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Review Article

Closed-Loop Ventilation Strategies During Major Surgical Procedures

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ABSTRACT

Closed-loop ventilation systems continuously adjust minute ventilation, tidal volume, or inspired oxygen fraction using real-time capnography and pulse oximetry, offering an alternative to the intermittent manual titration typical of conventional intraoperative ventilator management.

This review synthesizes the evidence for closed-loop ventilation and oxygen titration across cardiac, thoracic, and general surgical populations, alongside the literature establishing individualized, driving-pressure-minimizing PEEP as a lung-protective target.

Closed-loop platforms such as IntelliVent-ASV and automated FiO2 titration systems consistently keep patients within protective ventilation and oxygenation targets more often than manual management, with evidence spanning intensive care, cardiac surgery, trauma care, and one-lung ventilation.

Evidence that this tighter physiological control reduces postoperative pulmonary complications or improves neurocognitive outcomes remains limited, whereas meta-analytic data on individualized, driving-pressure-guided PEEP show a firmer association with fewer pulmonary complications after abdominal and thoracic surgery.

We conclude that closed-loop ventilation usefully maintains protective targets with less manual effort, and that pairing it with driving-pressure-guided titration across the perioperative period is the most promising direction for future outcome trials.

Keywords: *closed-loop ventilation; intraoperative ventilation; driving pressure; lung-protective ventilation; automated oxygen titration*

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INTRODUCTION

Intraoperative mechanical ventilation has traditionally been a manually tuned exercise: an anesthesiologist sets a tidal volume, a respiratory rate, an inspired oxygen fraction, and a level of positive end-expiratory

pressure (PEEP) at induction, then adjusts these parameters intermittently based on blood gases, capnography, and clinical judgment. Over a four- or six-hour operation this means the ventilator largely runs on settings chosen at the start of the case, even as the patient's compliance, oxygenation, and hemodynamics evolve with surgical positioning, pneumoperitoneum, one-lung isolation, or blood loss. Closed-loop ventilation systems were built to close this gap. Rather than a clinician reacting to a blood gas drawn every hour or two, an algorithm continuously reads expired CO2, oxygen saturation, and mechanical variables such as compliance and resistance, and adjusts minute ventilation, tidal volume, respiratory rate, or FiO2 breath by breath [1].

The clinical case for automation in the operating room rests on two converging bodies of evidence. First, large trials in general anesthesia established that lung-protective ventilation—lower tidal volumes, individualized PEEP, and periodic recruitment—reduces postoperative pulmonary complications after abdominal and thoracic surgery [2,3]. Second, work in the intensive care unit with systems such as IntelliVent-ASV demonstrated that an algorithm can maintain patients within protective ventilation targets more consistently than manual titration, particularly overnight or during periods of high staff workload [4,5]. Bringing these two threads together in the operating room raises a natural question: if closed-loop control keeps ICU patients within protective bounds more reliably, does it do the same for a patient undergoing major surgery, and does that translate into measurable outcome benefit rather than simply tighter numbers on a ventilator display.

This review surveys the evidence for closed-loop ventilation strategies specifically in the perioperative and intraoperative setting, covering automated minute-ventilation and tidal-volume control, closed-loop oxygen titration, and the parallel but distinct effort to individualize driving pressure and PEEP. We also consider what closed-loop systems mean for the anesthesiologist's workload and attention during a case, and where the evidence remains preliminary.

AUTOMATED MINUTE VENTILATION AND TIDAL VOLUME CONTROL

The core function of most closed-loop ventilation modes is to hold end-tidal or arterial CO2 within a target range by adjusting tidal volume and respiratory rate automatically, rather than requiring the clinician to reset these values after every capnography trend change. IntelliVent-ASV, the most extensively studied closed-loop platform, layers this CO2-targeting function on top of adaptive support ventilation's compliance-based tidal volume selection, and extends the same logic to FiO2 and PEEP based on pulse oximetry. In a randomized ICU trial, IntelliVent-ASV kept patients within a protective ventilation zone for a larger proportion of ventilation time than conventional management, without increasing adverse events [4]. A feasibility study of full closed-loop control in patients with acute respiratory failure reached a similar conclusion: the system tracked changing respiratory mechanics and reduced the need for manual ventilator adjustment, though the patient populations studied were heterogeneous and the primary endpoints were largely process measures rather than mortality or length of stay [5].

Translating this into the operating room, a randomized trial of anesthetic management using multiple closed-loop systems—automated propofol and remifentanil titration paired with closed-loop ventilation—examined whether this bundle of automation reduced delayed neurocognitive recovery after major noncardiac surgery. The closed-loop arm achieved tighter control of depth of anesthesia and ventilation parameters than manual management, though the effect on neurocognitive outcomes was more nuanced, underscoring that better process metrics do not automatically translate into a measurable difference in a downstream clinical endpoint [6]. In cardiac surgery, a trial comparing sidestream and mainstream capnography as the sensor input for closed-loop minute ventilation adjustment found both approaches feasible for automated titration, with the choice of capnography method affecting response time and stability of control rather than whether closed-loop ventilation itself was workable in this population [7]. Earlier work evaluating fully automated ventilation after cardiac surgery similarly found that closed-loop control could manage the early postoperative ventilation period—typically a brief, relatively stable window—at least as well as protocol-driven manual weaning, with less need for clinician intervention [8].

Systematic reviews of closed-loop ventilation across critical care and perioperative settings converge on a consistent pattern: automated systems reliably reduce the number of manual ventilator adjustments and the time spent outside pre-specified target ranges for tidal volume, respiratory rate, and blood gas values, but the evidence for improvements in hard clinical outcomes—mortality, ventilator-free days, duration of mechanical ventilation—remains inconsistent and is often underpowered because trials are sized around physiological or process endpoints [9,10,11]. A dedicated systematic review of IntelliVent-ASV's effectiveness and safety reached the same conclusion specifically for that platform, finding good evidence for improved adherence to protective ventilation settings but only limited data on mortality or length of stay [12]. A narrative review focused specifically on ventilation strategies across the perioperative continuum makes the related point that intraoperative and early postoperative ventilation are often managed as separate problems by separate teams, and that closed-loop platforms capable of following a patient

from induction through extubation and into recovery could, in principle, smooth that transition, though few studies have actually tested continuity of automated management across that handoff [13].

CLOSED-LOOP OXYGEN TITRATION

A parallel line of automation targets FiO2 rather than minute ventilation, using pulse oximetry as the closed-loop input to keep oxygen saturation within a narrow target band. The rationale is straightforward: both hypoxemia and hyperoxemia carry risk, hyperoxia in particular having been associated with absorption atelectasis, oxidative injury, and in some populations worse outcomes, yet manual FiO2 titration tends to drift toward comfortably high settings that a busy clinician does not revisit often. A crossover trial in pediatric patients found that automated closed-loop FiO2 titration increased the proportion of time spent within the intended oxygen saturation range compared with manual titration by bedside staff, a finding consistent with the general premise that an algorithm attending to saturation continuously outperforms a human sampling it intermittently [14]. A randomized trial in mechanically ventilated trauma and acute care surgery patients similarly found that automated inspired oxygen control improved time in target range relative to standard titration protocols [15], and comparable benefit has been reported in cardiac surgical patients recovering in the ICU, where automated titration increased time within a prescribed saturation range without increasing adverse events [16].

Intraoperatively, one-lung ventilation for thoracic surgery is a setting where oxygen exposure is often high by necessity and where a device-based approach to continuous titration has particular appeal, since desaturation events can occur quickly during lung isolation. A randomized trial using an oxygen reserve index to continuously titrate inspired oxygen during one-lung ventilation found that this approach reduced excess oxygen exposure relative to a fixed or intermittently adjusted FiO2 strategy, without compromising oxygenation safety margins [17]. A broader systematic review and meta-analysis of closed-loop oxygen control in critically ill patients—spanning ICU and some perioperative populations—found consistent improvement in time within target oxygenation range across studies, again with more heterogeneous evidence for whether this translates into fewer complications such as pneumonia, retinopathy in neonatal populations, or mortality [18]. A recent review of intraoperative oxygen titration practice concluded that despite decades of physiological rationale for avoiding both hypoxemia and unnecessary hyperoxia, actual practice remains variable and under-protocolized, which is precisely the gap that closed-loop titration is positioned to fill, even though large outcome trials specific to the intraoperative period are still lacking [19].

DRIVING PRESSURE, INDIVIDUALIZED PEEP, AND LUNG-PROTECTIVE TARGETS

Closed-loop control of minute ventilation and oxygen is only as good as the targets it is asked to maintain, and a substantial parallel literature has worked to define what those targets should be for the surgical patient. The landmark IMPROVE trial showed that a lung-protective ventilation strategy—reduced tidal volume, moderate PEEP, and recruitment maneuvers—reduced postoperative pulmonary and extrapulmonary complications after major abdominal surgery compared with a more conventional, higher-tidal-volume approach [2]. This established the broad protective ventilation package as a reasonable default, but subsequent work has focused on driving pressure—the difference between plateau pressure and PEEP—as arguably a more mechanistically relevant single target than tidal volume or PEEP considered in isolation, since driving pressure reflects the tidal volume actually being delivered relative to the individual patient's respiratory system compliance.

A meta-analysis with trial sequential analysis examining driving-pressure-guided ventilation across surgical populations found an association between lower driving pressure and reduced postoperative pulmonary complications, with the trial sequential analysis suggesting the accumulated evidence had reached a threshold of reasonable confidence for this association, though the authors were careful to note that association in observational and mixed-design pooled data does not equal a causal demonstration from adequately powered dedicated randomized trials [20]. A more recent systematic review and meta-analysis specifically addressing individualized PEEP titrated to minimize driving pressure in minimally invasive thoracic and abdominal surgery reported that this individualized approach reduced postoperative pulmonary complications relative to a fixed, non-individualized PEEP strategy, reinforcing the idea that a patient-specific PEEP chosen to minimize driving pressure—something a closed-loop or decision-support algorithm could in principle titrate continuously—outperforms a one-size-fits-all setting [21]. A network meta-analysis comparing multiple lung-protective ventilation strategies head-to-head after noncardiac surgery similarly found that combinations incorporating individualized PEEP and recruitment maneuvers ranked more favorably for reducing pulmonary complications than low tidal volume alone, suggesting that the choice of PEEP strategy, not just tidal volume, is a meaningful lever [22].

These findings matter for closed-loop ventilation because driving-pressure minimization is exactly the kind of continuous, calculation-heavy titration task that benefits from automation: identifying the PEEP level that minimizes driving pressure requires repeated small ventilator adjustments and reassessment of

compliance, which is tedious to perform manually but straightforward for an algorithm with continuous access to airway pressure and flow data. To date, however, most of the closed-loop literature has focused on CO2 and oxygen targets rather than on automated driving-pressure or compliance-guided PEEP titration specifically, meaning that the theoretical case for combining closed-loop control with individualized PEEP is currently ahead of the direct trial evidence. The two literatures—automated ventilator control and individualized lung-protective targets—have largely developed in parallel rather than being tested together in the same protocol, which we return to below.

CLINICAL WORKLOAD, SAFETY, AND IMPLEMENTATION CONSIDERATIONS

Beyond physiological targets, a recurring theme in the closed-loop literature is workload: does automation actually free the clinician's attention for other tasks, or does it simply relocate the cognitive burden to monitoring the algorithm itself. Systematic review evidence in ICU settings suggests that closed-loop ventilation reduces the frequency of manual ventilator interventions and, in some studies, nursing or respiratory therapy time spent adjusting the ventilator, which is a plausible mechanism for benefit even in the absence of a clear mortality signal [9]. In the operating room, where the anesthesiologist is simultaneously managing hemodynamics, depth of anesthesia, fluid administration, and surgical communication, offloading routine ventilator titration to an algorithm has intuitive appeal, and the trial of combined closed-loop anesthetic and ventilatory management suggests this is technically feasible during major noncardiac surgery [6].

Safety considerations are not trivial, however. Closed-loop systems depend on the fidelity of their sensor inputs—capnography waveform quality, pulse oximetry signal, airway pressure transduction—and a degraded or artifactual signal can drive the algorithm toward an inappropriate adjustment just as readily as it can toward an appropriate one; the comparison of sidestream versus mainstream capnography for closed-loop minute ventilation control is itself partly a study of how sensor choice affects the reliability of the control loop [7]. Clinicians using these systems still need to understand the underlying ventilation strategy well enough to recognize when the algorithm's behavior is inappropriate for the clinical context—for instance, during one-lung ventilation, sudden hemodynamic instability, or a surgical maneuver that transiently changes chest wall or abdominal compliance—rather than treating the device as a fully autonomous replacement for clinical judgment. The narrative review of perioperative ventilation strategy explicitly frames closed-loop tools as decision support that augments rather than replaces the anesthesiologist's oversight, a framing echoed across the ICU systematic reviews of these platforms [13,10].

Regulatory and practical adoption barriers also shape how quickly this technology moves from trial settings into routine intraoperative use. Most published closed-loop ventilation trials to date have been single-center, and the platforms studied (IntelliVent-ASV being the most represented) are not universally available on operating room ventilators, so much of the current evidence base describes what is achievable under close research supervision rather than what typical practice looks like once these systems are deployed more broadly [5,11].

CONCLUSION

The evidence for closed-loop ventilation during major surgery is strongest where it is easiest to measure: these systems reliably keep patients closer to pre-specified targets for tidal volume, minute ventilation, and oxygen saturation than manual titration does, across cardiac, thoracic, and general surgical populations [4,7,14,15]. What remains less settled is whether this tighter physiological control reliably converts into fewer postoperative pulmonary complications, shorter recovery, or better neurocognitive outcomes, since the trials designed to test those harder endpoints have so far been smaller, more heterogeneous, and occasionally equivocal, as in the delayed neurocognitive recovery trial that combined closed-loop anesthesia with closed-loop ventilation [6]. Separately, the literature on lung-protective ventilation targets themselves has matured considerably, with individualized PEEP chosen to minimize driving pressure now supported by meta-analytic evidence of a reduction in postoperative pulmonary complications relative to fixed-PEEP strategies [21,20,22].

The most promising direction for closed-loop ventilation during major surgery is likely the marriage of these two threads: platforms that do not merely hold CO2 and oxygen saturation within a target range but that continuously identify and titrate to the individualized driving pressure and PEEP known to be protective, carried across the full perioperative period rather than confined to the intraoperative window alone [13]. Achieving that will require dedicated trials powered for clinical outcomes rather than physiological surrogates, broader commercial availability of closed-loop-capable operating room ventilators, and continued attention to how clinicians supervise rather than simply defer to an automated system [9,1]. Until that evidence accumulates, closed-loop ventilation is best regarded as a genuinely useful tool for maintaining protective ventilation targets with less manual effort, rather than as an established means of improving hard surgical outcomes on its own.

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Conflict of Interest

The authors declare no conflicts of interest relevant to this work.

Author Contributions

E. Lefevre conceived the review, conducted the literature synthesis, and drafted the manuscript. D. Bakker contributed to the literature search, critically revised the sections on oxygen titration and driving pressure, and reviewed the final draft. M. Sorensen contributed to the sections on clinical workload and implementation, revised the manuscript for intellectual content, and approved the final version. All authors read and approved the final manuscript.

Ethics Statement

This is a literature review; no new human or animal data were collected, and no ethics committee approval was required.

Data Availability

No new data were generated for this review. All sources discussed are cited and publicly available through their respective publishers.

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