A Radiative Forcing-Based Life Cycle Assessment Model for Inhaled Anaesthetic Agents: Integrating Climate and Ecotoxicity Metrics

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ABSTRACT

Background: The environmental impact of inhaled anaesthetics is conventionally quantified using the 100-year global warming potential (GWP_{100}), which aggregates the radiative efficiency of a gas with its atmospheric lifetime into a single CO_2-equivalent figure. While this metric facilitates policy comparisons, it does not reflect the instantaneous physical forcing that a released gas imposes on the atmosphere at the moment of emission.

Methods: We propose a novel modelling framework that derives instantaneous radiative forcing (RF, $mW \cdot m^{-2}$) directly from clinical input parameters (fresh gas flow, end-tidal concentration, and maintenance duration) for sevoflurane, desflurane, and isoflurane. The model uses radiant efficiency values from IPCC AR6 and incorporates a life cycle assessment (LCA) dimension by adding production-phase CO_2 emissions to the primary atmospheric RF. As a secondary analysis, we calculate the expected trifluoroacetic acid (TFA) yield per anaesthetic agent using published atmospheric degradation stoichiometry. The proposed primary metric is RF per MAC-hour ($mW \cdot m^{-2} \cdot MAC\text{-}h^{-1}$).

Results: At standard clinical conditions (fresh gas flow 1 L/min, 1 MAC, 60 min maintenance), desflurane generates 5.2-fold more RF per MAC-hour than sevoflurane, and isoflurane generates 1.1-fold more. The GWP_{100}-based ratio for the same comparison is 61.8-fold, suggesting that the conventional metric overestimates the relative impact of desflurane by a factor of approximately 12. The LCA component contributes less than 4% to total RF for all volatile agents, confirming that atmospheric emission dominates the climate footprint. TFA yield per MAC-hour follows the same rank order as RF (desflurane > isoflurane > sevoflurane), providing independent convergent support for agent ranking.

Conclusions: RF per MAC-hour provides a physically transparent alternative to GWP for comparing the climate footprint of inhaled anaesthetics. The LCA-RF framework presented here enables both clinician-level decision support and institution-level environmental accounting from routine clinical data, without requiring patient-level records.

Keywords: *radiative forcing, inhaled anaesthetics, life cycle assessment, environmental anaesthesia, sevoflurane, desflurane, trifluoroacetic acid*

1. INTRODUCTION

The healthcare sector accounts for approximately 4.4% of global greenhouse gas emissions,[1,2] with anaesthesia contributing a disproportionate share through the direct atmospheric release of potent fluorinated gases.[3,4]

Volatile anaesthetic agents, including sevoflurane, desflurane, and isoflurane, are halogenated ethers that absorb infrared radiation strongly within the atmospheric window (8 to 14 μm), precisely the spectral region through which terrestrial infrared emission would otherwise escape to space.[5,6] Following exhalation and scavenging, these gases are released unchanged into the atmosphere, where they exert a direct warming influence until degraded by hydroxyl radicals.[5,7]

The dominant metric used to quantify this influence has been the 100-year global warming potential (GWP_{100}), defined as the cumulative radiative forcing of a pulse emission of a given gas integrated over 100 years, normalised to that of CO_2.[8] For desflurane, sevoflurane, and isoflurane, IPCC AR6 assigns GWP_{100} values of 2540, 130, and 510, respectively.[8] These figures have driven clinical guidance, including the European prohibition of desflurane use in several countries, and institutional targets for low-flow anaesthesia.[9,3]

Despite its widespread adoption, GWP_{100} has well-recognised limitations as an emission metric for short-lived climate forcers.[10,6] As noted in IPCC AR5 and elaborated by Shine and colleagues,[10] GWP conflates two physically distinct quantities: the radiative efficiency (RE) of a molecule, which reflects its intrinsic capacity to absorb infrared radiation per unit concentration, and its atmospheric lifetime, which determines how long that forcing persists after emission.[8,10] A gas with high RE but short lifetime (such as sevoflurane) and a gas with lower RE but longer lifetime (such as desflurane) can produce substantially different instantaneous climate effects even when their GWP_{100} values appear comparable.[6,11]

A metric based on instantaneous radiative forcing, derived directly from the physical parameters of each gas, would better reflect the actual atmospheric perturbation at the moment of clinical use.[6] Furthermore, because the atmospheric release of volatile agents is only one stage of their environmental lifecycle, a more complete assessment requires consideration of production-phase emissions.[12] Life cycle assessment (LCA) methodology provides the systematic framework for this, tracing environmental impacts from raw material extraction through manufacturing, transport, clinical use, and waste handling.[12]

The environmental persistence of fluorinated volatile agents extends beyond their greenhouse gas properties.[13,14] Upon atmospheric degradation, sevoflurane, desflurane, and isoflurane yield trifluoroacetic acid (TFA), a terminal per- and polyfluoroalkyl substance (PFAS) that enters terrestrial and aquatic ecosystems via wet deposition.[13] TFA concentrations in surface waters have increased approximately six-fold over the past two decades, and healthcare-derived volatile agents represent one identifiable anthropogenic source.[15] While TFA ecotoxicity remains under investigation, its persistence and global distribution qualify it as a planetary boundary concern.[13]

To our knowledge, no published model derives instantaneous RF from clinical anaesthesia parameters and incorporates it within a life cycle framework.[6,9,12] Existing studies have used GWP to express the climate impact of either measured or modelled anaesthetic consumption, without separating the RE and lifetime contributions embedded in that metric.[16,9,12] The present work addresses this gap by proposing a dual-metric LCA-RF model that quantifies RF per MAC-hour as the primary climate endpoint, with TFA yield per MAC-hour as a secondary ecotoxicity indicator.

2. METHODS

2.1 Model Overview

The model translates three clinical input parameters, fresh gas flow (FGF, L/min), anaesthetic agent end-tidal concentration (%, corresponding to a specified fraction of MAC), and maintenance duration (min), into two environmental metrics: instantaneous radiative forcing (RF, $mW \cdot m^{-2}$) and trifluoroacetic acid yield (TFA, mg). Both metrics are subsequently normalised to MAC-hour to enable agent comparisons independent of anaesthetic depth and duration.

2.2 Agent Consumption

Liquid anaesthetic consumption was calculated using a physically derived vapour consumption formula consistent with Langbein et al. and subsequent calibration studies [7]:

$$\dot{V}_{lii}\ (mL/min) = FGF \times (C / 100) \times MW / (22.4 \times \rho \times 100)$$

where C is the delivered end-tidal concentration (%), MW is the molecular weight of the agent (g/mol), ρ is the liquid density (g/mL), and 22.4 L/mol is the molar volume of an ideal gas at standard conditions. Total liquid consumption over the maintenance period was obtained by multiplying by duration.

The molecular weights used were 200.06 g/mol for sevoflurane, 168.04 g/mol for desflurane, and 184.49 g/mol for isoflurane, with corresponding liquid densities of 1.52, 1.47, and 1.50 g/mL, respectively.

2.3 Radiative Forcing Calculation

The atmospheric mass increment per unit consumption was converted to a tropospheric mole fraction increment (ppb) using:

$$\Delta C\ (ppb) = m_k{}^{g}\bullet \times (MW_{air} / MW_a{}^{kira}) \times 10^9 / M_{atm}$$

where $m_k{}^{g}\bullet$ is the mass of agent released (kg), $\mathrm{MW_a{}^{kira}}$ is the mean molecular weight of dry air (28.97 g/mol), $\mathrm{MW_a{}^{kgi}}$ is the molecular weight of the specific agent, and $\mathrm{M_{atm}}$ is the total mass of the atmosphere (5.137×10^{18} kg).

Instantaneous RF was then calculated as:

$$RF\ (mW{\cdot}m^{-2}) = \Delta C \times RE \times 1000$$

where RE is the radiative efficiency of the agent ($\mathrm{W{\cdot}m^{-2}{\cdot}ppb^{-1}}$) taken from IPCC AR6 [8] Supplementary Table 7.SM.7. The values used were RE = 0.32 $\mathrm{W{\cdot}m^{-2}{\cdot}ppb^{-1}}$ for sevoflurane, 0.44 for desflurane, and 0.57 for isoflurane. The conversion factor of 1000 expresses RF in milliwatts per square metre.

This expression represents the instantaneous RF contribution of the incremental atmospheric burden produced by one clinical anaesthetic event, under the assumption that released gas is uniformly distributed across the atmospheric column, consistent with the global box model approximation used in IPCC characterisation factor derivations [8].

2.4 Life Cycle Assessment Component

To extend the model beyond the use phase, production-phase emissions were incorporated following Sherman et al. Production emission factors were 0.20, 0.30, and 0.25 kg CO_2e per gram of liquid agent for sevoflurane, desflurane, and isoflurane, respectively [12]. These emissions were converted to an RF equivalent using the corresponding radiative efficiency of CO_2 ($\mathrm{RE^{c}{}_{o2}} = 1.33 \times 10^{-5}$ $\mathrm{W{\cdot}m^{-2}{\cdot}ppb^{-1}}$, IPCC AR6 [8]) applied through the same atmospheric mass increment formula. Total LCA-RF was thus defined as:

$$RF_{l}{}^{c}{}_{a} = RF_{atm} + RF^{proou}$$

where $\mathrm{RF_{atm}}$ is the atmospheric use-phase RF and $\mathrm{RF^{proou}}$ is the production-phase RF derived from manufacturing CO_2.

2.5 Normalisation: RF per MAC-hour

To enable clinically meaningful comparison across agents that differ in MAC value and therefore in the delivered concentration required to achieve equivalent anaesthetic depth, RF was normalised to MAC-hour:

$$RF/MAC\text{-}h = RF_{l}{}^{c}{}_{a} \,/\, (C/MAC \times t_h)$$

where C/MAC is the delivered concentration expressed as a fraction of MAC, and t_h is the maintenance duration in hours. The MAC values used were 2.05% for sevoflurane, 6.70% for desflurane, and 1.20% for isoflurane.

2.6 Secondary Analysis: TFA Yield

As a secondary analysis, the expected atmospheric TFA yield was estimated from the stoichiometry of tropospheric oxidation. Sevoflurane undergoes OH-radical-initiated degradation with a reported molar TFA yield of approximately 0.57 mol per mol of parent compound, corresponding to a mass yield factor k_{tsa} of 0.325 kg TFA per kg sevoflurane (MW_{tsa} = 114.02 g/mol) [17]. For desflurane and isoflurane, the molar TFA yield approaches unity, yielding k_{tsa} values of 0.679 and 0.618, respectively [17].

Additionally, approximately 5% of administered sevoflurane undergoes hepatic metabolism with renal excretion of hexafluoroisopropanol (HFIP), which is itself subsequently converted to TFA equivalents in the environment; this pathway was included in the sevoflurane TFA estimate only [18]. TFA yield was normalised to MAC-hour using the same denominator as RF.

The TFA analysis is presented as a secondary descriptive analysis to assess convergent validity of the RF-based agent ranking, not as a co-primary outcome. No regulatory TFA threshold has been established for aquatic systems at the time of writing, and absolute TFA values should therefore be interpreted with caution.

2.7 Sensitivity Analysis

Fresh gas flow was varied from 0.3 to 6.0 L/min to characterise the linear relationship between FGF and both RF and TFA metrics. A secondary scenario used a fixed FGF of 4.0 L/min to simulate conventional (non-low-flow) practice. GWP_{100}-based CO_2 equivalents were calculated for each agent under identical clinical conditions to provide a methodological comparison between the GWP and RF approaches.

3. RESULTS

3.1 Radiative Forcing per MAC-hour

Under standard conditions (FGF 1 L/min, 1 MAC, 60 min), the LCA-RF model yielded the following values for RF/MAC-hour: sevoflurane 1.75×10^{-11} $mW \cdot m^{-2} \cdot MAC\text{-}h^{-1}$, desflurane 9.03×10^{-11} $mW \cdot m^{-2} \cdot MAC\text{-}h^{-1}$, and isoflurane 1.93×10^{-11} $mW \cdot m^{-2} \cdot MAC\text{-}h^{-1}$.

The agent ranking by RF/MAC-hour was: desflurane > isoflurane > sevoflurane. The ratio between desflurane and sevoflurane was 5.2-fold, while the isoflurane-to-sevoflurane ratio was 1.1-fold.

Parameter	Sevoflurane	Desflurane	Isoflurane	Unit
MW	200.06	168.04	184.49	g/mol
MAC	2.05	6.70	1.20	%
RE (IPCC AR6)	0.32	0.44	0.57	$W \cdot m^{-2} \cdot ppb^{-1}$
GWP_{100}	130	2540	510	CO_2e
RF/MAC-hour (1 L/min)	1.75×10^{-11}	9.03×10^{-11}	1.93×10^{-11}	$mW \cdot m^{-2} \cdot MAC\text{-}h^{-1}$
RF/MAC-hour (4 L/min)	7.00×10^{-11}	3.61×10^{-11}	7.71×10^{-11}	$mW \cdot m^{-2} \cdot MAC\text{-}h^{-1}$
Des/Sevo ratio (RF)	1.0	5.2	1.1	fold
Des/Sevo ratio (GWP)	1.0	61.8	3.9	fold

Table 1. Physical parameters, radiative efficiency values (IPCC AR6), and calculated RF/MAC-hour for the three volatile agents under standard (1 L/min) and high fresh gas flow (4 L/min) conditions. GWP_{100}-based ratios are shown for methodological comparison.

3.2 LCA Component

The production-phase RF contribution accounted for 3.6% of total RF/MAC-hour for sevoflurane, 3.3% for desflurane, and 2.4% for isoflurane. In all three agents, atmospheric use-phase emission dominated the total LCA-RF, comprising more than 96% of the metric. The LCA component did not change the agent ranking.

3.3 GWP versus RF: Methodological Comparison

Under identical clinical conditions, the Des/Sevo ratio derived from GWP_{100} was 61.8-fold, compared to 5.2-fold from the RF model, representing a 12-fold discrepancy. The GWP metric inflates the apparent relative impact of desflurane because its 100-year integration window captures the sustained forcing of its 14-year atmospheric lifetime, whereas the RF metric reflects only the instantaneous radiative perturbation per unit of agent released. The Iso/Sevo ratio was 3.9-fold by GWP and 1.1-fold by RF, a 3.5-fold discrepancy arising from the same mechanism.

3.4 Fresh Gas Flow Sensitivity

RF/MAC-hour increased linearly with FGF for all three agents across the range 0.3 to 6.0 L/min. The Des/Sevo ratio of 5.2-fold remained constant across all FGF values, demonstrating that FGF reduction, while reducing absolute RF, does not alter the relative environmental advantage of agent substitution. Reducing FGF from 4.0 to 1.0 L/min reduced RF/MAC-hour by a factor of four for each agent independently.

3.5 Secondary Analysis: TFA Yield

TFA yield per MAC-hour followed the same rank order as RF. Under standard conditions (FGF 1 L/min, 1 MAC, 60 min), desflurane produced approximately 5.3-fold more TFA per MAC-hour than sevoflurane and 5.0-fold more than isoflurane. The convergence of the TFA and RF ratios (5.3 versus 5.2-fold for Des/Sevo) reflects the shared dependence of both metrics on agent mass consumption, and independently supports the RF-based agent ranking.

Over a hypothetical annual series of 2000 procedures of 60 min at 1 MAC and 1 L/min FGF, the estimated annual TFA yield would be approximately 816 g for sevoflurane, 4380 g for desflurane, and 884 g for isoflurane.

4. DISCUSSION

4.1 Principal Findings

This study presents, to our knowledge, the first modelling framework that quantifies the instantaneous radiative forcing of inhaled anaesthetic agents from routine clinical parameters within a life cycle context.[6,9,12] The primary finding is that the Des/Sevo RF ratio (5.2-fold) is substantially lower than the corresponding GWP_{100}-based ratio (61.8-fold), because GWP embeds atmospheric lifetime into its characterisation factor while RF isolates the physical perturbation at the moment of emission.[8,10]

4.2 Physical Basis of the RF Metric

The radiative efficiency values used in this model represent empirically measured infrared absorption cross-sections for each agent, obtained through spectroscopic experiments and reported in IPCC AR6.[8] These values reflect the intrinsic capacity of each molecule to trap outgoing terrestrial infrared radiation in the atmospheric window and are therefore not subject to the time-horizon choice that limits GWP.[10,6] As a consequence, RF provides a time-horizon-independent characterisation of the immediate climate perturbation of an anaesthetic event.

The discrepancy between GWP and RF rankings is largest for desflurane because its 14-year atmospheric lifetime means that GWP_{100} accumulates its forcing over many years, whereas RE, which determines RF, is only modestly higher than that of sevoflurane (0.44 versus 0.32 $W \cdot m^{-2} \cdot ppb^{-1}$).[8,5] This does not imply that desflurane is without concern; its long atmospheric persistence means that RF accumulates over years following emission, and on long time horizons the cumulative RF of desflurane substantially exceeds that of sevoflurane.[9] The two metrics thus answer different questions: RF addresses the contemporaneous atmospheric perturbation, while GWP addresses the long-term integrated forcing.[10,6]

4.3 Role of the LCA Component

The incorporation of production-phase emissions into the RF metric is methodologically important even though the quantitative contribution is small. The finding that manufacturing CO_2 accounts for less than 4% of total RF/MAC-hour confirms that atmospheric release of the volatile agent itself is the dominant environmental pathway, consistent with Sherman et al. who reported comparable proportions using GWP.[12] This result also clarifies a frequent misconception in the clinical literature: substituting volatile anaesthesia with total intravenous anaesthesia eliminates nearly all of the use-phase climate impact, but the remaining production and waste-disposal footprint of propofol, while small, is not zero and should be acknowledged in full lifecycle comparisons.[19,12]

4.4 TFA as a Convergent Secondary Metric

Trifluoroacetic acid is a terminal atmospheric degradation product of all three volatile agents studied.[17] Its environmental relevance lies in its classification as a PFAS compound, its resistance to biodegradation, and its documented accumulation in global precipitation and surface waters.[13,14]

Surface water TFA concentrations have increased approximately six-fold over the past 23 years, and volatile anaesthetics represent one quantifiable anthropogenic source.[15]

The convergence between the RF and TFA agent rankings (Des/Sevo ratios of 5.2 and 5.3, respectively) is mechanistically expected, since both metrics scale with the mass of agent consumed per unit of anaesthetic effect. This convergence serves primarily as internal validation of the model: two physically independent environmental metrics, one atmospheric and one aquatic, yield the same clinical conclusion regarding agent preference.

The TFA analysis is presented as secondary for three reasons. First, no exposure guideline for TFA in drinking water or surface water has been finalised in most jurisdictions at the time of writing.[13,15] Second, the molar TFA yield coefficients for isoflurane and desflurane carry experimental uncertainties not fully captured in the single-value estimates used here.[17] Third, the ecotoxicological significance of healthcare-derived TFA relative to refrigerant-derived TFA, which constitutes the larger anthropogenic source, has not been quantified at a system level.[15] Future work incorporating probabilistic TFA yield estimates and regional deposition modelling would strengthen this analysis.

4.5 Clinical and Policy Implications

The RF per MAC-hour metric offers two practical advantages over GWP-based reporting. First, it can be calculated from data routinely recorded on anaesthetic machine logs (agent delivery, FGF, duration) without requiring patient-level clinical data, making it suitable for institutional environmental auditing.[9,3] Second, by separating radiative efficiency from atmospheric lifetime, it avoids attributing long-term planetary warming to short clinical events in a way that clinicians may find difficult to interpret intuitively.[6,10]

The finding that FGF reduction decreases RF linearly, but does not change the Des/Sevo ratio, carries a direct clinical message. Low-flow anaesthesia is beneficial for all three agents, but it does not substitute for agent selection as a strategy for reducing climate impact.[3,9] At a given FGF, desflurane always imposes approximately 5.2-fold more instantaneous RF per MAC-hour than sevoflurane, regardless of flow rate.

4.6 Limitations

This model makes several simplifying assumptions. The atmospheric mass increment formula assumes instantaneous uniform global distribution, which overestimates the immediate concentration increment in practice but is consistent with the assumptions used to derive RE values in IPCC AR6, maintaining internal consistency.[8] The production emission factors for volatile agents are derived from a single published LCA study and have not been independently verified across manufacturers or supply chains.[12] The model does not account for scavenging efficiency, which varies by institution and may reduce the atmospheric release fraction below 100%.[3] Finally, the TFA yield coefficients are derived from chamber experiment data and may not fully represent tropospheric oxidation under all conditions.[17]

5. CONCLUSION

We present a radiative forcing-based life cycle assessment model for inhaled anaesthetic agents that derives instantaneous climate impact from clinical input parameters without requiring patient-level data. The primary metric, RF per MAC-hour, provides a physically transparent alternative to GWP_{100} for comparing the atmospheric effects of volatile agents. Under this framework, desflurane imposes 5.2-

fold greater RF per MAC-hour than sevoflurane, compared with the 61.8-fold ratio yielded by GWP_{100}. As a secondary analysis, TFA yield per MAC-hour independently confirms this ranking. The model is fully calculable from routine anaesthetic machine output and is intended to support both clinical decision-making and institution-level sustainability reporting.

DECLARATIONS

Ethical approval: This study is a mathematical modelling analysis using published physicochemical data. No patient data were used. No ethical approval was required.

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Data availability: The full model and calculation spreadsheet are available as supplementary material.

REFERENCES

1. Pichler PP, Jaccard IS, Weisz U, Weisz H. International comparison of health care carbon footprints. Environ Res Lett. 2019;14(6):064004. doi:10.1088/1748-9326/ab19e1

2. Tennison I, Roschnik S, Ashby B, et al. Health care's response to climate change: a carbon footprint assessment of the NHS in England. Lancet Planet Health. 2021;5(2):e84-e92. doi:10.1016/S2542-5196(20)30271-0

3. McGain F, Muret J, Lawson C, Sherman JD. Environmental sustainability in anaesthesia and critical care. Br J Anaesth. 2020;125(5):680-692. doi:10.1016/j.bja.2020.06.055

4. Vollmer MK, Rhee TS, Rigby M, et al. Modern inhalation anesthetics: potent greenhouse gases in the global atmosphere. Geophys Res Lett. 2015;42(5):1606-1611. doi:10.1002/2014GL062785

5. Sulbaek Andersen MP, Sander SP, Nielsen OJ, Wagner DS, Sanford TJ Jr, Wallington TJ. Inhalation anaesthetics and climate change. Br J Anaesth. 2010;105(6):760-766. doi:10.1093/bja/aeq259

6. Slingo JM, Slingo ME. The science of climate change and the effect of anaesthetic gas emissions. Anaesthesia. 2024;79(3):252-260. doi:10.1111/anae.16189

7. Langbein T, Sonntag H, Trapp D, et al. Volatile anaesthetics and the atmosphere: atmospheric lifetimes and atmospheric effects of halothane, enflurane, isoflurane, desflurane and sevoflurane. Br J Anaesth. 1999;82(1):66-73. doi:10.1093/bja/82.1.66

8. IPCC. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press; 2021. Chapter 7 and Supplementary Table 7.SM.7.

9. Sulbaek Andersen MP, Nielsen OJ, Sherman JD. Assessing the potential climate impact of anaesthetic gases. Lancet Planet Health. 2023;7(7):e622-e629. doi:10.1016/S2542-5196(23)00084-0

10. Shine KP, Fuglestvedt JS, Hailemariam K, Stuber N. Alternatives to the global warming potential for comparing climate impacts of emissions of greenhouse gases. Clim Change. 2005;68(3):281-302. doi:10.1007/s10584-005-1146-9

11. Sulbaek Andersen MP, Nielsen OJ. The global warming potentials for anesthetic gas sevoflurane need significant corrections. Environ Sci Technol. 2021;55(15):10189-10191. doi:10.1021/acs.est.1c02573

12. Sherman J, Le C, Lamers V, Eckelman M. Life cycle greenhouse gas emissions of anesthetic drugs. Anesth Analg. 2012;114(5):1086-1090. doi:10.1213/ANE.0b013e31824f6940

13. Remels I, et al. Volatile anaesthetics and PFAS forever chemicals: a critical gap in environmental impact assessments. Perioper Care Oper Room Manag. 2025;38:100317. doi:10.1016/j.pcorm.2025.100317

14. Voglmeier S, Tran C, Karabegovic A, Schoepf UJ, Eberle B. PK/PD of volatile anaesthetics in the atmosphere: climate science for anaesthetists. Best Pract Res Clin Anaesthesiol. 2025;39(1):3-13. doi:10.1016/j.bpa.2024.10.001

15. Cahill TM. Increases in trifluoroacetate concentrations in surface waters over two decades. Environ Sci Technol. 2022;56(9):5542-5549. doi:10.1021/acs.est.2c01826

16. Ryan SM, Nielsen CJ. Global warming potential of inhaled anesthetics: application to clinical use. Anesth Analg. 2010;111(1):92-98. doi:10.1213/ANE.0b013e3181e058d7

17. Sulbaek Andersen MP, Nielsen OJ, Karpichev B, Wallington TJ, Sander SP. Atmospheric chemistry of isoflurane, desflurane, and sevoflurane. J Phys Chem A. 2012;116(24):5806-5820. doi:10.1021/jp2077598

18. Kharasch ED, Armstrong AS, Gunn K, Miyoshi A, Painter R, Hoffer C. Clinical sevoflurane metabolism and disposition. I. Sevoflurane and metabolite pharmacokinetics. Anesthesiology. 1995;82(6):1369-1378. doi:10.1097/00000542-199506000-00008

19. Varrier M. The environmental sustainability of propofol use in daily practice. Br J Anaesth. 2020;124(3):221-222. doi:10.1016/j.bja.2020.03.009