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Healing the Patient, Protecting the Planet: The Practice and Paradigm of Green Anaesthesia

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ABSTRACT

Healthcare systems globally confront a profound paradox: the delivery of medical care inadvertently drives environmental degradation, contributing approximately 4–5% of global greenhouse gas (GHG) emissions. Within this ecosystem, the operating theatre acts as a hyper-intensive carbon epicenter, with clinical anaesthesia bearing a disproportionate ecological footprint. This article comprehensively reviews the paradigm of "Green Anaesthesia"—an evidence-based approach to mitigating the environmental impact of perioperative care without compromising patient outcomes. We examine the atmospheric dynamics of halogenated volatile anaesthetics (desflurane, isoflurane, sevoflurane) and nitrous oxide (N_2O), emphasizing their respective global warming potentials (GWP) and life-cycle assessments (LCAs).

Clinical mitigation strategies-including ultra-low-flow anaesthesia, total intravenous anaesthesia (TIVA), and regional anaesthesia-are appraised alongside structural interventions across Scope 1, 2, and 3 emissions. Global consensus mandates from the World Federation of Societies of Anaesthesiologists (WFSA), the European Society of Anaesthesiology and Intensive Care (ESAIC), and recent national guidelines provide a standardized operational blueprint. Finally, this paper addresses systemic structural and behavioral barriers to widespread adoption, mapping out a collaborative roadmap to reconcile patient safety with planetary health.

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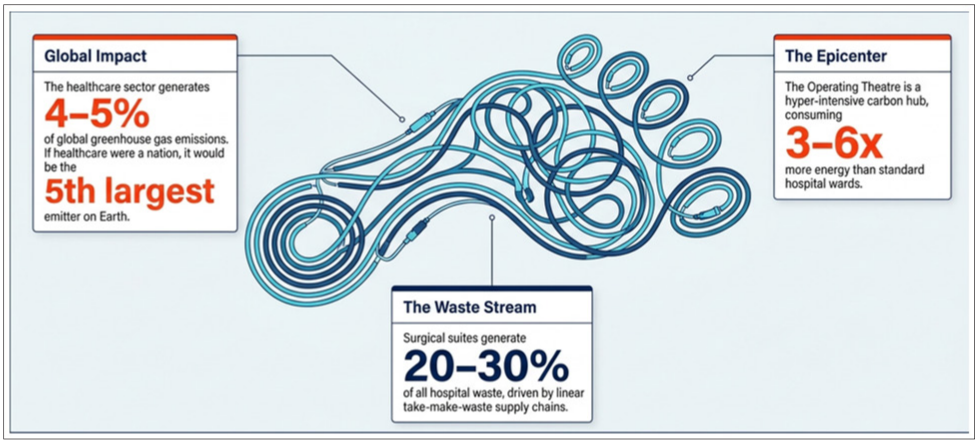
Introduction

The fundamental guiding principle of medical practice, primum non nocere ("first, do no harm"), has traditionally been confined to the immediate sphere of the individual patient. However, the modern climate crisis demands a systemic expansion of this bioethical mandate. The global healthcare sector generates a staggering ecological footprint; if it were a nation, it would rank as the fifth-largest emitter of greenhouse gases on Earth [1]. Operating theatres are highly resource-intensive environments, generating up to 20–30% of total hospital waste and consuming energy at rates three to six times higher than baseline ward environments [2]. Within this context, anaesthesiologists wield unique clinical and administrative influence over substantial carbon expenditures.

The environmental burden of anaesthesia is primarily driven by the routine release of volatile halogenated ethers and nitrous oxide (N_2O) into the atmosphere via waste anaesthetic gas scavenging systems (AGSS). These compounds are potent greenhouse gases that exhibit prolonged atmospheric lifetimes and high radiative efficiencies. Furthermore, the modern surgical suite has become deeply dependent on linear supply chains ("take-make-waste"), resulting in a vast accumulation of single-use biomedical plastics, excessive pharmaceutical wastage, and high carbon emissions across procurement networks.

Over the past decade, and accelerating rapidly into 2026, the global anaesthesia community has mobilized to construct a robust framework for environmental sustainability. Variously termed "Green Anaesthesia" or "Sustainable Perioperative Care," this framework seeks to rapidly decarbonize the operating theatre. This article provides an extensive, evidence-based synthesis of the current science, clinical interventions, international policy agreements, systemic barriers, and future technical trajectories defining sustainable anaesthetic practice today.



Atmospheric Chemistry and the Carbon Footprint of Inhaled Agents

To understand the clinical mandate for green anaesthesia, one must examine the atmospheric chemistry of volatile inhalational agents. All commonly used volatile anaesthetics belong to the class of halogenated hydrocarbons. Once administered to a patient, these agents undergo minimal in vivo metabolism (ranging from less than 0.02% for desflurane to roughly 5% for sevoflurane); the overwhelming majority is exhaled unchanged and vented directly into the ambient atmosphere [3].

Global Warming Potential and Radiative Forcing

The climate impact of a gas is quantified by its Global Warming Potential over a 100-year horizon (GWP_{100}), which measures the heat-trapping capacity of a gas relative to carbon dioxide (CO_2, defined as $GWP_{100} = 1$). The structural integration of fluorine and chlorine atoms into these molecules shields them from rapid destruction by atmospheric hydroxyl (OH) radicals, allowing them to persist in the troposphere and stratosphere where they absorb infrared radiation.

Agent	Atmospheric Lifespan	Global Warming Potential (GWP_{100})*	Clinical Note
Desflurane	14.0 years	2,540	Highly disproportionate atmospheric impact.
Isoflurane	3.2 years	510	Moderate persistence.
Nitrous Oxide / N_2O	114.0 years	298	The #1 global ozone-depleting substance emitted today.
Sevoflurane	1.1 years	130	Rapid degradation; optimal volatile choice.
Carbon Dioxide / CO_2 (Baseline)	Variable	1	Baseline reference standard.

*GWP_{100} measures the heat-trapping capacity of a gas relative to CO_2 over a 100-year horizon.

The stark disparity between desflurane and sevoflurane is clinically definitive. Desflurane possesses an atmospheric lifetime of 14 years and a GWP_{100} of 2,540 [4]. Conversely, sevoflurane degrades within approximately 1.1 years, yielding a GWP_{100} of 130.

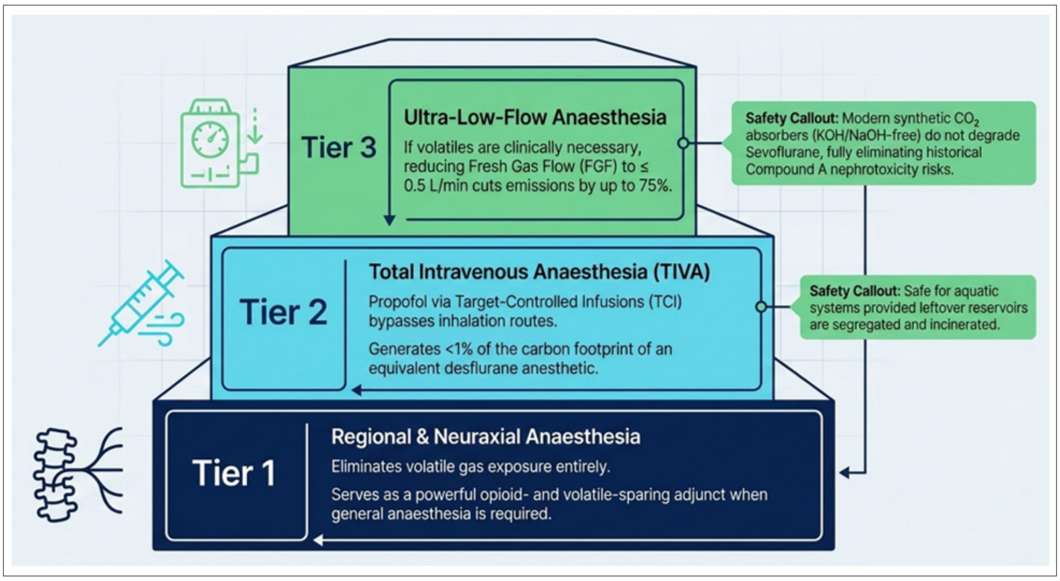
To contextualize these values in clinical practice, maintaining a surgical patient on desflurane at a fresh gas flow (FGF) of 2 L/min for one hour generates an emissions profile equivalent to driving a standard internal combustion vehicle approximately 320 to 400 kilometers. The same procedure conducted with sevoflurane equates to less than 10 kilometers of driving distance [5].

The Compounded Impact of Nitrous Oxide

Nitrous oxide (N_2O) presents a dual environmental hazard. Though its absolute GWP_{100} of 298 is lower than that of the volatile halogenated ethers, its clinical administration at high concentrations (typically 50–70% of inspired volume) results in immense mass emissions. Furthermore, N_2O features an atmospheric residence time exceeding a century (114 years). Upon ascending to the stratosphere, photolysis reactions trigger the release of nitric oxide (NO) radicals, which catalytically destroy ozone (O_3). Today, N_2O represents the single largest ozone-depleting substance emitted globally [6].

Core Clinical Strategies for Decarbonization

Decarbonizing clinical practice does not require compromising patient safety, depth of anaesthesia, or predictability of emergence. Instead, it demands shifting from historical practices to precise, modern delivery strategies.



Modernizing Flow Rates: Low and Ultra-Low Fresh Gas Flow

The historical standard of utilizing high fresh gas flows (FGF ≥ 2–4 L/min) was designed to prevent carbon dioxide rebreathing and ensure rapid adjustments in volatile agent concentrations within older circle systems. Modern anaesthesia workstations, however, feature highly efficient circle systems and advanced carbon dioxide absorbers, rendering high flow rates obsolete.

Reducing the FGF directly minimizes the volume of carrier gas (oxygen/air) passing through the vaporizer chamber, thereby conserving the liquid anesthetic agent. The clinical application of low-flow anaesthesia (FGF ≤ 1 L/min) or ultra-low-flow anaesthesia (FGF ≤ 0.5 L/min) scales down both volatile agent consumption and subsequent greenhouse emissions by up to 75% [7].

Safety Check: Compound A and Sevoflurane

Historical concerns regarding the accumulation of Compound A—a potentially nephrotoxic vinyl ether produced by the degradation of sevoflurane in traditional baralyme or soda lime absorbers—previously limited low-flow sevoflurane practices. Modern CO_2 absorbers utilize synthetic formulations entirely free of potassium hydroxide (KOH) and sodium hydroxide (NaOH). These modern compounds do not degrade sevoflurane, establishing ultra-low-flow delivery as an exceptionally safe standard globally [8].

Total Intravenous Anaesthesia (TIVA)

Total Intravenous Anaesthesia—predominantly executed via target-controlled infusions (TCI) of propofol coupled with short-acting opioids like remifentanil—completely bypasses the inhalation route. Comprehensive Life Cycle Assessments (LCAs) demonstrate that when accounting for the entire life cycle of propofol (including synthesis, electrical demands of syringe pumps, manufacturing of plastic syringes, and eventual incineration waste), TIVA incurs a global warming footprint less than 1% of an equivalent desflurane-based anesthetic, and roughly 10–20% of a low-flow sevoflurane-based anesthetic [9]. While propofol is ecotoxic to aquatic life if discarded directly into wastewater streams, proper disposal protocols involving the segregation and incineration of leftover drug reservoirs eliminate this risk, preserving TIVA's standing as a highly sustainable choice.

Regional and Neuraxial Anaesthesia

Transitioning suitable surgical candidates to regional or neuraxial techniques (such as spinal, epidural, or peripheral nerve blocks) eliminates the need for general airway management and volatile gas exposure. When general anaesthesia is required, regional blocks can serve as powerful opioid- and volatile-sparing adjuncts. This lower required MAC (Minimum Alveolar Concentration) fractions during maintenance and accelerates recovery times.

Operationalizing Sustainability: The Three Scopes of Emissions

To systematically analyze and mitigate the environmental impact of the surgical suite, green anaesthesia leverages the greenhouse gas accounting architecture established by the World Business Council for Sustainable Development and the World Resources Institute. This model categorizes greenhouse gas emissions into three distinct corporate reporting scopes.

Scope 1: Direct Emissions (The Clinical Sphere)

Scope 1 emissions encompass direct greenhouse gases emitted from sources owned or controlled by the healthcare institution. In anaesthesiology, this is dominated by volatile gas venting and central pipeline infrastructure. Beyond clinical choices at the vaporizer, a significant portion of Scope 1 emissions stems from structural leaks within central medical gas piping networks. Institutional audits have revealed that up to 80–90% of a hospital's purchased nitrous oxide can be lost to systemic pipeline degradation before ever reaching a patient's breathing circuit [10]. Decommissioning central pipelines in favor of localized, cylinder-based manifolds mounted directly onto anaesthesia workstations represents a vital institutional intervention.

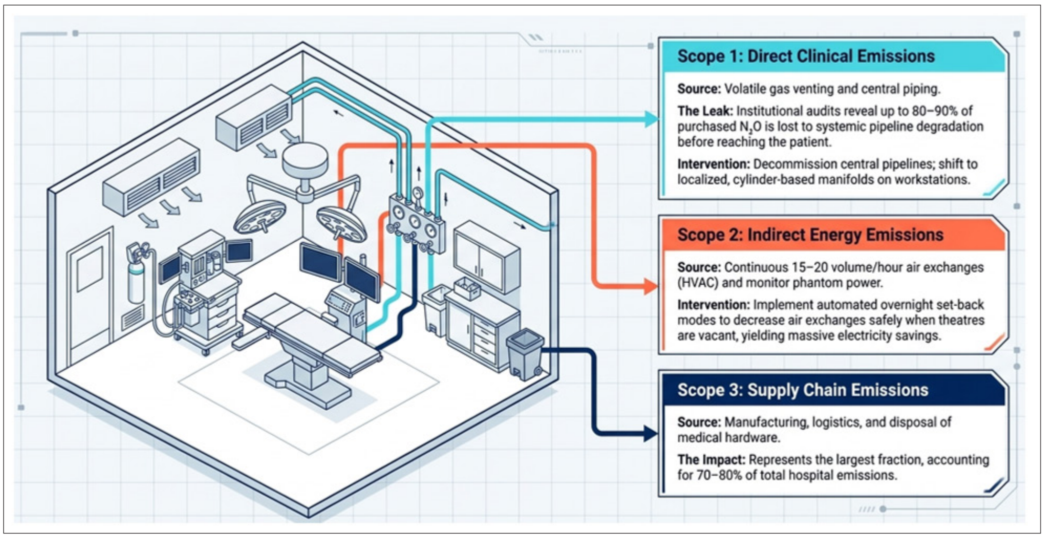
Scope 2: Indirect Energy Emissions (The Infrastructure Sphere)

Scope 2 covers indirect greenhouse gas emissions resulting from the generation of electricity, heating, and cooling purchased and consumed by the hospital. The operating room requires rigorous air change rates (typically 15–20 volume exchanges per hour) and tight climate controls to maintain sterile fields and prevent surgical site infections. These Heating, Ventilation, and Air Conditioning (HVAC) systems run continuously, consuming vast amounts of electricity. Green anaesthesia protocols advocate for the integration of automated "set-back" modes. When theatres are vacant outside operational hours, air exchange rates can safely decrease to baseline levels while preserving appropriate positive pressure differentials. Furthermore, turning off anaesthesia workstations and monitors overnight avoids phantom power draws, yielding substantial energy and financial savings [11].

Scope 3: Supply Chain and Lifecycle Emissions (The Procurement Sphere)

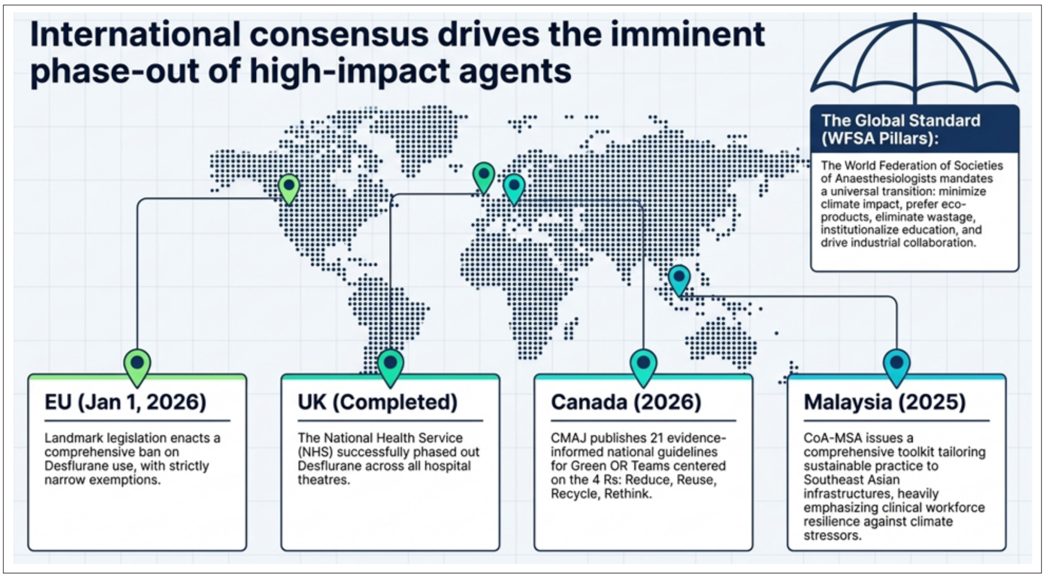
Scope 3 emissions comprise all other indirect emissions embedded within an institution's value chain, including the production, logistics, and disposal of medical hardware and pharmaceuticals. This domain represents the largest and most complex fraction of healthcare's carbon footprint, frequently accounting for over 70–80% of total hospital emissions [12].

The rapid transition toward single-use medical devices—such as disposable laryngoscope blades, single-use laryngeal mask airways (LMAs), single-use drug trays, and disposable surgical gowns—is primarily driven by convenience and infection control concerns. However, modern comparative LCAs indicate that when accounting for sterilizing infrastructure, water purification, and energy-efficient wash cycles, reusable alternatives consistently generate significantly lower carbon emissions and material waste across their lifespan than single-use alternatives [13].



Global Policy and International Consensus Mandates

The transition toward green anaesthesia is no longer driven solely by grassroots clinical advocates; it is supported by formal international consensus policies and professional mandates.



The WFSA Global Principles

The World Federation of Societies of Anaesthesiologists (WFSA) convened an international expert panel to ratify a definitive global consensus statement. This framework outlines seven fundamental pillars of sustainable practice designed for universal implementation, irrespective of a nation's baseline resource level [14]

- **Minimize Climate Impact:** Prioritize clinically appropriate low-GWP agents, low-flow delivery, TIVA, or regional techniques.
- **Prefer Environmentally Friendly Products:** Incorporate eco-conscious materials and reusable hardware where clinically safe.
- **Eliminate Wastage:** Minimize the overuse of medications, medical consumables, water, and grid energy.
- **Institutional Education:** Embed environmental sustainability principles directly into undergraduate and postgraduate medical curricula.
- **Research and Quality Improvement:** Direct funding and academic infrastructure toward green perioperative research and clinical auditing.
- **System Leadership:** Empower anaesthesiologists to serve as key sustainability stakeholders within institutional boardrooms.
- **Industrial Collaboration:** Partner with biomedical manufacturers to optimize product life cycles and supply chain transparency.

The Accelerating Elimination of Desflurane

Due to its high GWP_{100}, desflurane has become a primary target for regulatory phase-outs. The European Union passed landmark legislation implementing a comprehensive ban on the use of desflurane, effective January 1, 2026, except under narrow, strictly defined clinical exemptions [15].

Similarly, the National Health Service (NHS) in the United Kingdom successfully phased out desflurane across its theatres, a milestone that significantly reduced the overall carbon footprint of UK surgical units. These regulatory shifts demonstrate a growing international consensus that agents with highly disproportionate global warming potentials are no longer clinically justifiable when viable alternatives exist.

Emerging National Frameworks (2025-2026)

Recent updates to clinical guidelines highlight how rapidly these sustainability concepts are being institutionalized:

• **Canada (2026):** A new national evidence-informed guideline published in the Canadian Medical Association Journal (CMAJ) targets the operating room footprint. It outlines 21 distinct recommendations across the "4 Rs" (Reduce, Reuse, Recycle, Rethink), advocating for a shift toward reusable gowns and devices, optimized surgical trays, and the formation of multidisciplinary "green OR teams" [16].

• **Malaysia (2025):** The College of Anaesthesiologists and the Malaysian Society of Anaesthesiologists (CoA-MSA) issued a comprehensive national Consensus Statement on Green Anaesthesia. This framework builds on the WFSA principles, offering a structured toolkit tailored to Southeast Asian healthcare infrastructures. Notably, it integrates healthcare provider well-being directly into the sustainability equation, recognizing that climate-related stressors (such as heat stress and extreme weather disruptions) impact clinical workforce resilience [17].

Systemic Barriers and Paradigms of Resistance

Despite clear clinical evidence and institutional consensus, implementing green anaesthesia across daily practices faces several persistent challenges.

The Infection Control Paradox: The most formidable barrier to adopting reusable medical equipment is the strict, often dogmatic focus on infection control. The rapid expansion of single-use plastics has been driven by the assumption that disposable items guarantee a lower risk of healthcare-associated infections (HAIs). However, robust epidemiological data reveals that reusable items-when processed via standardized, high-level disinfection or autoclaving-carry zero excess risk of surgical site infections compared to single-use options [18]. Overcoming this barrier requires open, cross-departmental dialogue with infection control committees, shifting the institutional goal from "zero risk via disposables" to an integrated assessment of both patient safety and long-term environmental health.

Behavioral Inertia and Clinical Autonomy: Clinical practice patterns are deeply rooted in habit and individual training histories. Anesthesiologists accustomed to running high fresh gas flows or routinely utilizing desflurane for predictable emergence times may resist changing their workflows. This inertia is often compounded by a perceived threat to clinical autonomy. Overcoming behavioral resistance requires framing sustainability not as a restriction on practice, but as an evolution in clinical precision.

The "Green Premium" Misconception: Hospital administrators frequently assume that implementing sustainable alternatives requires high upfront capital investments or premium operational costs. This misconception is refuted by data. A systematic review published in The Lancet examining healthcare sustainability initiatives discovered that 54 out of 57 audited interventions resulted in substantial financial savings [19]. Strategies such as reducing fresh gas flows, substituting desflurane with sevoflurane, eliminating nitrous oxide pipeline leaks, and down-sizing waste streams consistently reduce procurement costs and waste disposal fees, creating a clear alignment between economic efficiency and environmental stewardship.

Technological Frameworks and Future Directions

As healthcare systems work toward net-zero goals, technical innovations are expanding what is achievable within sustainable anaesthesia.

Automated End-Tidal Control (EtC): Manually adjusting fresh gas flows during low- or ultra-low-flow anaesthesia requires close attention to avoid hypoxia or unintended light sedation. Modern anaesthesia workstations address this with automated end-tidal control software. The clinician sets the target end-tidal oxygen concentration (EtO_2) and target MAC fraction. The workstation's closed-loop algorithms then continuously adjust the fresh gas flow and vaporizer output on a breath-by-breath basis. By maintaining the circuit at optimal efficiency, automated EtC systems reduce volatile agent consumption by up to 40–50% compared to conventional manual adjustments [20].

Volatile Anesthetic Capture and Recycling Systems: For clinical scenarios where inhaled agents remain necessary, advanced gas scavenging technologies offer a way to prevent atmospheric release. Modern volatile gas capture systems can be retrofitted directly to the exhaust ports of standard AGSS networks. These devices utilize specialized activated charcoal or silica-matrix filters to selectively capture up to 95% of imaged halogenated ethers. Once the filter canisters reach saturation, they are collected and processed via thermal desorption, allowing the captured anesthetic agents to be purified, refined, and recycled back into clinical-grade compounds. This transforms a traditional linear emission path into a sustainable, closed-loop circular economy.

Conclusion

The practice of green anaesthesia represents a crucial evolution in perioperative medicine. The scientific evidence establishes that historical habits-such as using high fresh gas flows, relying on highly potent greenhouse gases like desflurane, and defaulting to a single-use disposal culture-incur a heavy environmental cost without offering clinical advantages.

Mitigation strategies are readily available, safe, and cost-effective. By adopting ultra-low-flow techniques, expanding the use of TIVA and regional anaesthesia, optimizing clinical supply chains, and decommissioning wasteful nitrous oxide pipelines, the anaesthesia community can achieve immediate, scalable reductions in its carbon footprint. With international bodies like the WFSA providing clear blueprints and regulatory updates formalizing these changes worldwide, environmental sustainability is fast becoming a core benchmark of clinical excellence. Ultimately, green anaesthesia reminds us that protecting the patient in the theatre and protecting the planet outside it are deeply interconnected missions.

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