow alveolar recruitment without side effects.</td>
</tr>
<tr>
<td>Hans et al, 24</td>
<td>2008</td>
<td>40 / 42</td>
<td>Laparoscopic or open Roux-en-Y surgery</td>
<td>Not applicable</td>
<td>Group VCV: VT titrated to maintain ETCO₂ around 35 mm Hg Group PCV: pressure was adjusted to provide the same VT as in VCV Crossover: 30 minutes of VCV followed by 30 minutes of PCV, and vice versa</td>
<td>BP, HR, ETCO₂, Spo₂, PAP, Pₚₚₐₜₑᵤₑ Pₘₑᵃⁿ</td>
<td>Peak inspiratory airway pressures were significantly lower during PCV than during VCV. There was no difference in other respiratory parameters. Crossover design of the study reduces the effect of intergroup heterogeneity, but the study did not report the absence of carryover effect.</td>
</tr>
<tr>
<td>Mousa, 25</td>
<td>2013</td>
<td>30 / 49</td>
<td>Laparoscopic gastric band ligation</td>
<td>Substantial obstructive or restrictive pulmonary disease (&lt;70% of predicted values for PFT variables or PaCO₂ &gt; 45 mm Hg), active asthma, substantial cardiac dysfunction (LVEF ≤ 40 %)</td>
<td>Group 1: I:E = 1:1 Group 2: I:E = 1:2 Crossover: group 1: I:E = 1:2; group 2: I:E = 1:1</td>
<td>Pao₂, Paco₂, ETCO₂, PAP, Pₚₚₐₜₑᵤₑ, MAP, HR</td>
<td>1. Pao₂ and C₀₂₉ were significantly increased during ERV compared with conventional ventilation after the carryover effect was ruled out. 2. PAP was lower with ERV than conventional 1:2 ratio ventilation. Study was the first to evaluate the effect of equal ratio ventilation in this patient population. It provides an alternative to RM.</td>
</tr>
</tbody>
</table>
PEEP alone, recruitment maneuver plus PEEP, induction PEEP, induction PEEP plus intraoperative recruitment maneuver and PEEP, PCV, VCV, and equal ratio ventilation. The ventilation strategies and associated findings are summarized in Table 3.

Multiple RCTs showed no beneficial effects in applying recruitment maneuver alone without use of PEEP regardless of the delivery method of the recruitment maneuver.14,16-18 When PEEP alone without preceding recruitment maneuver was used, some studies found improvement in oxygenation,15 or respiratory compliance,17 but the results were not consistent among the studies. In contrast, irrespective of the delivery method, recruitment maneuver immediately followed by PEEP exhibited consistent positive effects in multiple RCTs on oxygenation, respiratory compliance, and atelectasis reduction.13-19 Furthermore, some studies demonstrated that repeated recruitment maneuver may be more beneficial than single recruitment maneuver in maintaining the achieved oxygen status and improved pulmonary mechanics.13,16

In the studies, recruitment maneuver was delivered with several methods, including (1) incremental increase in PEEP to 20 cm H2O, then decreased to the maintenance PEEP level,13 and (2) inspiratory pressure set at 40 to 55 cm H2O, which was held for 5 to 40 seconds with a variety of combinations between the 2 variables, with PEEP of 40 cm H2O for 15 seconds or 40 seconds being the most frequently used strategy. The succeeding PEEP levels used in the aforementioned studies ranged from 5 to 12 cm H2O, with 10 cm H2O being the most frequently used. Most of the studies used predetermined PEEP levels. Talab et al18 compared 2 different PEEP levels preceded by the same recruitment maneuver and found that PEEP of 10 cm H2O was effective in maintaining the recruitment benefit, whereas PEEP of 5 cm H2O was not. All the studies reported either no incidence of barotrauma or no postoperative complications.13-19

Despite the consistent finding that recruitment maneuver followed by PEEP is an effective ventilation strategy for intraoperative management during bariatric surgery, its postoperative benefits remain undetermined. Almarakhi and colleagues16 found significantly higher pulse oximeter oxygen saturation (SpO2) and shorter hospital length of stay in the groups with single or repeated recruitment maneuver followed by PEEP compared with the groups with PEEP or recruitment maneuver alone. Similarly, Talab and colleagues18 reported better oxygenation, fewer postoperative complications, and shorter postanesthesia care unit and hospital stay in patients who received recruitment maneuver followed by PEEP of 10 cm H2O than in patients who received recruitment maneuver followed by PEEP of 5 cm H2O or zero PEEP. In addition, the computed tomography (CT) results in Talab et al18 showed significantly lower postoperative atelectasis score in the recruitment maneuver with PEEP of 10 cm H2O group compared with PEEP of 5 cm H2O and zero PEEP. Two other studies, however, did not find extended benefits of recruitment maneuver with PEEP in oxygenation, pulmonary mechanics, or length of stay.13,19

Two studies20,21 examined noninvasive positive pressure ventilation (NIPPV) during induction (see Table 2) and found that it was more effective in preventing atelectasis compared with conventional preoxygenation. Before induction, the experimental groups received continuous positive airway pressure (CPAP) at 10 cm H2O20 or pressure support ventilation with a PEEP of 6 to 8 cm H2O,21 whereas the control groups received conventional preoxygenation without CPAP or pressure support ventilation with PEEP.20,21 After induction, Coussa et al20 continued with NIPPV via VCV with PEEP of 10 cm H2O in the experimental group, and the control group received VCV without PEEP. Futier et al21 proceeded with intubation without further ventilation after induction but used recruitment maneuver with PEEP after intubation in the group receiving NIPPV with recruitment maneuver. Coussa et al20 found better oxygenation and demonstrated significantly less atelectasis on CT scans immediately after intubation in the PEEP group than in the control group. Futier et al21 measured the end-expiratory lung volume with helium dilution and found better oxygenation and higher end-expiratory lung volume in the NIPPV groups compared with the control group.

Among the studies that compared VCV and PCV (see Table 2),22-24 2 of the 3 studies22,24 found no significant difference, whereas the other study23 found PCV to be more effective than VCV in oxygenating and improving respiratory compliance in obese patients undergoing bariatric surgery. Cadi et al23 achieved better arterial partial pressure of oxygen/inspired fraction of oxygen ratio (PaO2/FI O2; P < .011) in the PCV group than in the VCV group, probably because the intensive care unit (ICU) ventilators used were able to generate high flow (> 150 L/min). The authors argued that the decelerating flow during inspiration from PCV contributed to the improvement in pulmonary dynamic compliance and oxygenation.23 Hans et al24 also used ICU ventilators and achieved comparable tidal volume between the study groups but found no significant difference in PaO2 or arterial partial pressure of carbon dioxide (PaCO2). Similarly, De Baerdemaecker et al22 demonstrated no difference in alveolar-arterial oxygen difference (A-aDO2) between the PCV and the VCV groups, but the VCV group exhibited more efficient carbon dioxide elimination manifested in significantly lower PaCO2 (P < .01).

Finally, Mousa25 (see Table 2) compared equal ratio ventilation and conventional 1:2 ratio ventilation and found that equal ratio ventilation was associated with a significant increase in PaO2 and dynamic compliance of the respiratory system. The study ruled out the carryover...
### Table 3. Summary of Results

<table>
<thead>
<tr>
<th>Ventilation maneuver</th>
<th>Studies</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>RM alone</td>
<td>Valenza et al,14 Almarakbi et al,16 Reinius et al,17 Talab et al18</td>
<td>RM alone did not improve oxygenation or pulmonary mechanics.</td>
</tr>
<tr>
<td>PEEP alone</td>
<td>Whalen et al13</td>
<td>PEEP of 4 cm H₂O did not significantly improve oxygenation or respiratory compliance.</td>
</tr>
<tr>
<td></td>
<td>Chalhoub et al15</td>
<td>PEEP of 8 cm H₂O did not show significant results at 10 minutes after application of PEEP but showed significant improvement in oxygenation (SaO₂, PaO₂, and A-aDO₂) at the end of the open bariatric surgeries. Compliance was not measured.</td>
</tr>
<tr>
<td></td>
<td>Almarakbi et al16</td>
<td>PEEP of 10 cm H₂O did not reverse the decrease in PaO₂ and respiratory compliance elicited by anesthesia, paralysis, and pneumoperitoneum during laparoscopic bariatric surgery.</td>
</tr>
<tr>
<td></td>
<td>Reinius et al17</td>
<td>PEEP of 10 cm H₂O resulted in a significant increase in compliance but not in PaO₂/FI O₂ ratio compared with immediately after anesthesia in open bariatric surgery. CT showed an increase in normally aerated volume and a reduction of poorly aerated volume, but atelectasis remained the same in the PEEP alone group.</td>
</tr>
<tr>
<td></td>
<td>Defresne et al19</td>
<td>PEEP of 10 cm H₂O group, similar to RM + PEEP group, showed significantly decreased FVC and FEV1 24 hours after the laparoscopic gastric bypass.</td>
</tr>
<tr>
<td>RM + PEEP</td>
<td>Whalen et al,13 Valenza et al,14 Chalhoub et al,15 Almarakbi et al,16 Reinius et al,17 Talab et al,18 Defresne et al19</td>
<td>Intraoperative effect: RM with PEEP significantly improved intraoperative oxygenation (PaO₂, SaO₂, PaO₂/FI O₂, and A-aDO₂) and respiratory compliance, and reduced atelectasis. RM followed by PEEP was more effective than either RM or PEEP alone. PEEP of ≤ 5 cm H₂O was not effective in maintaining the recruited alveoli.</td>
</tr>
<tr>
<td></td>
<td>Coussa et al,20 Futier et al21</td>
<td>PEEP during induction significantly reduced atelectasis formation, and resulted in better oxygenation and higher EELV compared with conventional zero PEEP induction.</td>
</tr>
<tr>
<td></td>
<td>Induction PEEP + intraoperative RM and PEEP Futier et al21</td>
<td>NIPPV during induction + intraoperative RM and PEEP resulted in further improvement in oxygenation and EELV compared with NIPPV alone.</td>
</tr>
<tr>
<td></td>
<td>De Baerdemaeker et al,22 Cadi et al,23 Hans et al24</td>
<td>One study found PCV was more effective than VCV in oxygenation and V/Q improvement,21 whereas the other 2 studies did not find any advantage in PCV vs VCV.20,22</td>
</tr>
<tr>
<td></td>
<td>De Baerdemaeker et al,22 Cadi et al,23 Hans et al24</td>
<td>One study found VCV was less effective than PCV in oxygenation and V/Q improvement,21 whereas the other 2 studies did not find any advantage in PCV vs VCV.20,22</td>
</tr>
<tr>
<td></td>
<td>Mousa25</td>
<td>ERV was associated with significant increase in PaO₂ and CDYN, and lower PAP compared with conventional ventilation.</td>
</tr>
</tbody>
</table>

Abbreviations: A-aDO₂, alveolar-arterial oxygen difference; CDYN, dynamic compliance; CT, computed tomography; EELV, end-expiratory lung volume; ERV, equal ratio (1:1) ventilation; FEV₁, forced expiratory volume in 1 second; FVC, forced vital capacity; NIPPV, noninvasive positive pressure ventilation; PACU, post-anesthesia care unit; PaO₂, arterial partial pressure of oxygen; PaO₂/FI O₂, ratio of arterial oxygen tension and fraction of inspired oxygen; PAP, peak airway pressure; PCV, pressure-controlled ventilation; PEEP, positive end-expiratory pressure; RM, recruitment maneuver; SaO₂, arterial O₂ saturation; VCV, volume-controlled ventilation; V/Q, ventilation/perfusion ratio.
effect, which is a crucial step in crossover studies to establish the validity of the results.26

Discussion
The ventilation maneuvers evaluated in these studies were used to compensate for the respiratory pathophysiology of obesity. Alterations in the pulmonary mechanics associated with obesity include decreased compliance, increased elastance, decreased FRC, shunt, and susceptibility to hypoxemia.7 Aside from traditional mechanical ventilation modes such as PCV vs VCV, most of the ventilation strategies for the obese population have been derived from ventilation strategies for acute respiratory distress syndrome (ARDS) in the ICU. Some examples are recruitment maneuver, PEEP, and equal ratio ventilation, which was derived from inverse ratio ventilation from ICU studies.25 In this section, the aforementioned ventilation strategies are discussed based on the current evidence, to draw conclusions to guide clinical practice and future research.

Recruitment Maneuver and PEEP. Recruitment maneuvers consistently produced statistically significant improvement in oxygenation, lung volume expansion, and atelectasis prevention in multiple RCTs included in this review.13-19 The results were irrespective of the delivery methods of recruitment maneuver. In other words, regardless of the methods used to achieve alveolar recruitment, recruitment maneuver across the studies generated positive results.13-19 A systematic review and meta-analysis of ventilation strategies in obese surgical patients conducted by Aldenkortt et al27 found similar results. However, the authors were unable to generate specific recommendations regarding recruitment maneuvers, probably because of high heterogeneity in the delivery methods of recruitment maneuver as well as the metrics used to measure the effect of recruitment maneuver.

Recruitment maneuver is only effective, however, when it is followed by adequate PEEP. Recruitment maneuver uses sustained pressure to open the closed or collapsed alveoli, and it thereby improves compliance, alveolar ventilation, and oxygenation and decreases elastance and airway resistance. The succeeding PEEP is used to maintain the recruited alveoli. The technique is also known as “open the lungs and keep them open.” In the studies,13-19 recruitment maneuver was delivered via a variety of methods, all of which were effective and without adverse effects such as barotrauma. The most commonly used methods were PEEP of 40 cm held for 15 seconds and PEEP of 40 cm H2O held for 40 seconds. There is currently no consensus on the optimal method. Similarly, the range of effective PEEP has not yet been identified, although PEEP of 5 cm H2O or below was shown to be ineffective in maintaining the recruitment effect in morbidly obese patients.18 In the studies included in this review,13-19 PEEP levels of 8 to 12 cm H2O demonstrated effectiveness without significantly affecting the hemodynamic stability. The difficulty in determining the optimal recruitment maneuver method and PEEP level is partly attributed to lack of consensus on the best metrics to measure the effectiveness of recruitment maneuver and PEEP.28-30

The different postoperative effects of recruitment maneuver and PEEP in the studies may have arisen from the difference in methods. Whalen et al13 repeated recruitment maneuver only when the PaO2 decreased more than 25 mm Hg below the maximal PaO2 achieved, whereas Almarakbi et al16 used repeated recruitment maneuver every 10 minutes in the repeated recruitment maneuver plus PEEP group. The only study that focused on the postoperative effect of recruitment maneuver with PEEP19 failed to measure the immediate postoperative respiratory parameters. In addition, the same study used a nonrebreather mask for all subjects immediately after extubation, when high FiO2 has been demonstrated to promote atelectasis.31-33 Future high-quality studies are needed to confirm or negate the postoperative benefits of recruitment maneuver with PEEP.

Concerns related to recruitment maneuver and PEEP include barotrauma, hemodynamic instability, and increased intracranial pressure.15 None of the studies reported barotrauma. Studies of the effect of high volume vs high pressure on lung parenchyma found that high-volume–low-pressure ventilation, rather than high-pressure–low-volume ventilation, induces severe cellular injury leading to pulmonary edema, and that PEEP has a significant protective effect on the pulmonary epithelium.34-36 In other words, “volutrauma” rather than barotrauma is the concern.37 Large tidal volume ventilation leads to shear stress on pulmonary tissue because of cyclic recruitment-derecruitment, which can be prevented with PEEP.38 Similarly, repeated recruitment maneuvers without PEEP can also induce cyclic recruitment-derecruitment, which explains its lack of efficacy and even potential damage to pulmonary parenchyma.

As for the hemodynamic effect of recruitment maneuver with PEEP, one study reported significantly higher total dose of vasopressor used for the recruitment maneuver group compared with the control group.13 The subsequent studies, however, reported no significant difference in hemodynamics between the experimental and the control groups, probably due to intravascular fluid preload used in these studies.14-19 From the current studies, it appears that preloadning with either crystalloid or colloid is effective in preventing hemodynamic instability associated with recruitment maneuver and PEEP.14-19

Pressure-Controlled Ventilation Versus Volume-Controlled Ventilation. Based on the studies included in this review,22-24 PCV and VCV do not differ significantly in their efficacy in ventilating obese patients undergo-
ing bariatric surgery. Only 1 of the 3 studies found significant difference in oxygenation between PCV and VCV groups, whereas the other 2 studies found no intergroup difference.

Pressure controlled ventilation versus VCV studies in ICU settings exhibit similarly inhomogeneous results. After reviewing the current evidence, Garnero et al. concluded that the 2 ventilator modes were comparable in their efficacy. Campbell and Davis. opined that with advanced ventilators neither mode was better than the other; they suggested that “a volume-targeted, pressure-limited, and time-cycled” ventilator mode could combine all the beneficial characteristics of PCV and VCV. Indeed, the suggested mode is now available in newer anesthesia ventilators as pressure control with volume guarantee, which aims to deliver a targeted volume within the set pressure limit.

- **Noninvasive Positive Pressure Ventilation During Induction.** Farmery and Roe. noted that the rate of oxyhemoglobin desaturation to 85% in obese patients is 46 seconds without preoxygenation and 171 seconds with preoxygenation, compared with 84 seconds without and 502 seconds with preoxygenation in normal-weight patients. Adequate preoxygenation provides a longer nonhypoxic apnea duration and thus a safer intubation period. In addition, a large amount of absorption atelectasis can form during the induction period, especially in obese patients. Coussa et al. and Futier et al. found that noninvasive positive pressure of 6 to 10 cm H\textsubscript{2}O is effective in preventing atelectasis and optimizing oxygen reserve during induction. Futier et al. used recruitment maneuver and PEEP after intubation and were able to further improve arterial oxygenation and end-expiratory lung volume. Results of other studies of nonbariatric surgical patients also support the benefits of NIPPV during induction. For example, Gander et al. found longer nonhypoxic apnea duration (P = .002) and higher Pa\textsubscript{O\textsubscript{2}} (P = .038) in the PEEP group of the morbidly obese patients than in the zero-PEEP group. Although inspiring 100% oxygen on anesthesia induction promotes atelectasis, it is desirable to use high Fi\textsubscript{O\textsubscript{2}} to prolong the safe apneic duration in morbidly obese patients. Even with concurrent administration of 100% oxygen, Rusca et al. were able to prevent atelectasis and improve Pa\textsubscript{O\textsubscript{2}} (P = .005) in the experimental group with CPAP during spontaneous ventilation and PEEP with VCV during the apnea period before intubation in normal-weight patients. Use of CPAP and PEEP during induction can minimize the atelectatic effect of high Fi\textsubscript{O\textsubscript{2}}, increase Pa\textsubscript{O\textsubscript{2}}, and prolong the nonhypoxic apnea duration.

The concerns for positive pressure use during the induction period include claustrophobia during spontaneous breathing and increased risk of aspiration when NIPPV is used during the apnea period before intubation. The patients in the studies seemed to have tolerated the tight seal of the mask well, but patients with known claustrophobia may have not consented in the first place. No incidence of aspiration was reported in the studies, probably because both studies limited peak airway pressure to less than 20 cm H\textsubscript{2}O. Coussa and colleagues. argued that the risk of aspiration was low when patients did not have gastroesophageal reflux disease and when aspiration prophylaxis with H\textsubscript{2} receptor antagonists, antacids, and prokinetic agents was used.

- **Equal Ratio Ventilation.** Moussa was the first to study the effect of equal ratio ventilation in obese patients undergoing bariatric surgery. The ventilation strategy was derived from inverse ratio ventilation, which has been well researched in patients with ARDS and acute lung injury in ICUs. In operating room, inverse ratio ventilation was found to decrease A-aDO\textsubscript{2} and increase compliance, concurrent with the ICU findings. By increasing the length of inspiration time, inverse ratio ventilation and equal ratio ventilation possibly recruit collapsed alveoli and improve ventilation. On the other hand, decreased expiration time could cause production of auto-PEEP, accumulation of carbon dioxide, and subsequently increased intracranial pressure. In two intraoperative studies, however, neither end-tidal carbon dioxide (ETCO\textsubscript{2}) nor intracranial pressure was affected when the respiration rate and peak inspiratory pressure were adjusted to keep the ETCO\textsubscript{2} within normal limits. Equal ratio ventilation as a novel approach may offer some advantages over recruitment maneuver with PEEP in patients who cannot tolerate high inflation pressure. The efficacy and safety of equal ratio ventilation requires more studies in the future.

**Conclusion**

Recruitment maneuver followed by PEEP is an effective ventilation strategy for obese patients undergoing bariatric surgery. Recruitment maneuver alone is not effective and PEEP alone is less effective than recruitment maneuver followed by PEEP. During induction, NIPPV provides further benefits by preventing atelectasis formation and prolonging nonhypoxic apnea duration. There is no significant difference between PCV and VCV, especially when advanced ventilator modes such as pressure control with volume guarantee are used. Further studies are needed to examine the postoperative effects of recruitment maneuver with PEEP as well as the efficacy and safety of equal ratio ventilation.

**REFERENCES**


AUTHOR

Xin Yan Hu, MA, MSN, CRNA, graduated from the nurse anesthesia program of Lourdes University in Sylvania, Ohio. She is currently a nurse anesthetist in Allegiance Health, Jackson, Michigan. The manuscript was part of the capstone project for the MSN nurse anesthesia program. Email: kellyhuxinyan@yahoo.com.

DISCLOSURE

The author has declared no financial relationships with any commercial interest related to the content of this activity. The author did not discuss off-label use within the article.

ACKNOWLEDGMENTS

The author would like to thank Jill Ann Liebnau, MS, CRNA, and Lynne Zajac, PhD, RN, for mentoring her capstone project and for their support through the CRNA program.