

ARTIGO DE REVISÃO SISTEMÁTICA / SYSTEMATIC REVIEW ARTICLE

Effect of Low-Flow versus Conventional-Flow Inhalational Anaesthesia on Pulmonary and Oxygenation Outcomes in Adult Surgical Patients: A Systematic Review and Meta-Analysis of Randomised Controlled Trials

Efeito da Anestesia Inalatória de Baixo Fluxo versus Fluxo Convencional nos Resultados Pulmonares e de Oxigenação em Doentes Adultos Submetidos a Cirurgia: Revisão Sistemática e Meta-Análise de Ensaios Clínicos Aleatorizados

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Keywords

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Palavras-chave

Anestesia Geral; Anestésicos por Inalação; Complicações Pós-Operatórias; Oxigenação; Testes de Função Respiratória.

ABSTRACT

Introduction: Low-flow inhalational anaesthesia reduces volatile anaesthetic consumption, cost, and environmental emissions, but its effects on postoperative pulmonary function and oxygenation remain uncertain.

We aimed to evaluate the effect of low-flow compared with conventional- or high-flow inhalational anaesthesia on pulmonary and oxygenation outcomes in adult surgical patients.

Methods: A systematic review and meta-analysis of randomised controlled trials was performed. Eligible studies included adult surgical patients undergoing general anaesthesia and compared low-flow or minimal-flow inhalational anaesthesia with conventional-, medium-, or high-flow techniques. Primary outcomes were postoperative pulmonary function parameters, particularly FEV₁ and FVC. Secondary outcomes included SpO₂, PaO₂, ORI, respiratory mechanics, and postoperative pulmonary complications. Mean differences with 95% confidence intervals were pooled when outcomes were sufficiently comparable. Risk of bias was assessed using the Cochrane RoB 2 tool, and certainty of evidence was evaluated using GRADE.

Results: Nine randomised controlled trials were included. Two studies provided sufficient data for meta-analysis of postoperative spirometric outcomes at 24 hours. There was no statistically significant difference between low-flow and high-flow anaesthesia in FEV₁ at 24 hours (MD 0.18 L, 95% CI -0.09 to 0.44; $p = 0.19$; $I^2 = 24\%$) or FVC at 24 hours (MD 0.19 L, 95% CI -0.19 to 0.58; $p = 0.32$; $I^2 = 54\%$). Seven studies were narratively synthesised because of heterogeneity in outcome definitions, instruments, and timing.

Across these studies, no consistent clinically important differences were observed in SpO₂, PaO₂, ORI, or respiratory mechanics. No study formally reported postoperative pulmonary complications as a predefined outcome. Certainty of evidence was very low for FEV₁ and FVC and low to very low for other outcomes.

Conclusion: Low-flow inhalational anaesthesia appears comparable to conventional- or high-flow anaesthesia for short-term postoperative pulmonary function and oxygenation outcomes in adult surgical patients. However, certainty of evidence is low to very low because of small sample sizes and heterogeneous outcome reporting. Larger standardised trials are needed to evaluate clinically meaningful postoperative pulmonary complications.

RESUMO

Introdução: A anestesia inalatória de baixo fluxo reduz o consumo de anestésicos voláteis, os custos e as emissões ambientais, mas seus efeitos sobre a função pulmonar e a oxigenação no período pós-operatório permanecem incertos.

O nosso objetivo foi avaliar o efeito da anestesia inalatória de baixo fluxo, em comparação com a anestesia inalatória de fluxo convencional ou alto fluxo, sobre os desfechos pulmonares e de oxigenação em pacientes cirúrgicos adultos.

Métodos: Foi realizada uma revisão sistemática e meta-análise de ensaios clínicos randomizados. Foram incluídos estudos com pacientes cirúrgicos adultos submetidos à anestesia geral que compararam anestesia inalatória de baixo fluxo ou fluxo mínimo com técnicas de fluxo convencional, médio ou alto. Os desfechos primários foram parâmetros de função pulmonar pós-operatória, particularmente VEF₁ e CVF. Os desfechos secundários incluíram SpO₂, PaO₂, ORI, mecânica respiratória e complicações pulmonares pós-operatórias. As diferenças médias, com intervalos de confiança de 95%, foram combinadas quando os desfechos eram suficientemente comparáveis. O risco de viés foi avaliado utilizando a ferramenta Cochrane RoB 2, e a certeza da evidência foi avaliada utilizando o sistema GRADE.

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Resultados: Foram incluídos nove ensaios clínicos randomizados. Dois estudos forneceram dados suficientes para a meta-análise dos desfechos espirométricos pós-operatórios em 24 horas. Não houve diferença estatisticamente significativa entre a anestesia de baixo fluxo e a de alto fluxo no VEF₁ em 24 horas (DM 0,18 L; IC 95% -0,09 a 0,44; $p = 0,19$; $I^2 = 24\%$) ou na CVF em 24 horas (DM 0,19 L; IC 95% -0,19 a 0,58; $p = 0,32$; $I^2 = 54\%$). Sete estudos foram sintetizados narrativamente devido à heterogeneidade nas definições dos desfechos, instrumentos de avaliação e momentos de mensuração. Nesses estudos, não foram observadas diferenças clinicamente importantes e consistentes na SpO₂, PaO₂, ORI ou mecânica respiratória. Nenhum estudo relatou

formalmente complicações pulmonares pós-operatórias como um desfecho predefinido. A certeza da evidência foi muito baixa para VEF₁ e CVF e baixa a muito baixa para os demais desfechos.

Conclusão: A anestesia inalatória de baixo fluxo parece ser comparável à anestesia de fluxo convencional ou alto fluxo em relação aos desfechos de função pulmonar e oxigenação no pós-operatório de curto prazo em pacientes cirúrgicos adultos. No entanto, a certeza da evidência é baixa a muito baixa devido ao pequeno tamanho das amostras e à heterogeneidade na avaliação e no relato dos desfechos. São necessários estudos maiores e padronizados para avaliar complicações pulmonares pós-operatórias clinicamente relevantes.

INTRODUCTION

Low-flow inhalational anaesthesia, defined as the administration of volatile agents with a fresh gas flow (FGF) rate of ≤ 1 L/min, has become increasingly relevant in contemporary anaesthetic practice.^{1,2} By reducing the consumption of volatile agents, this technique offers clear economic benefits and contributes to limiting the environmental impact of anaesthesia, particularly through decreased emission of greenhouse gases.^{3,4} Advances in anaesthesia workstations, including closed-circuit systems and automated end-tidal control, have further enabled the safe and controlled application of low-flow techniques in routine clinical settings.⁵

Although early concerns regarding hypoxic gas mixtures and inadequate depth of anaesthesia historically limited adoption of low-flow techniques, modern anaesthesia machines with real time gas monitoring and automated control systems have largely mitigated these risks.¹ Lower FGF alters inspired gas composition and slows equilibration between fresh gas and alveolar anaesthetic concentrations, necessitating careful monitoring and adjustment of delivered gas mixtures.⁶ These effects are especially relevant in the perioperative period, where even transient impairments in pulmonary function can contribute to postoperative complications.⁷ As a result, the question of whether low-flow anaesthesia is physiologically equivalent to conventional- or high-flow techniques remains clinically important.

Pulmonary function parameters such as forced expiratory volume in one second (FEV₁) and forced vital capacity (FVC), together with measures of oxygenation including arterial oxygen tension (PaO₂) and peripheral oxygen saturation (SpO₂), represent key endpoints for evaluating the respiratory impact of anaesthetic strategies.⁸ Postoperative reductions in these parameters are associated with adverse outcomes, including atelectasis, impaired gas exchange, and increased risk of pulmonary complications.⁹ However, existing studies examining low-flow anaesthesia have reported variable findings, with some demonstrating comparable respiratory outcomes between techniques and others suggesting subtle differences in pulmonary mechanics or oxygenation profiles.^{10,11} To date, most evidence syntheses in perioperative respiratory care have focused on ventilatory strategies such as tidal volume selection, positive end-expiratory pressure (PEEP), and recruitment maneuvers rather than fresh gas flow as an

independent variable.^{12,13} Consequently, the specific impact of low-flow versus conventional-flow anaesthesia on postoperative pulmonary function and oxygenation has not been clearly established. Given the increasing integration of low-flow techniques into routine anaesthetic practice, clarifying their effects on pulmonary function and oxygenation is of clear clinical importance.

The present systematic review and meta-analysis aim to assess the effect of low-flow compared with conventional-flow inhalational anaesthesia on pulmonary and oxygenation outcomes in adult surgical patients. Emphasis is placed on clinically meaningful postoperative respiratory parameters, particularly FEV₁ and FVC, alongside available oxygenation indices. By integrating quantitative findings with a structured synthesis of complementary outcomes, this study seeks to provide a clear and clinically applicable interpretation of the current evidence.

METHODS

Study Design and Registration

This systematic review and meta-analysis was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines. The review was designed to evaluate the effect of low-flow compared with conventional- or high-flow inhalational anaesthesia on pulmonary function and oxygenation outcomes in adult surgical patients. The protocol was developed before completion of the review process and defined the population, intervention, comparator, outcomes, eligibility criteria, and planned synthesis methods. Registration on PROSPERO (CRD420261390448).

Eligibility Criteria

Randomised controlled trials were eligible for inclusion if they enrolled adult patients undergoing surgery under general anaesthesia and compared low-flow or minimal-flow inhalational anaesthesia with conventional-, medium-, or high-flow inhalational anaesthesia. Low-flow anaesthesia was defined as a fresh gas flow rate of ≤ 1 L/min, while minimal-flow anaesthesia was defined as ≤ 0.5 L/min. Comparator groups included fresh gas flow rates ≥ 2 L/min or the conventional-flow strategy defined by the individual study. Studies were required to report at least one pulmonary or oxygenation-related outcome, including forced expiratory

volume in one second, forced vital capacity, peripheral oxygen saturation, arterial oxygen tension, oxygen reserve index, respiratory mechanics, or postoperative pulmonary complications. Non-randomised studies, paediatric studies, non-operative studies, studies of high-flow nasal cannula or supplemental oxygen therapy not involving volatile anaesthetic delivery, and studies without extractable pulmonary or oxygenation outcomes were excluded.

Search Strategy and Study Selection

A systematic literature search was conducted in PubMed/MEDLINE, Embase, and the Cochrane Central Register of Controlled Trials (CENTRAL) using combinations of terms related to low-flow anaesthesia, minimal-flow anaesthesia, reduced fresh gas flow, inhalational anaesthesia, surgery, and randomised trials. Reference lists of included studies and relevant reviews were also manually screened to identify additional eligible studies. Retrieved records were screened by title and abstract, followed by full-text review of potentially eligible articles. Study selection was performed according to predefined eligibility criteria, and disagreements were resolved by discussion.

Data Extraction

Data were extracted using a standardised form. Extracted variables included study author, publication year, country, study design, sample size, patient characteristics, type of surgery, volatile anaesthetic agent, fresh gas flow rates in each group, timing of outcome assessment, and reported pulmonary or oxygenation outcomes. For continuous outcomes, means, standard deviations, and sample sizes were extracted when available. When studies reported outcomes using different instruments, timepoints, or non-comparable definitions, these data were narratively synthesised rather than pooled.

Outcomes

The primary outcomes were pulmonary function and oxygenation parameters, including FEV₁, FVC, SpO₂, PaO₂, and PaO₂/FiO₂ where reported. FEV₁ and FVC at 24 hours were the only outcomes reported with sufficient methodological similarity and extractable data to permit quantitative pooling. Secondary and exploratory outcomes included ORL, vital capacity, inspiratory reserve volume, peak expiratory flow rate, dynamic lung compliance, peak inspiratory pressure, and postoperative pulmonary complications where reported.

Statistical Analysis

Meta-analysis was performed when at least two studies reported sufficiently comparable outcomes with extractable numerical data. Continuous outcomes were pooled as mean differences with 95% confidence intervals. A random-effects model was used because of expected clinical and methodological heterogeneity across studies, including differences in surgical populations, volatile agents, fresh gas flow thresholds, and timing of outcome assessment. Statistical heterogeneity was assessed using the I² statistic, with values of approximately 25%, 50%, and 75% interpreted as low, moderate,

and high heterogeneity, respectively.

Outcomes reported by only one study or measured using substantially different methods were not pooled and were instead presented descriptively. Publication bias was not formally assessed because fewer than 10 studies contributed to each quantitative analysis.

Risk of Bias Assessment

Risk of bias was assessed using the version 2 of the Cochrane risk-of-bias tool for randomized trials (RoB 2). The following domains were evaluated: bias arising from the randomisation process, bias due to deviations from intended interventions, bias due to missing outcome data, bias in outcome measurement, and bias in selection of the reported result. Each study was judged as low risk of bias, some concerns, or high risk of bias.

Certainty of Evidence

The certainty of evidence was assessed using the Grading of Recommendations Assessment, Development and Evaluation (GRADE) framework. Certainty was rated as high, moderate, low, or very low based on risk of bias, inconsistency, indirectness, imprecision, and publication bias. Summary of Findings and domain-by-domain GRADE tables were prepared for the main outcomes.

RESULTS

Study Inclusion and Overview

A total of nine studies were included in the systematic review. Of these, two studies provided sufficient quantitative data on postoperative spirometric outcomes (FEV₁ and FVC at 24 hours) and were included in the meta-analysis. The remaining seven studies were included in the qualitative synthesis because their outcomes were reported using heterogeneous

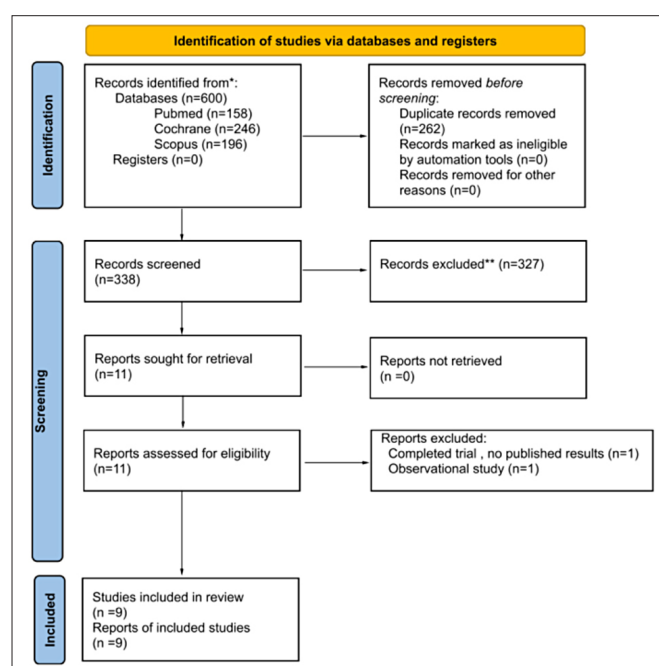


Figure 1. PRISMA 2020 flow diagram of study identification, screening, eligibility assessment, and inclusion.

measurement tools, timepoints, or non-comparable summary statistics. Quantitative pooling was limited by substantial heterogeneity in outcome definitions, measurement tools, and timing of assessment. Several studies reported spirometer-derived variables (e.g., VC, IRV, PEFr), while others focused primarily on intraoperative oxygenation indices (e.g., ORI, PaO₂) or respiratory mechanics, which precluded clinically meaningful pooling across studies. Quantitative synthesis of postoperative pulmonary function outcomes is presented below. The study selection process is shown in Fig. 1. A total of nine studies were included in the systematic review. Of these, two studies provided sufficient quantitative data on postoperative spirometric outcomes and were included in the meta-analysis. The remaining seven studies were included in the qualitative synthesis because their outcomes were reported using heterogeneous measurement tools, timepoints, or non-comparable summary statistics.

Primary Outcome: FEV₁ at 24 Hours

At 24 hours postoperatively, two studies including 110 patients were pooled. There was no statistically significant difference in FEV₁ between low-flow and high-flow anesthesia (MD 0.18, 95% CI -0.09 to 0.44; $p = 0.19$). Low heterogeneity was observed ($I^2 = 24\%$). Although a trend toward higher FEV₁ values was noted in the low-flow group, this did not reach statistical significance. Data were drawn from Bilgi 2011¹⁰ and Doger 2016,¹¹ both of which reported postoperative FEV₁ at 24 hours.

Exploratory Single-Study Analyses

At 2 hours postoperatively, a single study (Doger, *et al*)¹¹ demonstrated no significant difference in FEV₁ between low-flow and high-flow anesthesia (MD -0.15, 95% CI -0.47 to 0.17; $p = 0.37$). This timepoint was presented descriptively because only one study provided extractable data. Doger *et al*¹¹ measured pulmonary function before surgery and again at 2, 8, and 24 hours postoperatively.

At 8 hours postoperatively, a single study (Doger *et al*)¹¹ demonstrated no significant difference in FEV₁ between low-flow and high-flow anesthesia (MD 0.02, 95% CI -0.29 to 0.33; $p = 0.90$). This analysis was also descriptive because only one study contributed data at this timepoint.

Secondary Outcome: FVC at 24 hours

Two studies including 110 patients were pooled for postoperative FVC at 24 hours. There was no statistically significant difference between low-flow and high-flow anesthesia (MD 0.19, 95% CI -0.19 to 0.58; $p = 0.32$). Moderate heterogeneity was observed ($I^2 = 54\%$). Although one study demonstrated higher FVC values in the low-flow group, this effect was not consistent across studies, and the overall pooled estimate did not reach statistical significance. Both Bilgi *et al*¹⁰ and Doger *et al*¹¹ reported postoperative FVC outcomes suitable for this comparison.

Qualitative Synthesis of Additional Outcomes

Seven studies not included in the quantitative meta-analysis reported pulmonary, oxygenation, or respiratory mechanics

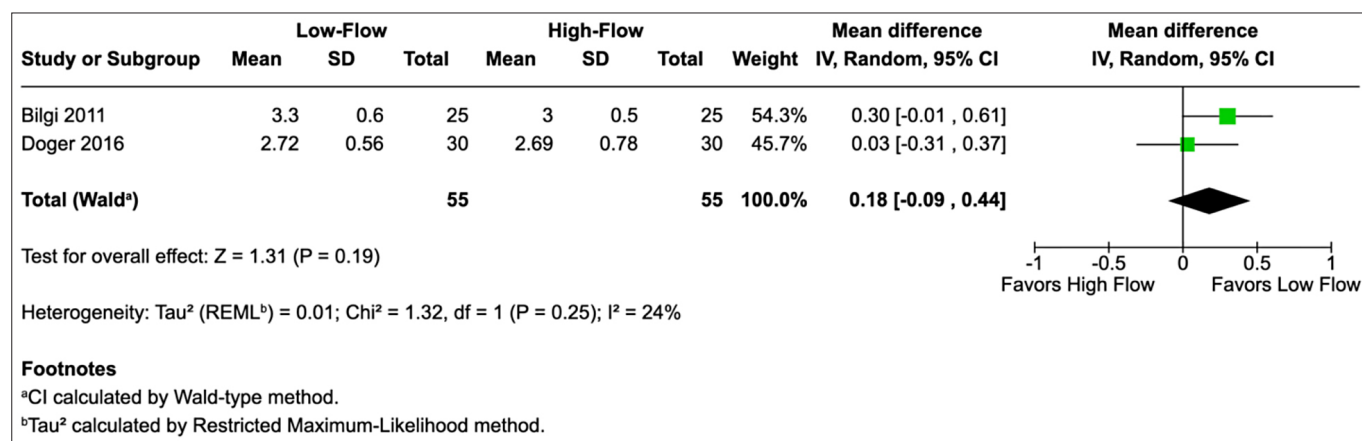


Figure 2. Forest plot of postoperative FEV₁ at 24 hours comparing low-flow versus high-flow anesthesia.

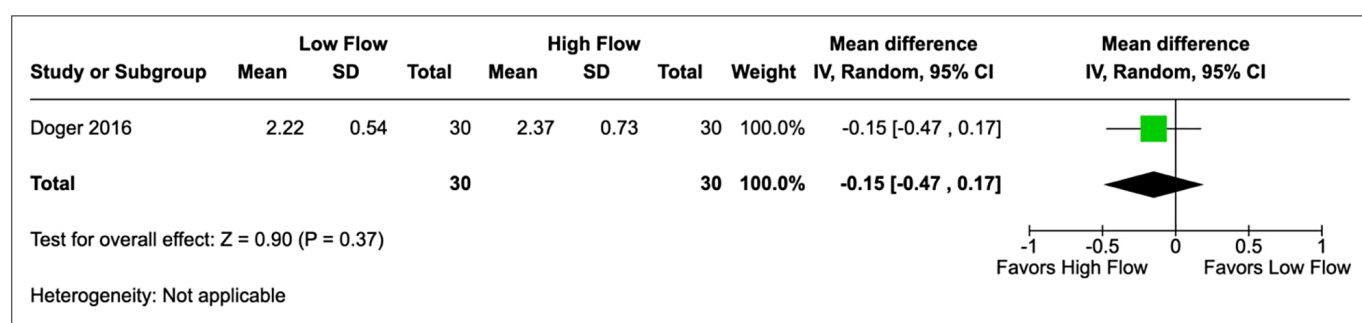


Figure 3. Forest plot of FEV₁ at 2 hours postoperatively comparing low-flow versus high-flow anesthesia.

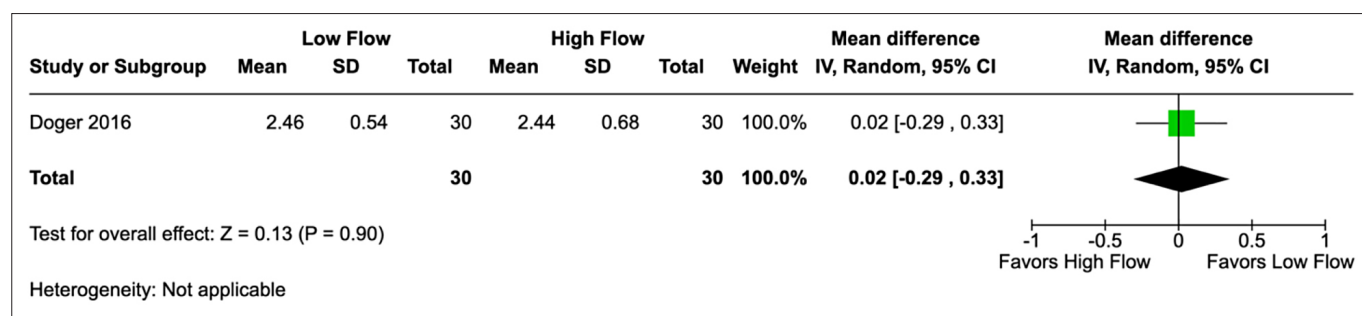


Figure 4. Forest plot of FEV₁ at 8 hours postoperatively comparing low-flow versus high-flow anesthesia.

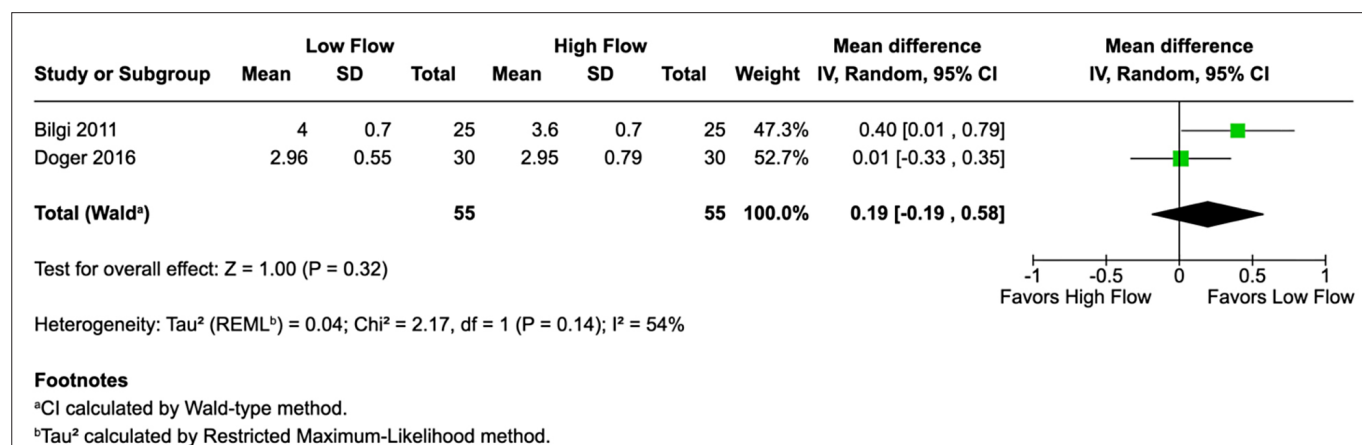


Figure 5. Forest plot of postoperative FVC at 24 hours comparing low-flow versus high-flow anesthesia.

outcomes that were not suitable for pooling because of differences in measurement tools, timepoints, comparator flow rates, or outcome definitions.

Prasad *et al*¹⁴ and Agarwal *et al*¹⁵ assessed postoperative lung function using respirometer-derived parameters, including vital capacity, inspiratory reserve volume, and peak expiratory flow rate. Both studies reported no statistically significant differences between low-flow and high-flow anaesthesia in postoperative pulmonary function measures.

Öterkuş *et al*¹⁶ evaluated low-flow anaesthesia in obese patients undergoing laparoscopic bariatric surgery and found comparable peripheral oxygen saturation, arterial blood gas parameters, lactate levels, and recovery variables between low-flow and high-flow groups.

Oztoprak *et al*,¹⁷ Dastan *et al*,¹⁸ and Sahin *et al*¹⁹ focused primarily on intraoperative oxygenation monitoring using ORI, PaO₂, FiO₂, or end-tidal oxygen measures. These studies demonstrated physiologic differences across fresh gas flow strategies and supported the use of ORI as a continuous adjunct for oxygenation monitoring, but they did not demonstrate consistent clinically important hypoxemia with low-flow or minimal-flow anaesthesia.

Çelik *et al*²⁰ evaluated minimal-flow versus medium-flow anaesthesia in laparoscopic cholecystectomy and reported no significant between-group difference in postoperative respiratory function tests, although minimal-flow anaesthesia was associated with more favorable intraoperative compliance and peak inspiratory pressure at the end of surgery.

Overall, the qualitative findings were broadly consistent with

the quantitative analysis, suggesting no clear evidence of worse short-term pulmonary function or oxygenation with low-flow or minimal-flow anaesthesia.

Risk of Bias

Risk of bias across the included studies was generally low to moderate. Two studies were judged to be at overall low risk of bias, while the remaining studies raised some concerns. The most frequent concerns related to incomplete reporting of the randomisation process, limited information on allocation concealment, and the inherent difficulty of blinding

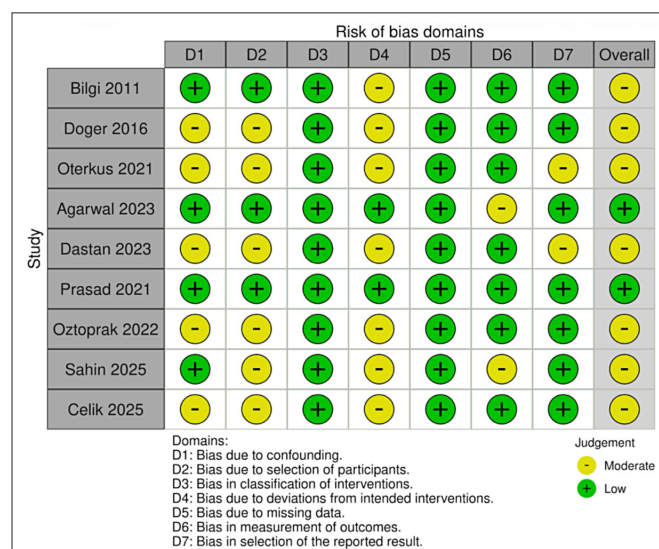


Figure 6. The study-level RoB 2 assessments

anaesthesia providers to fresh gas flow allocation. Risk of bias due to missing outcome data, outcome measurement, and selective reporting was generally low. No study was judged to be at overall high risk of bias. The study-level RoB 2 assessments are presented in **Fig. 6**.

Certainty of Evidence (GRADE)

The certainty of evidence was assessed using the GRADE framework. Certainty was rated as very low for postoperative FEV₁ and FVC at 24 hours, mainly because of imprecision, indirectness, and study limitations. Certainty was low for narratively synthesised oxygenation outcomes such as SpO₂, PaO₂, and ORI. Evidence for dynamic lung compliance, peak inspiratory pressure, and postoperative pulmonary complications was judged to be very low because of reliance on single-study or absent data. A Summary of Findings Table and domain-by-domain GRADE assessment are presented in **Tables 1** and **2**.

DISCUSSION

This systematic review and meta-analysis found no statistically significant difference in postoperative spirometric outcomes between low-flow or minimal-flow and conventional- or high-flow inhalational anaesthesia in adult surgical patients. The certainty of evidence was very low for both primary outcomes because only two small trials contributed to

the pooled analyses, and no included study evaluated postoperative pulmonary complications as a predefined endpoint. The absence of statistically significant differences should not be interpreted as evidence of equivalence, as the available studies were not powered for non-inferiority analyses and the confidence intervals remained wide. Although the pooled differences in FEV₁ (MD 0.18 L, 95% CI 0.09 lower to 0.44 higher) and FVC (MD 0.19 L, 95% CI 0.19 lower to 0.58 higher) were numerically small, the upper bounds of both intervals are large enough that clinically relevant postoperative changes cannot be excluded, particularly in patients with reduced baseline pulmonary reserve.

Interpretation of the pooled findings is further complicated by substantial methodological heterogeneity across included studies, encompassing differences in volatile anaesthetic agent, fresh gas flow thresholds, intraoperative FiO₂ adjustment protocols, outcome measurement instruments, and timing of postoperative assessment. The moderate heterogeneity in the FVC analysis ($I^2 = 54\%$) reflects a meaningful directional inconsistency between the two contributing trials. Bilgi *et al.* found significantly greater postoperative declines in FVC and FEV₁ in the high-flow desflurane group, whereas Doger *et al.*¹¹ found comparable spirometric values between groups with sevoflurane. This divergence is likely attributable to differences in volatile agent properties rather than fresh gas flow rate alone, and should caution against treating

Table 1. Summary of Findings: low-flow versus conventional-flow inhalational anaesthesia for adult surgical patients.

Outcome (timing; instrument)	Anticipated absolute effect (95% CI)	Relative effect (95% CI)	Nº of participants (studies)	Certainty of the evidence (GRADE)	What happens
Postoperative FEV₁ at 24 h (litres; spirometry)	MD 0.18 L higher in the low-flow group (0.09 lower to 0.44 higher)	—	110 (2 RCTs)	⊕○○○ Very low	Low-flow anaesthesia probably results in little to no difference in postoperative FEV ₁ at 24 h, but the evidence is very uncertain.
Postoperative FVC at 24 h (litres; spirometry)	MD 0.19 L higher in the low-flow group (0.19 lower to 0.58 higher)	—	110 (2 RCTs)	⊕○○○ Very low	Low-flow anaesthesia may result in little to no difference in postoperative FVC at 24 h; the evidence is very uncertain.
Intra- and post-operative peripheral oxygen saturation (SpO₂, %)	No consistent between-group difference; not quantitatively pooled	—	Intra- and/or postoperative SpO ₂ , where reported	⊕⊕○○ Low	Low-flow anaesthesia may result in little to no difference in intra- or postoperative SpO ₂ compared with conventional-flow anaesthesia.
Intra-operative arterial oxygen tension (PaO₂, mmHg)	No consistent between-group difference; pooling not feasible owing to heterogeneous timing and reporting	—	204 (3 RCTs)	⊕⊕○○ Low	Low-flow anaesthesia may result in little to no clinically important difference in intraoperative PaO ₂ , but the evidence is limited by heterogeneous timing and reporting.
Oxygen reserve index (ORI, dimensionless)	Higher ORI values with low- or minimal-flow than with high-flow at selected intra-operative time points in individual studies	—	224 (3 RCTs)	⊕⊕○○ Low	Low-flow and minimal-flow anaesthesia may be associated with higher intra-operative oxygen reserve compared with high-flow, but clinical relevance is unclear.
Dynamic lung compliance (mL/cmH₂O; perioperative)	Minimal-flow group maintained compliance; medium-flow group showed a significant decline at end of surgery (T6, $p < 0.05$)	—	60 (1 RCT)	⊕○○○ Very low	Minimal-flow anaesthesia may better preserve intra-operative dynamic lung compliance, but the evidence is very uncertain.
Peak inspiratory pressure (cmH₂O; perioperative)	Minimal-flow group had lower PIP values than medium-flow group at end of surgery (T6, $p < 0.05$)	—	60 (1 RCT)	⊕○○○ Very low	Minimal-flow anaesthesia may result in lower peak inspiratory pressures at the end of surgery, but the evidence is very uncertain.
Postoperative pulmonary complications	No study reported formally adjudicated PPCs as a pre-defined outcome	—	— (0 RCTs)	⊕○○○ Very low	The effect of low-flow anaesthesia on postoperative pulmonary complications is unknown.

Table 2. Domain-by- domain GRADE assessment.

Study, Country	Design	N analysed	Population (age, ASA)	Surgery	Intervention (low- / minimal-flow)	Comparator (high- / medium-flow)	Pulmonary / oxygenation outcomes reported	Timing of outcome assessment
FEV ₁ at 24 h	2	RCT	Serious (–1): RoB 2 judgements of 'some concerns' for randomisation and deviations in both contributing studies	Not serious: $I^2 = 24\%$	Serious (–1): different surgeries (tympanoplasty vs laparoscopic cholecystectomy) and volatile agents (desflurane vs sevoflurane)	Very serious (–2): only 2 studies, $n = 110$, CI crosses no-effect line and includes clinically important differences	Not assessed (< 10 studies)	⊕○○○ Very low
FVC at 24 h	2	RCT	Serious (–1): as above	Serious (–1): $I^2 = 54\%$; divergent direction of within-study effects	Serious (–1): as above	Very serious (–2): as above	Not assessed (< 10 studies)	⊕○○○ Very low
SpO ₂ (intra-/post-op)	9	RCT	Serious (–1): majority of studies rated 'some concerns'	Not serious: consistent direction across narratively synthesised studies	Not serious	Not serious: large combined sample; consistent findings	Not assessed	⊕⊕○○ Low
PaO ₂ (intra-op)	3	RCT	Serious (–1): as above	Not serious: consistent narrative findings	Not serious	Serious (–1): narrative synthesis only; heterogeneous timepoints preclude formal precision estimation	Not assessed	⊕⊕○○ Low
Oxygen reserve index (ORI)	3	RCT	Serious (–1): as above	Not serious	Not serious	Serious (–1): narrative synthesis; small combined sample	Not assessed	⊕⊕○○ Low
Dynamic lung compliance	1	RCT	Serious (–1): single study with 'some concerns' on RoB 2	Cannot be assessed (single study)	Serious (–1): single-centre laparoscopic cholecystectomy population only	Very serious (–2): single study, $n = 60$	Cannot be assessed	⊕○○○ Very low
Peak inspiratory pressure	1	RCT	Serious (–1): as above	Cannot be assessed	Serious (–1): as above	Very serious (–2): as above	Cannot be assessed	⊕○○○ Very low
Postoperative pulmonary complications	0	—	No data	No data	No data	No data	No data	⊕○○○ Very low

pooled effect estimates as generalisable across anaesthetic agents or surgical contexts.

The mechanistic basis of this heterogeneity is best understood through two distinct but related pathways. The first concerns humidification and mucociliary clearance. Low-flow anaesthesia recirculates warmed, humidified expired gas within the circle system, thereby preserving ciliary function and reducing mucus retention more effectively than high-flow techniques, which continuously introduce cool, dry fresh gas into the airway.¹⁰ The superior mucociliary clearance observed in the Bilgi *et al*¹⁰ trial, measured using saccharin transit time, is consistent with this mechanism and plausibly explains the larger spirometric benefit of low-flow anaesthesia in that study. The second pathway concerns volatile agent airway effects. Desflurane is associated with greater airway reactivity and more pronounced epithelial irritation than sevoflurane,²¹ meaning that the combination of high-flow delivery and desflurane may produce additive impairment of mucociliary function that neither agent nor flow rate alone would produce. Future trials should therefore pre-specify volatile agent as an effect modifier rather than treating fresh gas flow rate as the sole intervention variable.

Beyond postoperative spirometry, several included studies examined intraoperative oxygenation physiology and respiratory monitoring. Across three trials evaluating the oxygen reserve index, ORI demonstrated a meaningful positive correlation with arterial oxygen tension and detected oxygenation changes earlier than pulse oximetry, consistent with its sensitivity in the moderately hyperoxic range where haemoglobin is fully saturated and SpO₂ provides no additional discriminatory information.^{16,18,22} None of these trials identified clinically significant intraoperative hypoxaemia in the low-flow or minimal-flow groups, provided that inspired oxygen fraction was appropriately increased to compensate for the higher re-breathing fraction. This adjustment is contingent on functioning CO₂ absorbents, continuous gas analysis, and deliberate clinical titration, and should be regarded as a non-negotiable prerequisite rather than a routine precaution. The single trial evaluating intraoperative lung mechanics, Çelik *et al*,²⁰ found more favorable dynamic compliance and lower peak inspiratory pressure at the end of surgery with minimal-flow anaesthesia, an effect that may relate to improved airway humidification, although this mechanism was not directly assessed and the finding rests on single-study, single-centre evidence.

These findings are broadly consistent with the wider perioperative ventilation literature, which has demonstrated that intraoperative respiratory physiology does not always translate into clinically meaningful postoperative pulmonary outcomes.^{12,13} While spirometric parameters provide useful physiological information, postoperative pulmonary complications represent more clinically meaningful patient-centred outcomes because they are directly associated with perioperative morbidity, mortality, and healthcare utilisation.^{7,23} No included trial formally adjudicated complications such as atelectasis requiring treatment, pneumonia, respiratory failure, or unplanned ventilatory support, and the current evidence therefore does not permit any conclusion about whether fresh gas flow strategy affects the risk of clinically important respiratory morbidity. This absence of patient-centred outcome data is the central limitation of this review and the primary reason that clinical recommendations cannot be drawn from the available evidence.

The findings nonetheless carry practical relevance. The evidence does not identify a consistent pulmonary disadvantage to the use of low-flow anaesthesia in appropriately monitored patients undergoing elective surgery, and this is meaningful in the context of contemporary practice. Most included trials enrolled relatively low-risk patients undergoing short elective procedures on modern anaesthesia workstations, which may limit applicability to patients with severe pulmonary disease, prolonged surgery, morbid obesity with hypoventilation syndrome, or resource-limited settings where continuous gas monitoring is unavailable. Within these boundaries, the findings are consistent with the view that low-flow and minimal-flow techniques are physiologically reasonable when denitrogenation phases, protocol-driven FiO_2 adjustment, and real-time monitoring are reliably employed. These findings are also relevant in the context of increasing efforts to reduce the environmental impact of anaesthetic practice. Volatile anaesthetic agents contribute substantially to greenhouse gas emissions, and reducing fresh gas flow is one of the most effective strategies for limiting anaesthetic waste and operating theatre carbon footprint.^{2,3} The absence of a detected pulmonary disadvantage strengthens, though does not definitively establish, the case for preferring lower flow rates in appropriate patients.

Overall, current evidence suggests that low-flow inhalational anaesthesia does not produce major short-term deterioration in pulmonary function or oxygenation when applied with appropriate monitoring and FiO_2 adjustment. However, this conclusion is bounded by very low certainty evidence, small combined sample sizes, and the complete absence of clinically adjudicated postoperative pulmonary complication data. Larger multicentre trials are required before definitive recommendations regarding pulmonary safety across the full spectrum of surgical patients can be established.

Strengths and Limitations

This review was restricted to randomised controlled trials, employed predefined eligibility criteria, assessed risk of bias using the domain-based Cochrane RoB 2 tool, and evaluated certainty of evidence using the GRADE framework. The de-

cision to pool only FEV_1 and FVC at 24 hours and to present all other outcomes narratively reflects the level of methodological comparability actually achievable within this evidence base and avoids the misleading precision that forced aggregation of heterogeneous endpoints would produce. Several limitations must be acknowledged. Only two trials contributed to the primary pooled analyses, yielding a combined sample of 110 patients and confidence intervals too wide to exclude clinically meaningful differences in either direction. The included trials varied substantially in surgical setting, volatile agent, and fresh gas flow thresholds, where high-flow ranged from 2 to 4 L/min and low-flow from 0.5 to 1 L/min across studies, such that no single flow threshold can be identified as the point at which pulmonary effects diverge. Blinding of anaesthesia providers is inherently difficult in trials of this design and contributes to performance bias concerns across most included studies. The small number of trials precluded formal assessment of publication bias. Most importantly, no included trial reported formally adjudicated postoperative pulmonary complications, which is the central evidence gap constraining the clinical utility of this review.

Future Research

Future trials should adopt operationally precise, consensus-based definitions of low-flow and minimal-flow anaesthesia, specify fresh gas flow rates and FiO_2 values in sufficient detail to permit replication, and pre-specify volatile agent as a subgroup variable. Primary endpoints should be adjudicated postoperative pulmonary complications using validated definitions such as those proposed by the European Perioperative Clinical Outcome initiative,²⁴ rather than surrogate spirometric parameters alone. Standardised reporting of FEV_1 , FVC, SpO_2 , PaO_2 , ORI, dynamic lung compliance, peak inspiratory pressure, and mucociliary clearance at harmonised perioperative timepoints would substantially improve the feasibility of future meta-analyses. Stratification by surgical site, anaesthesia duration, body mass index, baseline pulmonary disease, and volatile agent should be pre-specified to address the mechanistic heterogeneity identified in this review. Larger, adequately powered, multicentre randomised trials are needed before definitive clinical guidance on fresh gas flow strategy and postoperative pulmonary morbidity can be issued.

CONCLUSION

In adult surgical patients undergoing general inhalational anaesthesia, low-flow or minimal-flow techniques were not associated with worse short-term postoperative FEV_1 or FVC compared with conventional- or high-flow anaesthesia. Qualitative evidence from additional trials similarly did not show consistent clinically important deterioration in oxygenation or respiratory mechanics. However, the certainty of evidence remains low to very low because of small sample sizes, heterogeneous outcome reporting, and limited assessment of clinically meaningful postoperative pulmonary complications. Low-flow anaesthesia appears clinically comparable to

Table 3. Characteristics of included studies.

Study, Country	Design	N analysed	Population (age, ASA)	Surgery	Intervention (low- / minimal-flow)	Comparator (high- / medium-flow)	Pulmonary / oxygenation outcomes reported	Timing of outcome assessment
Bilgi 2011 Turkey	RCT, single-centre Computer-generated randomisation; assessor-blinded	50 (25 / 25)	Adults 18–70 y ASA I–II Excluded: smokers, chronic lung / cardiac / renal / hepatic disease	Elective tympano-mastoidectomy	Low-flow: FGF 1 L/min (0.5 L/min O ₂ + 0.5 L/min N ₂ O) + desflurane 1 MAC After 8–10 min denitrogenation at 4–5 L/min	High-flow: FGF 3 L/min (1.5 L/min O ₂ + 1.5 L/min N ₂ O) + desflurane 1 MAC	FEV ₁ , FVC, FEV ₁ /FVC SpO ₂ , HR, MAP Saccharin clearance time Inspired-gas humidity & temperature	Pre-op and 24 h post-op (PFTs, STT) Intra-op at 5, 10, 15, 30, 45, 60, 90, 120 min (haemodynamics, gas humidity/temp)
Doger 2016 Turkey	Prospective RCT, multi-centre Web-based randomisation; patient- and assessor-blinded	60 (30 / 30)	Adults 20–55 y ASA I–II Excluded: COPD, smokers, cardiac/renal/hepatic disease	Elective laparoscopic cholecystectomy	Low-flow: FGF 1 L/min (after 10 min at 4 L/min) Sevoflurane 3.4 % + 50 % N ₂ O in O ₂	High-flow: FGF 4 L/min throughout Sevoflurane 3.4 % + 50 % N ₂ O in O ₂	FEV ₁ , FVC, FEV ₁ /FVC SpO ₂ , HR, MABP, EtCO ₂	Pre-op Post-op at 2 h, 8 h and 24 h (PFTs) Intra-op every 5 min (haemodynamics)
Öterkuş 2021 Turkey	Prospective RCT, single-centre Coin-flip randomisation; single-blinded	44 (27 LF / 17 HF)	Adults 18–75 y ASA I–II BMI > 35 kg/m ² Excluded: cardiovascular, hepatic, pulmonary or cerebrovascular disease	Laparoscopic sleeve gastrectomy (bariatric)	Low-flow: FGF 1 L/min (50 % O ₂ / 50 % N ₂ O) + sevoflurane 2–3 % Initial high-flow phase before transition	High-flow: FGF 4 L/min (2 L/min O ₂ + 2 L/min N ₂ O) + sevoflurane 2–3 % throughout	SpO ₂ , HR, BP, EtCO ₂ Arterial blood gas (incl. PaO ₂ , lactate) Recovery / extubation times	Pre-op, intra-op at 30, 60, 90, 120 min, post-op
Prasad 2021 India	Prospective RCT, single-centre Computer-generated randomisation; double-blinded	110 (55 / 55)	Adults 18–60 y ASA I–II Excluded: ASA ≥ III, emergency or thoraco-abdominal surgery	Elective peripheral surgeries under GA	Low-flow: FGF 1 L/min (0.5 L/min O ₂ + 0.5 L/min N ₂ O) + sevoflurane 3.5 %	High-flow: FGF 4 L/min (2 L/min O ₂ + 2 L/min N ₂ O) + sevoflurane 2 %	VC, IRV, PEFR (respirometer-derived) Single-breath count, breath-holding time, RR SpO ₂ , HR, NIBP, EtCO ₂	Pre-op and post-op (recovery period) Intra-op haemodynamics every 30 min
Oztoprak 2022 Turkey	Prospective RCT, single-centre Sealed-envelope randomisation (NCT04698863)	70 (35 / 35)	Adults 18–65 y ASA I–II Excluded: morbid obesity, cardiac, renal, hepatic disease, anaemia	Elective tympano-mastoidectomy (min. 1.5 h)	Low-flow: FGF 1 L/min 50 % O ₂ / 50 % air + 6 % desflurane After 10 min at 6 L/min	High-flow: FGF 4 L/min 50 % O ₂ / 50 % air + 6 % desflurane	ORI, PaO ₂ , SpO ₂ HR, MAP	Pre-preoxygenation, intra-op at 10, 15, 30, 45, 60 min, then every 30 min ABG; pre-preox, intra-op 60 min, end of surgery
Agarwal 2023 India	Prospective RCT, single-centre Lottery / opaque envelopes; double-blinded	80 (40 / 40)	Adults 18–60 y ASA I–II Excluded: ASA ≥ III, emergency or thoraco-abdominal surgery	Elective peripheral surgeries under GA	Low-flow: FGF 1 L/min (0.5 L/min O ₂ + 0.5 L/min N ₂ O) + sevoflurane 2.5 %	High-flow: FGF 4 L/min (2 L/min O ₂ + 2 L/min N ₂ O) + sevoflurane 1.5 %	VC, IRV, PEFR (respirometer-derived) Single-breath count, breath-holding time, RR SpO ₂ , HR, MAP	Pre-op and post-op at 1 h, 2 h, 8 h and 24 h Intra-op every 5 min (haemodynamics)
Dastan 2023 Turkey	RCT, three-arm, single-centre Closed-envelope; single-blinded (NCT05329233)	90 (30 / 30 / 30)	Adults 18–75 y ASA II–III Excluded: morbid obesity (BMI > 40), COPD, severe organ disease, anaemia	Elective open abdominal surgery (< 60 min)	Minimal-flow: FGF 0.5 L/min, FiO ₂ 68 % Low-flow: FGF 1 L/min, FiO ₂ 50 % Both with desflurane (MAC 1) + remifentanyl	High-flow: FGF 4 L/min, FiO ₂ 40 % Desflurane (MAC 1) + remifentanyl	ORI, PaO ₂ , SpO ₂ Correlation analyses ORI vs PaO ₂	10 time points: pre-induction, post-intubation, intra-op at 10, 30, 60, 90, 120 min, end of surgery, 5 min post-extubation
Sahin 2025 Turkey	RCT, single-centre Computerised randomisation (NCT06649279)	64 (32 / 32)	Adults 18–75 y ASA I–III Excluded: severe anaemia, COPD, organ failure, BMI > 40	Elective ENT surgery (> 60 min)	Minimal-flow: FGF 0.5 L/min, FiO ₂ 70 % Sevoflurane (MAC 1) + remifentanyl After 5 min at 4 L/min	High-flow: FGF 4 L/min, FiO ₂ 40 % Sevoflurane (MAC 1) + remifentanyl	ORI, SpO ₂ , end-tidal O ₂ Inspiratory / expiratory O ₂ HR, BP	Preoxygenation, post-intubation, 5/10/15/20/35 min after intubation, then 1/5/10 min after FGF increase
Çelik 2025 Turkey	Prospective RCT, single-centre Closed-envelope; patient-blinded (NCT06055335)	66 enrolled / 60 analysed (MiFA 32 / MeFA 28 after 6 exclusions)	Adults 18–65 y ASA I–II Excluded: smokers, BMI > 40, cardiovascular or chronic respiratory disease	Elective laparoscopic cholecystectomy	Minimal-flow (MiFA): FGF 0.5 L/min Desflurane (MAC 1) + remifentanyl After induction at 4 L/min	Medium-flow (MeFA): FGF 2 L/min Desflurane (MAC 1) + remifentanyl	Dynamic lung compliance, PIP FEV ₁ , FVC (spirometry) Total inhalation / remifentanyl consumption	Intra-op T1–T6 (5 min post-intubation, then 5/10/30/60 min post-incision and post-suturing) PFTs pre-op and 2 h, 8 h, 24 h post-op

higher-flow techniques in appropriately monitored patients, but larger standardised trials are needed to confirm its effects on postoperative pulmonary morbidity.

Data Availability

Data extracted for this review are available from the corresponding author upon reasonable request.

CONTRIBUTORSHIP STATEMENT / DECLARAÇÃO DE CONTRIBUIÇÃO

Carlos Neto: Conceptualization, Methodology, Investigation,

Data curation, Formal analysis. Emre Adalier: Methodology, Investigation, Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. Ines Shopi: Investigation, Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. Ana Luiza Alves de Castilho: Investigation, Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. Alina Akural: Formal analysis, Visualization, Writing – original draft, Writing – review & editing. Ingridy Sodre: Investigation, Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. Jacopo Bagnoli: Investigation, Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review &

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Todos os autores reviram e aprovaram a versão final deste manuscrito.

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REFERENCES

1. Brattwall M, Warrén-Stomberg M, Hesselvik F, Jakobsson J. Brief review: Theory and practice of minimal fresh gas flow anesthesia. *Can J Anesth*. 2012;59:785-97. doi:10.1007/s12630-012-9736-2
2. Rübsam ML, Kruse P, Dietzler Y, Kropf M, Bette B, Zarbock A, et al. A call for immediate climate action in anesthesiology: routine use of minimal or metabolic fresh gas flow reduces our ecological footprint. *Can J Anesth*. 2023;70:301-12. doi:10.1007/s12630-022-02393-z
3. Varughese S, Ahmed R. Environmental and Occupational Considerations of Anesthesia: A Narrative Review and Update. *Anesth Analg*. 2021;133:826-35. doi:10.1213/ANE.0000000000005504
4. Glenski TA, Levine L. The implementation of low-flow anesthesia at a tertiary pediatric center: A quality improvement initiative. *Pediatr Anesth*. 2020;30:1139-45. doi:10.1111/pan.13994

5. Colak YZ, Toprak HI. Feasibility, safety, and economic consequences of using minimal flow anaesthesia by Maquet FLOW-i equipped with automated gas control. *Sci Rep*. 2021;11:20074. doi:10.1038/s41598-021-99648-4
6. Conway CM. Gaseous homeostasis and the circle system. *Br J Anaesth*. 1986;58:1167-80. doi:10.1093/bja/58.10.1167
7. Fernandez-Bustamante A, Frendl G, Sprung J, Kor DJ, Subramaniam B, Martinez Ruiz R, et al. Postoperative Pulmonary Complications, Early Mortality, and Hospital Stay Following Noncardiothoracic Surgery: A Multicenter Study by the Perioperative Research Network Investigators. *JAMA Surg*. 2017;152:157. doi:10.1001/jamasurg.2016.4065
8. Stanojevic S, Kaminsky DA, Miller MR, Thompson B, Aliverti A, Barjaktarevic I, et al. ERS/ATS technical standard on interpretive strategies for routine lung function tests. *Eur Respir J*. 2022;60:2101499. doi:10.1183/13993003.01499-2021
9. Brunelli A, Kim AW, Berger KI, Addrizzo-Harris DJ. Physiologic Evaluation of the Patient With Lung Cancer Being Considered for Resectional Surgery. *Chest*. 2013;143:e166S-e190S. doi:10.1378/chest.12-2395
10. Bilgi M, Goksu S, Mizrak A, Cevik C, Gul R, Koruk S, et al. Comparison of the effects of low-flow and high-flow inhalational anaesthesia with nitrous oxide and desflurane on mucociliary activity and pulmonary function tests. *Eur J Anaesthesiol*. 2011;28:279-83. doi:10.1097/EJA.0b013e3283414cb7
11. Doger C, Kahveci K, Ornek D, But A, Aksoy M, Gokcinar D, et al. Effects of low-flow sevoflurane anesthesia on pulmonary functions in patients undergoing laparoscopic abdominal surgery. *BioMed Res Int*. 2016;2016:1-5. doi:10.1155/2016/3068467
12. Yang D, Grant MC, Stone A, Wu CL, Wick EC. A Meta-analysis of intraoperative ventilation strategies to prevent pulmonary complications: is low tidal volume alone sufficient to protect healthy lungs? *Ann Surg*. 2016;263:881-7. doi:10.1097/SLA.0000000000001443
13. Deng QW, Tan WC, Zhao BC, Wen SH, Shen JT, Xu M. Intraoperative ventilation strategies to prevent postoperative pulmonary complications: a network meta-analysis of randomised controlled trials. *Br J Anaesth*. 2020;124:324-35. doi:10.1016/j.bja.2019.10.024
14. Prasad TK, Gnanasekar N, Priyadharsini KS, Chacko RS. Randomized double-blind trial comparing effects of low-flow vs high-flow anesthesia on postoperative lung functions using respirometer. *J Anaesthesiol Clin Pharmacol*. 2020;36:535-540. doi:10.4103/joacp.JOACP_410_19
15. Agarwal A, Sant S, Panwar A, Ningthoujam SS. Post-operative lung functions after low-flow versus high-flow anaesthesia: a randomized, double blind comparative study. *Int J Acad Med Pharm*. 2023;5:674-80. doi:10.47009/jamp.2023.5.4.134
16. Öterkuş M, Dönmez İ, Nadir AH, Rencüzoğulları İ, Karabağ Y, Binnetoğlu K. The effect of low flow anesthesia on hemodynamic and peripheral oxygenation parameters in obesity surgery. *Saudi Med J*. 2021;42:264-9. doi:10.15537/smj.2021.42.3.20200575
17. Oztoprak H, Kucukosman G, Aydin BG, Okyay RD, Piskin O, Ayoglu H. Evaluation of Oxygenation in Low- and High-Flow Anesthesia Applications by Oxygen Reserve Index: A Randomized Prospective Study. *Med Bull Haseki*. 2022;60:104-12. doi:10.4274/haseki.galenos.2022.7753
18. High, low, and minimal flow anaesthesia management: effects on oxygen reserve index and arterial partial oxygen pressure. *J Coll Physicians Surg Pak*. 2023;33:1223-8. doi:10.29271/jcpsp.2023.11.1223
19. Sahin F. Variations in oxygen reserve index in different fresh gas flow rates. *Signa Vitae*. 2025;21:58. doi:10.22514/sv.2025.084
20. Çelik EC, Yayık AM, Aydin ME, Köksal EN, Dişçi E, Kerget B, et al. Evaluation of lung dynamics and respiratory functions in patients undergoing minimal flow anesthesia: a prospective, randomized controlled trial. *Med Gas Res*. 2026;16:110-15. doi:10.4103/mgr.MEDGASRES-D-25-00037
21. Braz JRC, Braz MG, Hayashi Y, Martins RH, Betini M, Braz LG, et al. Effects of different fresh gas flows with or without a heat and moisture exchanger on inhaled gas humidity in adults undergoing general anaesthesia: A systematic review and meta-analysis of randomised controlled trials. *Eur J Anaesthesiol*. 2017;34:515-25. doi:10.1097/EJA.0000000000000633
22. Klock PA, Czeslick EG, Kluft JM, Ovassapian A, Moss J. The effect of sevoflurane and desflurane on upper airway reactivity. *Anesthesiology*. 2001;94:963-7. doi:10.1097/0000542-200106000-00008
23. Scheeren TWL, Belda FJ, Perel A. The oxygen reserve index (ORI): a new tool to monitor oxygen therapy. *J Clin Monit Comput*. 2018;32:379-89. doi:10.1007/s10877-017-0049-4
24. Miskovic A, Lumb AB. Postoperative pulmonary complications. *Br J Anaesth*. 2017;118:317-34. doi:10.1093/bja/aex002
25. Janner I, Wickboldt N, Sander M, Smith A, Schultz MJ, Pelosi P, et al. Standards for definitions and use of outcome measures for clinical effectiveness research in perioperative medicine: European Perioperative Clinical Outcome (EPCO) definitions: a statement from the ESA-ESICM joint taskforce on perioperative outcome measures. *Eur J Anaesthesiol*. 2015;32:88-105. doi:10.1097/EJA.000000000000118