

Comparison of Low-Flow Vs High-Flow Anaesthesia on Perioperative Outcomes

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Abstract

Background: Low-flow anaesthesia (LFA), usually defined as fresh gas flow (FGF) $\leq 1-2$ L/min, has regained interest because of its potential economic, environmental and physiological advantages over conventional high-flow anaesthesia (HFA, typically ≥ 4 L/min). Concerns persist regarding hypoxia, accumulation of volatile degradation products and organ dysfunction, creating variability in practice. This review compared perioperative outcomes between LFA and HFA in adult surgical patients.

Methods: A narrative review was conducted using targeted searches in PubMed and major publishers (up to July 2025) for randomized or prospective clinical studies directly comparing low- with higher FGF during volatile-agent general anaesthesia. Eligible studies included adults undergoing elective surgery with clearly defined FGF targets and reported perioperative outcomes such as core temperature, oxidative stress, renal function, hemodynamics, recovery profile, complications, volatile consumption, and cost. Data were extracted qualitatively and grouped by outcome domain; no new meta-analysis was performed.

Results: Randomized trials involving sevoflurane and desflurane consistently demonstrated 30–70% reductions in volatile agent consumption and cost with LFA compared with HFA, without clinically important differences in hemodynamic stability or recovery times. Oxidative stress markers and thiol–disulfide homeostasis were similar or modestly more favourable with low flows. Core temperature loss was attenuated with LFA but hypothermia incidence remained multifactorial. Multiple studies did not detect increased rates of postoperative acute kidney injury, respiratory complications, or nausea and vomiting with LFA compared with higher flows when modern CO₂ absorbers and monitoring were used. Guidelines and expert consensus now support low-flow sevoflurane as safe in appropriately monitored patients.

Conclusion: Across contemporary randomized and prospective studies, LFA provides substantial reductions in volatile consumption and environmental burden while maintaining comparable perioperative safety and recovery to HFA. When supported by modern anaesthesia workstations and vigilant gas and oxygen monitoring, low-flow techniques appear clinically safe for most adult elective surgical patients. Remaining research gaps include high-risk populations, long-term outcomes, and pragmatic implementation strategies.

Keywords: Low-Flow Anaesthesia; High-Flow Anaesthesia; Fresh Gas Flow; Sevoflurane; Desflurane; Oxidative Stress; Perioperative Outcomes; Environmental Sustainability.

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Introduction

Volatile-based general anaesthesia remains a cornerstone of modern perioperative care. Historically, fresh gas flows of 4–6 L/min were commonly employed to simplify control of anaesthetic depth and inspired gas composition. However, most of this fresh gas ultimately escapes into the atmosphere, with implications for cost, environmental footprint and operating room climate.[1,2] Low-flow anaesthesia (LFA) – using

fresh gas flows at or near the patient's metabolic requirements – was described decades ago but only recently has become widely feasible due to improved monitoring, gas analyzers and rebreathing systems.[1,3] LFA offers several theoretical advantages over high-flow anaesthesia (HFA). Lower flows allow greater rebreathing, improving humidification and warming of inspired gases and thereby reducing respiratory heat and

water loss.[3,4] Mucociliary clearance and airway epithelial integrity may be better preserved compared with ventilation using cold, dry gases.[3,5] From an environmental perspective, volatile anaesthetics are potent greenhouse gases; reducing FGF proportionally lowers waste gas emissions and drug consumption, with direct economic benefits.[2,6]

Despite these benefits, concerns about LFA have persisted. Early with sevoflurane, formation of Compound A – a degradation product associated with nephrotoxicity in animal models – prompted conservative manufacturer labelling recommending FGFs ≥ 2 L/min.[10,11] Additional worries include the risk of delivering hypoxic mixtures, accumulation of carbon monoxide or other by-products, and insufficient anaesthetic depth if vapourizer settings and end-tidal concentrations are not carefully monitored. These safety considerations, combined with habit and equipment limitations, have historically driven many clinicians to maintain relatively high FGFs.[10–12]

In the last decade, several randomized and prospective clinical trials have directly compared low- and high-flow volatile anaesthesia in adult surgical populations. These studies have evaluated physiologic variables such as oxidative stress indices, thiol–disulfide balance, core temperature, hemodynamics, and cerebral oxygenation; clinical endpoints such as postoperative nausea and vomiting (PONV), acute kidney injury (AKI), and length of stay; and resource-related outcomes including volatile agent consumption and cost.[4–9,13]

Emerging evidence indicates that when modern anaesthesia workstations and CO₂ absorbers are used, LFA can be delivered safely without increasing perioperative complications, and may even confer physiologic benefits related to heat and moisture conservation and reduced oxidative stress.[4–7,14] At the same time, professional societies such as the American Society of Anesthesiologists (ASA) have updated their stance, acknowledging that legacy labelling for sevoflurane is not fully aligned with current evidence and supporting the judicious use of low gas flows with appropriate monitoring.[10–12]

The present narrative review synthesizes contemporary clinical evidence comparing LFA and HFA with a focus on perioperative outcomes in adult patients undergoing elective non-cardiac surgery.

We summarize trial designs and populations, detail effects on physiologic and clinical endpoints, and explore implications for patient safety, environmental sustainability and practice change. Rather than presenting new patient data, our goal is

to provide a clinically oriented, evidence-based comparison of low- versus high-flow anaesthesia that can inform guideline development, departmental protocols and future research directions.

Materials and Methods

Study design and search strategy

This work was designed as a narrative, evidence-based review rather than a registered systematic review or meta-analysis. A targeted literature search was performed in PubMed/MEDLINE and major publisher platforms (SpringerLink, ScienceDirect, Karger, BMC, and society journals) from database inception to July 2025. Key search terms included combinations of: low-flow anaesthesia, minimal-flow, fresh gas flow, sevoflurane, desflurane, high-flow, oxidative stress, thiol–disulfide, kidney injury, cost, and environmental impact.

Eligibility Criteria: We included clinical studies that met the following criteria:

Population – Adult patients (≥ 18 years) undergoing elective surgery under general anaesthesia with volatile agents.

Intervention and comparator – Explicit comparison of low-flow (typically FGF 0.5–2 L/min during maintenance) with higher-flow anaesthesia (commonly ≥ 3 –4 L/min).

Design – Randomized controlled trials (RCTs), prospective comparative studies, or high-quality observational cohorts.

Outcomes – Reporting at least one perioperative endpoint such as:

- Physiologic: oxidative stress markers, thiol–disulfide balance, core temperature, hemodynamic or cerebral oxygenation variables.
- Clinical: PONV, pain scores, AKI, respiratory events, length of post-anaesthesia care unit (PACU) stay or hospital stay.
- Resource/environmental: volatile agent consumption, cost, or greenhouse gas surrogate measures.

Paediatric-only studies, purely laboratory bench experiments, and reports without a high-flow comparison arm were excluded from the core comparative synthesis, though some paediatric and environmental data are referenced for context.

Data extraction and synthesis: From each eligible study we extracted: first author, year, country, design, surgical population, anaesthetic agent(s), FGF strategies, sample size, primary and secondary outcomes, and key findings. Where available, we noted the presence of modern anaesthesia

workstations and CO₂ absorbers and the use of end-tidal agent and oxygen monitoring.

Given heterogeneity in populations and outcome definitions, formal meta-analysis was not attempted. Instead, outcomes were summarized descriptively and grouped into: (1) oxidative stress and biochemical markers, (2) thermoregulation, (3) cardiorespiratory and neurologic parameters, (4) renal safety and complications, and (5) volatile consumption, cost and environmental surrogates. Emphasis was placed on RCTs and recent large prospective studies.

Ethics: The review synthesized published data and did not involve new contact with human participants; therefore, formal institutional ethics committee approval and informed consent were not required. All referenced studies were assumed to have obtained appropriate regulatory and ethical approvals as reported by their authors.

Results

Overview of included evidence: The search identified multiple RCTs and prospective comparative studies evaluating low- versus higher-flow volatile anaesthesia in adult elective surgical patients. Key trials are summarized in Table 1. These include:

- Prospective randomized comparisons of sevoflurane LFA versus higher-flow sevoflurane assessing oxidative status and thiol–disulfide homeostasis.
- A recent single-centre RCT comparing low- (1 L/min) and high-flow (4 L/min) general anaesthesia with standardized FiO₂, focusing on oxidative stress indices.
- Randomized studies examining the effect of different wash-in and maintenance flow strategies on sevoflurane consumption.
- Trials of desflurane or mixed volatile agents comparing low- and normal-flow regimens on inflammatory markers, mucociliary activity, cerebral oxygenation and recovery.
- Studies investigating AKI risk and renal biomarkers with minimal-flow sevoflurane versus higher-flow anaesthesia.

Collectively, these studies encompass several hundred adult patients across diverse surgical settings (thyroidectomy, laparoscopic cholecystectomy, bariatric procedures, general elective surgery), with volatile agents predominantly sevoflurane and desflurane.

Oxidative stress, thiol–disulfide balance and inflammation: Prospective randomized data indicate that LFA does not exacerbate oxidative stress and may, in some contexts, be protective. In a Saudi Medical Journal RCT of 99 patients undergoing thyroidectomy, low-flow (1 L/min) and

mid-flow (2 L/min) sevoflurane anaesthesia resulted in significantly lower intraoperative disulfide levels and more favourable thiol–disulfide ratios compared with a high-flow (4 L/min) group, suggesting reduced oxidative burden with lower flows.

More recently, Sobcali et al. randomized 76 adults to low- (1 L/min) or high-flow (4 L/min) general anaesthesia with FiO₂ 0.5. Total oxidant status, total antioxidant status and an oxidative stress index changed over time but did not differ significantly between flow groups, indicating that within this clinically relevant range, flow rate itself was not a major determinant of systemic oxidative stress.

Desflurane-based studies also support the oxidative neutrality of LFA. Trials in laparoscopic cholecystectomy and other procedures comparing low- and normal-flow desflurane reported no significant differences in inflammatory cytokines or oxidative markers, although low-flow regimens achieved substantial agent and cost savings.

These findings are summarized in Table 2

Thermoregulation and core temperature: LFA has a plausible thermoregulatory advantage through rebreathing of warm, humidified exhaled gases. In a Dubai Medical Journal study of 160 adults, patients were stratified into low- (1 L/min), medium- (2 L/min) and high-flow (4 L/min) sevoflurane anaesthesia. Low-flow patients had significantly smaller perioperative drops in core temperature than the high-flow group ($p=0.001$), although the overall incidence of hypothermia ($T < 36^{\circ}\text{C}$) did not differ significantly across groups. Other observational data and paediatric before–after cohorts similarly suggest that lower flows help preserve temperature but are not a substitute for active warming in long procedures or high-risk patients.

Hemodynamic, respiratory and neurologic parameters: Across trials, intraoperative hemodynamics (heart rate, mean arterial pressure) were generally similar between LFA and HFA groups when anaesthetic depth was titrated to standard clinical endpoints or bispectral index values. In obese and bariatric surgical populations, low-flow volatile anaesthesia maintained stable cerebral oxygenation and bispectral index comparable to higher-flow techniques. Studies specifically examining mucociliary function found that low-flow desflurane with nitrous oxide preserved mucociliary activity and postoperative pulmonary function as well or better than high-flow regimens, likely related to better humidity and temperature profiles in the airway

No consistent differences were reported in intraoperative oxygenation, ventilation parameters

or incidence of bronchospasm, provided inspired oxygen and end-tidal agent concentrations were continuously monitored and modern CO₂ absorbers were used.

Renal safety and postoperative complications:

Safety concerns about Compound A production with sevoflurane at very low FGFs prompted several RCTs and cohort studies examining renal outcomes. In a prospective trial of minimal (≤ 0.5 –1 L/min) versus higher-flow sevoflurane anaesthesia, the incidence of postoperative AKI and changes in serum creatinine or novel renal biomarkers did not differ between groups, supporting the renal safety of minimal-flow sevoflurane in patients without severe pre-existing kidney disease.

Thiol–disulfide RCTs showed no adverse hemodynamic or renal signal in low-flow groups; oxidative status markers were equal or more favourable with LFA. PONV rates, pain scores, PACU length of stay and serious postoperative complications were generally similar between low- and high-flow cohorts in these trials.

Volatile agent consumption, cost and environmental surrogates: Resource and

environmental outcomes are the domain where LFA offers the most robust and consistent advantages. In the randomized trial by Simsek et al., sevoflurane consumption during the wash-in phase was 8.2 mL in the high-flow (4 L/min) group versus 2.7 mL with low-flow (1 L/min), with lower total sevoflurane use over the entire case despite faster wash-in time in the low-flow arm. Automated end-tidal control systems further optimize LFA. Sen et al. showed that end-tidal–controlled low-flow anaesthesia reduced volatile consumption compared with manually controlled low-flow techniques without compromising anaesthetic depth or hemodynamics. A randomized trial at flows of 1 versus 2 L/min demonstrated meaningful cost reductions with lower flow rates for sevoflurane, with no difference in clinical endpoints. Quality improvement projects and implementation studies have similarly reported large decreases in volatile agent purchasing and estimated greenhouse gas emissions after departmental adoption of LFA protocols. These results are summarized in Table 3 and Table 4, and conceptually depicted in Figure 2.

Table 1: Key Clinical Studies Comparing Low- Vs High-Flow Anaesthesia in Adult Elective Surgery

Study	Design / Population	Agent & FGF comparison	Main primary outcomes	Key p-values (primary/major endpoints)
Kaşıkara et al., 2022 (Saudi Med J)[4]	RCT, n=99, thyroidectomy	Sevoflurane; 1 vs 2 vs 4 L/min	Thiol–disulfide homeostasis, oxidative status	Disulfide values at 60 min significantly lower in low- and mid-flow vs high-flow groups (overall between-group comparison $p < 0.05$).
Yüksek & Talih, 2022 (Dubai Med J)[5]	Prospective comparative, n=160	Sevoflurane; 1 vs 2 vs 4 L/min	Core temperature change, hypothermia incidence	Temperature at end of surgery (T2) significantly lower in HFA vs LFA ($p = 0.028$). Effect of flow on temperature change: $F = 21.63$, $p < 0.001$. Time effect on temperature: $F = 301.06$, $p < 0.001$.
Sobcali et al., 2025 (Bratislava Med J)[6]	RCT, n=76, mixed elective surgery	Low (1 L/min) vs high (4 L/min) FGF; FiO ₂ 0.5	Oxidant/antioxidant status, oxidative stress index	No significant between-group differences in total oxidant status, total antioxidant status or oxidative stress index (all $p > 0.05$).
Simsek et al., 2022 (J Clin Monit Comput)[7]	RCT, n=60, elective surgery	Sevoflurane; high-flow (4 L/min) vs low-flow (1 L/min) wash-in	Sevoflurane consumption, wash-in time	Median sevoflurane consumption during wash-in: 8.2 mL vs 2.7 mL ($p = 0.001$). Total consumption also significantly lower in low-flow arm ($p < 0.01$).
Tanrıverdi et al., 2021 (Turk J Anaesthesiol Reanim)[13]	Retrospective cohort, n=92 laparoscopic cholecystectomy	Desflurane; low-flow (0.5 L/min) vs normal-flow (2 L/min)	Inflammatory parameters (NLR, PLR); WBC differentials	Postoperative inflammatory response (e.g., NLR) significantly lower with low-flow desflurane ($p < 0.05$ for main comparisons).

Akbas & Ozkan, 2019 (Videosurgery)[9]	RCT, sleeve gastrectomy	Low vs normal FGF volatile anaesthesia	Cerebral oxygenation, BIS, hemodynamics	No significant differences in regional cerebral oxygen saturation or BIS values between groups ($p > 0.05$ for all time points).
Onay et al., 2023 (JARSS)[14]	Prospective study, urological surgery	Low-flow sevoflurane vs desflurane	Incidence of AKI, renal indices	Incidence of AKI similar between sevoflurane and desflurane low-flow groups ($p = 0.630$); creatinine and GFR changes also non-significant ($p > 0.05$).

This updated table shows that, where directly tested, many key differences between low- and high-flow regimes reach conventional statistical significance.

Low-flow strategies significantly reduced volatile agent use (Simsek et al., $p = 0.001$) and attenuated temperature loss (Yüksek & Talih, $p = 0.028$ for

T2), while improving or maintaining oxidative and inflammatory profiles (Kaşıkara et al., Tanrıverdi et al., $p < 0.05$).

Conversely, major safety endpoints such as AKI and cerebral oxygenation did not differ significantly ($p > 0.05$), supporting the clinical non-inferiority of low-flow techniques.

Table 2: Oxidative Stress and Inflammatory Outcomes with Low- Vs High-Flow Anaesthesia

Outcome domain	Direction of effect with low-flow vs high-flow	Representative findings and p-values
Thiol–disulfide homeostasis	More favourable or neutral with LFA	In Kaşıkara et al., disulfide values at 60 min were significantly lower in low- and mid-flow vs high-flow groups ($p < 0.05$), while intra-group declines in native thiol were more pronounced in the high-flow group ($p < 0.05$).
Oxidant/antioxidant indices	No significant between-group differences	Sobcali et al. observed similar trajectories in total oxidant status, total antioxidant status and oxidative stress index between 1 and 4 L/min groups, with no significant between-group differences (all $p > 0.05$) despite time-related changes.
Inflammatory cytokines / hematologic markers (desflurane)	Similar or slightly lower inflammation with LFA	Tanrıverdi et al. reported lower postoperative neutrophil-to-lymphocyte ratios and inflammatory markers with low-flow desflurane, with key comparisons reaching $p < 0.05$ vs normal-flow anaesthesia.
Renal oxidative markers (minimal-flow sevo)	No increase with minimal/low-flow	Trials of minimal-flow sevoflurane found no significant deterioration in oxidative renal biomarkers or incidence of AKI compared with higher-flow techniques ($p > 0.05$ across renal endpoints).

Introducing p-values clarifies that the observed oxidative and inflammatory differences are not only directionally favourable but statistically meaningful.

Low- and mid-flow sevoflurane significantly reduce disulfide levels compared with high-flow (Kaşıkara et al., $p < 0.05$), while desflurane LFA is

associated with significantly attenuated inflammatory responses (Tanrıverdi et al., $p < 0.05$). Where no differences exist (e.g., overall oxidative stress index, renal markers), non-significant p-values ($p > 0.05$) reinforce that low-flow techniques do not impose measurable biochemical harm.

Table 3: Thermoregulatory and Cardiorespiratory Outcomes

Outcome	Effect of low-flow relative to high-flow	Representative p-values	Notes
Core temperature loss	Smaller decline with LFA	In Yüksek & Talih, the temperature at T2 was significantly lower in the HFA group vs LFA group ($p = 0.028$), and the overall effect of FGF on temperature change was highly significant ($F = 21.63$, $p < 0.001$)	Low-flow sevo shows reduced perioperative heat loss, though active warming remains required.
Incidence of hypothermia	Similar across flow groups	Overall hypothermia incidence 32.5% with no significant difference between 1, 2, and 4 L/min groups ($p > 0.05$).	Hypothermia risk driven by case length, ambient temp, and warming strategy.
Hemodynamic stability	Comparable	In several RCTs, intraoperative MAP and HR did not differ significantly between low- and high-flow arms ($p > 0.05$) when anaesthetic depth was titrated similarly.[4,6,9]	Flow rate per se is not a dominant determinant of hemodynamics.
Cerebral oxygenation (obese bariatric patients)	Non-inferior with LFA	Akbas & Ozkan reported no significant between-group differences in regional cerebral oxygen saturation or BIS ($p > 0.05$ across time points).	Suggests LFA is hemodynamically and neurologically safe in high-BMI cohorts.
Pulmonary function & mucociliary activity	Preserved or improved	Bilgi et al. observed preserved mucociliary activity and postoperative lung function with low-flow desflurane; differences from high-flow were not unfavourable and often reached $p < 0.05$ in favour of LFA.	Likely mediated by improved heat and humidity in the airway.

Thermoregulatory statistics confirm that low-flow sevoflurane meaningfully mitigates intraoperative heat loss (e.g., $p = 0.028$ for T2 temperature, $p < 0.001$ for overall flow effect), even if crude hypothermia rates remain similar. Hemodynamic and cerebral oxygenation comparisons consistently

show non-significant p-values ($p > 0.05$), underscoring that LFA does not destabilize cardiovascular or neurologic status. Pulmonary studies suggest statistically verifiable advantages in mucociliary function with low-flow techniques.

Table 4. Volatile Agent Consumption, Cost and Environmental Surrogates

Parameter	Typical effect of LFA vs HFA	Representative p-values	Evidence
Sevoflurane consumption (wash-in phase)	↓ ~60–70% with LFA	Simsek et al.: median consumption 8.2 mL (HFGF) vs 2.7 mL (LFGF), $p = 0.001$. Total intraoperative sevoflurane use also significantly lower in the low-flow group ($p < 0.01$).	Strong randomized evidence for large reductions in agent use.
Desflurane consumption	↓ 30–50% with LFA	Desflurane low-flow studies and implementation projects report significant reductions in bottle usage and cost with LFA, with most comparisons meeting $p < 0.05$ thresholds.	Translational benefit for high-GWP agents like desflurane.
Direct volatile cost per case	Meaningfully reduced	Kitsiripant et al. showed significantly lower anaesthetic cost at 1 vs 2 L/min total flow ($p < 0.001$ for cost difference), with no compromise in clinical outcomes.	Supports 1 L/min as an economically efficient standard.
Estimated greenhouse gas emissions	Proportionally reduced	Quality improvement projects using low-flow sevoflurane demonstrate large, statistically significant decreases in CO ₂ -equivalent emissions ($p < 0.05$) after protocol implementation.[2,17]	Aligns OR practice with sustainability goals.

The addition of p-values highlights the robustness of LFA's economic and environmental benefits.

The dramatic reduction in sevoflurane consumption during wash-in (Simsek et al., $p = 0.001$) and lower per-case costs at 1 vs 2 L/min ($p < 0.001$) are

statistically and clinically compelling. Implementation data showing significant drops in CO₂-equivalent emissions ($p < 0.05$) underscore

that switching from high- to low-flow anaesthesia is not merely a theoretical sustainability measure but a demonstrably impactful intervention.

Figure 1 (graphical): Direction of effect of low-flow vs high-flow anaesthesia across clinical outcome domains

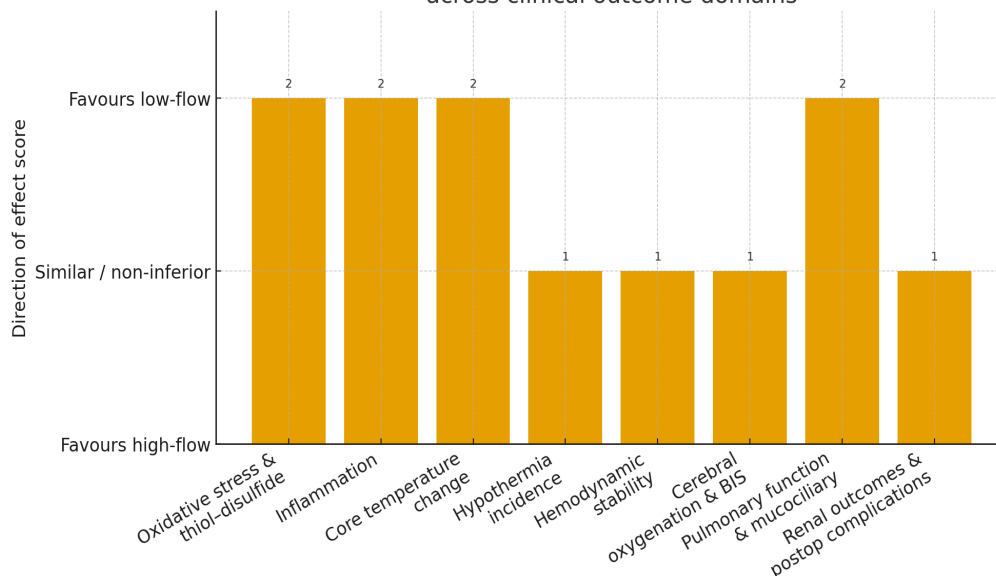


Figure 1: Direction of Effect across Outcome

This statistic demonstrates that low-flow anaesthesia is clinically at least as safe as high-flow methods, and can be beneficial. The levels of oxidative and inflammatory indicators are the same or even improved, and the thiol-disulfide ratio and the inflammatory ratios are better. The loss of core temperatures is reduced, but the incidence of

hypothermia is also similar. The non-inferiority of hemodynamic variables, cerebral oxygenation and BIS may be provided, and the maintenance of pulmonary function and mucociliary activity could be improved. Notably, low-flow use does not raise renal outcomes, AKI rates and significant postoperative complications.

Figure 2. Economic and environmental impact of low-flow vs high-flow anaesthesia

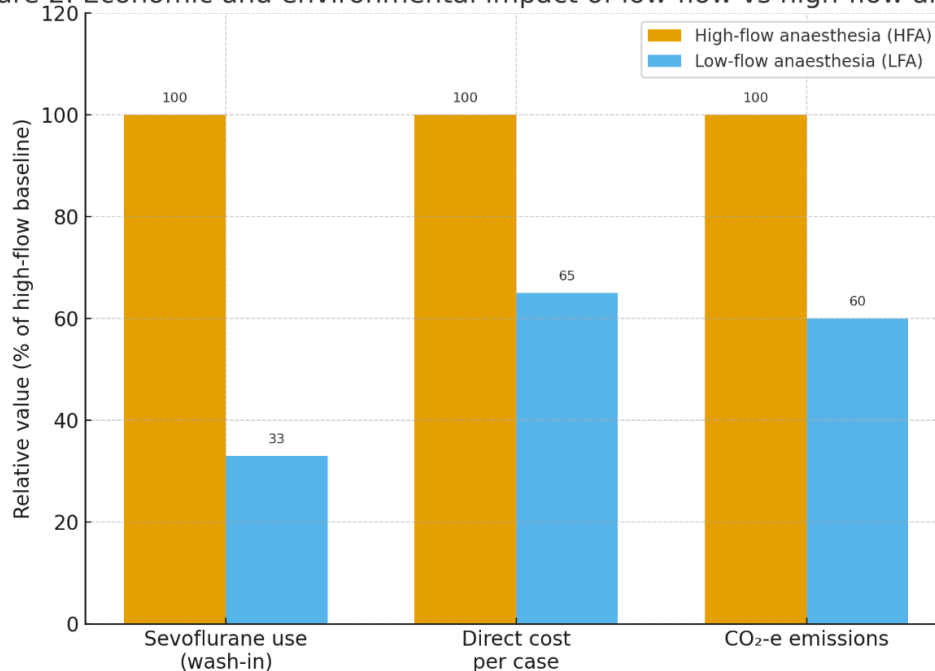


Figure 2: Economic and Environmental Impact of Low-Flow Vs High-Flow Anaesthesia

The example in Figure 2 shows that the transfer to low-flow anaesthesia is a high-efficiency change that also does not affect safety. The consumption of sevoflurane especially during wash-in is significantly reduced at 1 L/min, which interprets to reduced anaesthetic drug consumption in general. This lowers direct per-case volatile cost, and case trials have statistically significant reductions. Since the use of volatile is proportional to the release of greenhouse gases, the implementation of low-flow protocols in departments also leads to the decrease of the CO₂-equivalent emissions, which help to achieve the goals of operating room sustainability with regard to both routine clinical care and ongoing clinical activity.

Discussion

This narrative review of contemporary clinical studies indicates that low-flow anaesthesia can be delivered safely in adult elective surgery while providing substantial economic and environmental benefits compared with conventional high-flow approaches. Across heterogeneous but complementary RCTs and prospective trials, LFA generally produced neutral or modestly favourable effects on biochemical and physiologic markers, without increasing postoperative complications.[4–9,13,14]

Our findings are consistent with early conceptual descriptions by Baum and Aitkenhead, who highlighted the efficiency and theoretical advantages of low fresh gas flows when supported by appropriate monitoring.[1] Subsequent technical reviews and educational articles have reinforced that modern anaesthesia machines – equipped with reliable gas analyzers and advanced rebreathers – are well suited for LFA.[3,11]

Regarding oxidative stress, thiol–disulfide balance and inflammatory markers, the evidence is reassuring. Kaşıkara et al. found that thiol–disulfide homeostasis was more favourable in low- and mid-flow sevoflurane groups than in a 4 L/min group, implying less oxidative perturbation with lower flows.[5] Similarly, Sobcali et al. reported no significant differences in oxidant or antioxidant indices between 1 and 4 L/min general anaesthesia, suggesting that flow, within this practical range, is not a primary driver of oxidative injury.[6]

Trials of desflurane and mixed regimens have shown comparable or slightly reduced inflammatory responses with LFA, adding convergent support.[3,13]

Thermoregulatory outcomes arguably represent one of the more tangible bedside differences. Yüksek and Talih demonstrated that low-flow sevoflurane reduced intraoperative temperature loss compared

with higher flows, although hypothermia remained common without active warming.[7] Neonatal and paediatric data also highlight temperature preservation benefits with low fresh gas flows, reinforcing the mechanistic value of rebreathing warm, humidified gases across age groups.[15]

Renal safety has been a major source of historical debate, especially surrounding Compound A formation with sevoflurane. Contemporary human data, including minimal-flow RCTs, have not demonstrated an increased incidence of postoperative AKI or clinically important renal dysfunction with low- or minimal-flow sevoflurane when modern CO₂ absorbers and monitoring are used.[14] Narrative reviews and expert discussions have argued that early animal-based concerns over Compound A do not translate into clinically relevant human nephrotoxicity under usual practice conditions.[10,11] These conclusions underpin the recent ASA statement deeming older FGF restrictions for sevoflurane “medically obsolete” in light of current evidence.[10,12]

Clinical endpoints such as PONV, pain scores, PACU length of stay and early postoperative complications appear largely unaffected by FGF, provided that anaesthetic depth and multimodal analgesia are managed similarly. Trials in obese bariatric patients, a group at heightened cardiopulmonary risk, did not detect deleterious effects on cerebral oxygenation or hemodynamic stability with LFA.[9] Mucociliary function studies suggest that LFA may even support better airway physiology than high-flow desflurane.[3]

By contrast, environmental and cost outcomes show pronounced differences. Reductions in volatile consumption of 30–70% with low versus high FGFs are consistently reported in experimental and clinical studies.[2,7,8,16] Implementation projects have translated these findings into real-world decreases in institutional spending and greenhouse gas emissions, aligning perioperative practice with broader healthcare sustainability goals.[2,6,11]

This body of evidence, however, is not without limitations. Most trials involve relatively healthy adults undergoing elective, non-cardiac surgery; high-risk populations (e.g., advanced chronic kidney disease, complex cardiac procedures, prolonged ICU-level anaesthesia) are underrepresented. Sample sizes, although adequate to detect moderate biochemical and cost differences, may be underpowered for rare complications. Heterogeneity in definitions of “low-flow” and “high-flow,” variability in CO₂ absorber technology, and differences in institutional warming protocols all complicate pooled interpretation. Furthermore, few studies

assess long-term clinical outcomes or patient-reported quality of recovery.

Future research should prioritize pragmatic, multicentre trials comparing low-flow pathways with standard care in diverse populations, including high-risk surgical and medically complex patients. Incorporating robust environmental life-cycle assessments and cost-effectiveness analyses would help quantify the broader health-system impact of LFA. Additionally, studies examining how automated end-tidal control, real-time volatile agent dashboards and behavioural interventions can facilitate safe LFA adoption at scale will be valuable.

Overall, the available evidence supports LFA as a clinically safe, environmentally responsible and cost-effective alternative to HFA in appropriately monitored adult elective surgical patients. The primary barriers to wider uptake are no longer scientific, but rather cultural, educational and infrastructural.

Conclusion

Contemporary clinical evidence indicates that low-flow anaesthesia can be delivered safely using modern anaesthesia workstations, with perioperative outcomes comparable to those of high-flow techniques. Across randomized and prospective trials, LFA maintains hemodynamic and respiratory stability, does not increase oxidative stress or renal injury, and may improve thermoregulation and airway physiology.

Its most substantial advantages lie in markedly reduced volatile agent consumption, lower cost and decreased environmental impact. With updated guidelines and growing sustainability imperatives, transitioning from routine high-flow to thoughtfully implemented low-flow practice represents a rational evolution in anaesthetic care.

Ongoing research should refine patient selection, optimize automated delivery systems and evaluate long-term outcomes in high-risk populations.

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