



Universiteit
Leiden
The Netherlands

Carbon footprint reduction of the operating room: tools to mitigate the environmental impact of surgical practice

Friedericy, H.J.

Citation

Friedericy, H. J. (2026, September 30). *Carbon footprint reduction of the operating room: tools to mitigate the environmental impact of surgical practice*. Retrieved from <https://hdl.handle.net/1887/4310441>

Version: Publisher's Version

License: [Licence agreement concerning inclusion of doctoral thesis in the Institutional Repository of the University of Leiden](#)

Downloaded from: <https://hdl.handle.net/1887/4310441>

Note: To cite this publication please use the final published version (if applicable).



PART I

Investigating Ways to Lower
Carbon Emissions in the OR





CHAPTER 2

Greenhouse Gas Emissions Due to Inhalation Anaesthetics in the Netherlands, Usage Data and a Survey of Preferences Among Dutch Anaesthesiologists

Authors:

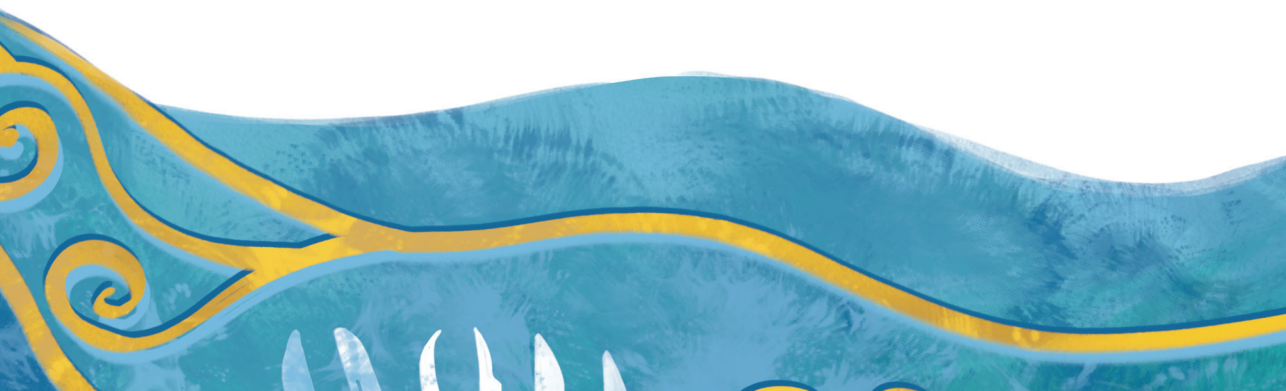
Herman J. Friedericy¹, Pascale A.H.T. Venema¹, Jessica F. Lockyer¹, Dinemarie M. Kweekel², Anne C. van der Eijk^{3,4}, Frank Willem Jansen^{4,5}, Elise Y. Sarton¹

Affiliations:

1. Department of Anaesthesiology, Leiden University Medical Centre, The Netherlands
2. Department of Clinical Pharmacy and Toxicology, Leiden University Medical Centre, The Netherlands
3. Operating Room Department & Central Sterile Supply Department, Leiden University Medical Centre, The Netherlands
4. Faculty of Biomedical Engineering, Delft University of Technology, The Netherlands
5. Department of Gynaecology, Leiden University Medical Centre, The Netherlands

Published in:

European Journal of Anaesthesiology and Intensive Care, 2025



Abstract

Background: Anaesthetic gases are an important source of greenhouse gas emissions in operating rooms and can attribute significantly to the carbon footprint of a nation's healthcare system.

Objective: To estimate the magnitude of the climate impact of inhaled anaesthetics in the Netherlands. Furthermore, the goal was to assess the preferences of Dutch anaesthesiologists for anaesthesia techniques, and to explore opportunities for reducing greenhouse gas emissions due to anaesthesia practice.

Design: A 2019 bottom-up purchase analysis of inhalation anaesthetics used in all Dutch hospitals was performed and an online survey was conducted among Dutch anaesthesiologists regarding their preferences for anaesthetic agents.

Results: Purchasing quantities of volatile anaesthetic agents were obtained from 61 of the 69 hospital organisations in the Netherlands (response rate 88.4%). A total of 12.2 kilotonne CO₂-eq (0.07% of the Dutch healthcare system) was emitted due to inhalation anaesthetics in the Netherlands in 2019. The volume of volatile anaesthetics purchased in 2019 was 9,178 litres of sevoflurane (93.4%), 404 litres of desflurane (4.1%) and 245 litres of isoflurane (2.5%). The survey in which 182 anaesthesiologists participated demonstrated that propofol was the first drug of choice of 70% of respondents, desflurane was available in 16% of Dutch hospitals and 83% of anaesthesiologists answered never to use desflurane. Nitrous oxide was not used by 63% of respondents, the remaining 27% reported using nitrous oxide only in less than 5% of their cases.

Conclusion: The relatively low emissions of greenhouse gases due to inhalation anaesthetics in Dutch healthcare compared to other countries can be explained by the limited use of nitrous oxide and desflurane by Dutch anaesthesiologists and their strong preference for intravenously administered propofol as an anaesthetic.

Introduction

Modern volatile inhalation anaesthetics (VAs) are inherently potent greenhouse gases (GHG).¹ They belong to the chlorofluocarbons (CFC) and hydrofluocarbons (HFC) that are short-lived climate pollutants (SLCP) with strong radiative forcing characteristics causing global warming. The Montreal Protocol (1987) and the Kigali Amendment (2016) aim to phase out CFCs and HFCs because of their respective ozone-depleting and GHG effects. Inhalation anaesthetics, being pharmaceuticals, have so far been exempted from these legally binding international agreements due to their medical necessity.²

The GHG effect of the globally emitted VAs in 2014 was estimated from atmospheric measurements and amounted to 3.1 million tonne of CO₂-equivalents (CO₂-eq) that year. In a period of 10 years (2004–2014) the atmospheric concentrations of desflurane and sevoflurane more than doubled, which can be explained by their popularity and the increase in the number of operations worldwide.³ Using the same global warming potential over 100 years (GWP₁₀₀), a bottom-up calculation based on the global number of bottles of sevoflurane, desflurane and isoflurane sold in 2019 came to 2.9 million tonne of CO₂-eq, a contribution of 0.01% of total global GHG emissions that year.⁴ Due to its high GWP₁₀₀ of 2540 and relatively low potency, desflurane accounted for about 80% of the total greenhouse effect of modern inhaled anaesthetics, despite accounting for only 20% of the volume sold in 2019.⁴

Nitrous oxide (N₂O) is also a significant GHG (GWP₁₀₀ of 298) but with a much longer atmospheric lifetime (114 years) than the aforementioned SLCP VAs.⁵ Traditionally N₂O was abundantly used as an adjuvant in the administration of older VAs to create a more favourable clinical profile. Nowadays, this technique is less essential with the clinically superior modern VAs. However, N₂O is still widely used in healthcare as an analgesic in obstetrics and emergency medicine.⁶ A breakdown of N₂O use in terms of clinical setting by Wong and colleagues showed that N₂O consumption during childbirth was a factor of 10 higher than during a single surgery (534 L. vs. 48 L.) and that during a paediatric emergency room procedure 61 L. was used.⁷ Today N₂O is the third most important GHG for global warming and accounts for about 7% of all GHG emissions globally. It is emitted for 57% from natural sources and approximately 43% from anthropogenic sources of which two-thirds is due to agriculture.⁸ Rough estimates regarding the share of N₂O emitted by healthcare range from 1–3% of the total annual amount of N₂O emitted globally.^{9,10} Recent reports have shown that a significant proportion of N₂O purchased by hospitals is released unused into the atmosphere. Leaking pipeline manifolds are cited as the main culprit. In addition, there is a residual volume of 1–2% in N₂O cylinders after use which is released into the atmosphere prior to refilling.¹¹ Studies from individual hospitals in the UK and Australia have reported a N₂O wastage percentage between 77–98 based on a discrepancy between purchase and usage data.^{11–13}



Anaesthetic gases are, aside from energy consumption, the most important source of GHG emissions of operating rooms (ORs).¹⁴ In a carbon footprint assessment of the National Health Service (NHS) in England, anaesthetic gases (including N₂O) account for 5% of the total emissions of England's healthcare services.¹⁵ In a carbon footprinting study of three Western academic hospitals it was shown that anaesthetic practice had a significant influence on the GHG emissions caused by VAs. The preferential use of desflurane resulted in a tenfold emission of GHGs due to VAs compared to the hospital in which sevoflurane was the standard of care.¹⁴ Life cycle assessments of anaesthetic drug use also show that the GHG emissions greatly vary with the choice of anaesthetic. Both the use of desflurane and N₂O result in significantly higher GHG emissions for general anaesthesia when compared to sevoflurane. When general anaesthesia is provided with the intravenous drug propofol the GHG emissions are almost negligible.^{16,17} However, other detrimental effects of propofol use on the environment should not be overlooked. Propofol poses an ecological risk if it enters surface water. It is poorly biodegradable and has a high potential for bioconcentration in marine life. Also a large portion of the manufactured propofol is wasted due to regulations for the administration of propofol.^{18,19} Furthermore intravenous drug administration results in large amounts of plastic waste and poses a hazard to drinking water supplies in water-scarce areas due to water pollution.²⁰

The aim of this study was to assess the magnitude of the climate impact of inhaled anaesthetics in the Netherlands, to assess the preferences of Dutch anaesthesiologists for anaesthetic agents and finally, to explore opportunities for reducing healthcare GHG emissions due to anaesthesia practice.

A bottom-up purchase analysis of VAs in all Dutch hospitals was performed by inquiring hospital pharmacists about purchasing data of isoflurane, desflurane and sevoflurane in the year 2019. Data on the use of N₂O in the Dutch healthcare system were obtained from the National Institute for Public Health and the Environment (RIVM). In addition, an online survey was conducted in which Dutch anaesthesiologists and anaesthesiology residents were asked about their preferences for anaesthetic agents and the reasons for them, focusing on side effects, pharmacological factors, environment, costs and practical considerations. In addition, questions were asked regarding the use of GHG emission-saving methods in their daily practice.

Methods

For our survey the Institutional Review Board of the Leiden University Medical Centre ruled that this research proposal (2022-03) does not fall under the Medical Research Involving Human Subjects Act. This research does not meet the criteria because participants are not subjected to procedures or are required to follow rules of behaviour.

As a template, the questionnaire from a survey conducted among Australian and New Zealand anaesthetists was modified and translated into Dutch.²¹ The adapted questionnaire was converted to a digital version using SurveyMonkey (<https://surveymonkey.com>) and to validate, submitted to ten fellow anaesthesiologists in the LUMC for assessment of the readability and comprehensibility of the questions. As a result of this pilot, there was no need to adjust the questions of the survey. In total, the survey consisted of 17 questions that would take less than five minutes to complete (For survey questions see Appendix A. Supplementary data). Questions were formulated to capture preferences by anaesthetic in order of preference. Apart from the three inhalation anaesthetics, respondents could also choose the intravenous anaesthetic drug propofol. Next, the rationale for these preferences was asked. Standard reasons were chosen which respondents could tick as reasons for preferences, in addition to a free-text comment for other reasons. These standard reasons were based on side effects, pharmacodynamic, pharmacokinetic and environmental properties of the agents, costs and practical considerations. In addition, questions were asked regarding the use of techniques on the efficient use of inhalation anaesthetics which can reduce the amount emitted into the atmosphere while achieving the same effect on the patient. These regarded the use of low fresh gas flows (FGF) and the use of automated control of end-tidal inhalation anaesthetic concentration (Et Control).^{22,23} The degree of willingness to adapt their anaesthesia technique for the benefit of the environment was surveyed as well as the demographic data of the participants (years of experience as an anaesthesiologist, type of hospital and its geographic location).

A request for participation in the survey was addressed to all staff anaesthesiologists and anaesthesia residents in the Netherlands. Information regarding the study and a web link to the survey was published in the newsletter of the Dutch Society of Anaesthesiologists (NVA) and in the Dutch Journal of Anaesthesiology (NTvA). Furthermore, the survey was advertised via social media (LinkedIn). The survey was open for six months from 30 June to 30 December 2022. The input data were manually exported from 'SurveyMonkey' to a Microsoft Excel sheet. Percentages and proportions were calculated for all quantitative results.



To obtain purchasing quantities of VAs in 2019, the anaesthesiology departments from all 69 hospital organisations in the Netherlands were first contacted by telephone to ask them for cooperation for the study. Subsequently, an email was sent to the contacts of these departments explaining the purpose of the study and instructions regarding the retrieval of the requested information. This comprised the purchased numbers of bottles of isoflurane, desflurane and sevoflurane for their hospital organisation in the year 2019. These numbers had to be entered into an online counting form that was created with the online platform JotForm (<https://jotform.com>). If no response was received after four weeks, a reminder email was sent and if again no response was received after four weeks, the hospital pharmacist of the respective hospital was contacted directly asking for their cooperation and to provide the requested information. The online counting form was accessible for six months from July 2021 to January 2022. All data from the online counting forms were manually entered into a Microsoft Excel spreadsheet for calculating total volumes of all participating hospital organisations. From the supplied volumes, first the calculated amount of theoretically metabolised anaesthetic was subtracted. Then, using the specific gravity of the inhalation anaesthetic and its GWP₁₀₀, the amount of emitted CO₂ equivalents was calculated. Table 1 provides the details of the characteristics that were used for the calculation of the emissions of the VAs. No correction was made for the possible use of vapor capture technology (VCT) which allows inhaled anaesthetics to be captured after use as this technique was not yet available for the Dutch market in 2019.

Table 1. *Characteristics of inhalation anaesthetics.*

	sevoflurane	desflurane	isoflurane	nitrous oxide
Density (g/ml)	1.52	1.47	1.50	
Molar mass (g/mol)	200	168	184.5	
Metabolism (%)	5	0.02	0.2	0.005
Bottle volume (ml)	250	240	250	
GWP ₁₀₀ ^a	130	2,540	510	298
Mass per bottle (g)	380	353	375	
kg CO₂-eq/ bottle	49	896	191	

^a GWP₁₀₀: global warming potential calculated over 100 years.

The amount of N₂O that was sold in the Netherlands for healthcare purposes was collected from the Emission Registration (<https://www.emissieregistratie.nl/>) which is the central location for all Dutch emission data under the auspices of the RIVM. It provides the formal historical and most recent emissions data for the Netherlands and is an independent and reliable data source in which emissions of about 375 substances

and substance groups are registered. Ideally, the consumed amount of N_2O would have been obtained either directly from the supplier or through hospital purchasing figures. Both options were attempted in our study but did not provide reliable (incomplete) data. Unfortunately the Emission Registration data gave no information regarding the breakdown into pure N_2O and Entonox.



Results

Bottom-up purchase analysis of inhalation anaesthetics

Purchasing quantities of VAs were obtained from 61 of the 69 hospital organisations in the Netherlands (response rate 88.4%). The volumes of the in 2019 purchased inhalation VAs were 9,178 litres of sevoflurane (93.4%), 404 litres of desflurane (4.1%) and 245 litres of isoflurane (2.5%). Sevoflurane was used in all 61 hospitals (100%), desflurane in 16 (26%) and isoflurane in 3 (5%). Calculated emissions from these volumes were 1,722 tonne CO_2 -eq sevoflurane (50%), 1,502 tonne CO_2 -eq desflurane (41%) and 186 tonne CO_2 -eq isoflurane (5%). Linear extrapolation of these figures from 88.4 to 100% results in a total of 3,859 tonne CO_2 -eq due to the emission of VAs in the Netherlands in 2019. According to the National Emission Registration the emission of N_2O stemming from the Dutch healthcare system in 2019 was 31.4 tonne (8,321 t CO_2 -eq). Thus the total emission of inhalation anaesthetics in 2019 in the Netherlands came to 12.2 kilotonne CO_2 -eq, which account for 0.07% of the 17,575 kilotonne CO_2 -eq environmental impact of the complete Dutch healthcare sector as calculated for 2016.²⁴

Survey of Dutch anaesthesiologists

The survey was completed by 182 respondents, 150 consultants (82%) and 32 specialist trainees (18%). Mean years of experience of the consultants were 10.2 (SD +/- 8.0) years. The exact distribution of years of training and experience of the participants are shown in Table 2.

Of the respondents, 66 (36%) were employed at a university hospital, 69 (38%) at a large top clinical hospital, 41 (23%) at a small peripheral hospital and 6 (3%) at a private hospital. On the question 'In my daily practice, the drugs I use for general anaesthesia are as follows, in order of preference' most respondents selected propofol as their drug of choice (70%) followed by sevoflurane (25%), desflurane (1%) and isoflurane (1%). As the second choice sevoflurane was selected by 56% and propofol by 22% of the respondents (Figure 1).

Table 2. Distribution of years of training (specialist trainees) and experience (consultants) of the participants.

	Training/experience (years)	No. of participants	% of total
Trainee specialists	1	1	3%
	2	11	34%
	3	7	22%
	4	5	16%
	5	8	25%
	Total	32	100%
Consultants	0-5	61	41%
	6-10	27	18%
	11-15	24	16%
	16-20	17	11%
	>20	19	13%
	Total	148^a	100%

^aTwo consultants did not provide this information.

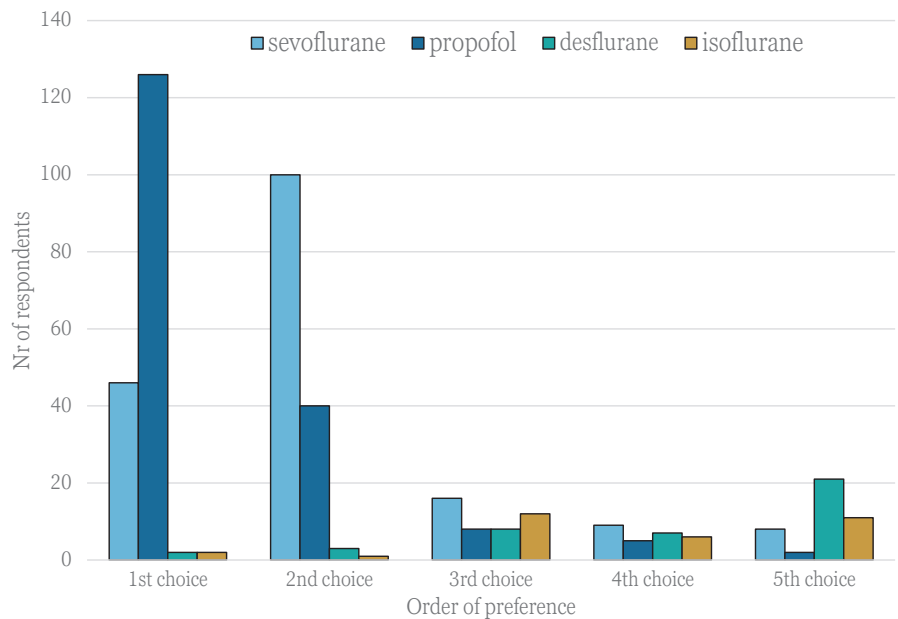


Figure 1. Ranking of preferences for anaesthetic agent use.

The reasons for choosing a particular anaesthetic (questions 3-7) are shown in Table 3. Propofol was most often chosen for low incidence of side-effects such as post-operative nausea and vomiting (PONV) by 94%, followed by environmental reasons (71%) and fast awakening and discharge times (64%). Sevoflurane was chosen for haemodynamic stability (48%), low chance of awareness (43%) and fast awakening and discharge times (36%).

Table 3. *Reasons for choosing a particular anaesthetic (questions 3-7).*

	sevoflurane		desflurane		isoflurane		propofol	
I do not use this agent	3	(2%)	151	(83%)	165	(91%)	0	(0%)
Low costs	23	(13%)	0	(0%)	7	(4%)	28	(15%)
Only available anaesthetic	21	(12%)	0	(0%)	1	(1%)	2	(1%)
Environmental reasons	7	(4%)	2	(1%)	2	(1%)	129	(71%)
Fast awakening/discharge	66	(36%)	21	(12%)	2	(1%)	116	(64%)
Low chance of awareness	78	(43%)	1	(1%)	6	(3%)	15	(8%)
Haemodynamic stability	88	(48%)	3	(2%)	6	(3%)	14	(8%)
Low incidence of side effects (PONV ^a)	5	(3%)	0	(0%)	0	(0%)	171	(94%)

Desflurane was not used by 83% of the respondents and isoflurane was not used by 91% of the respondents. Nitrous oxide was not used by 63% (115/182) of the respondents, 18/182 (10%) gave as reason for using N₂O the 'hemodynamic stability'. Almost 30% of respondents indicated under 'others' to use N₂O for the induction in children (as an adjuvant to sevoflurane) and also as an analgesic for painful moments during procedures. The estimated percentage of procedures where N₂O was used was indicated by 70 anaesthesiologists and was on average 4.6% (SD +/- 4.9).

Use of FGF <1 l/min was chosen by 138/182 (76%) and 1-2 l/min by 37/182 (20%), only 2 respondents indicated to use FGF > 2 l/min. Reasons for not using FGF <2 l/min were 'potentially unsafe' 4/182 (2%) and 'Against user's advice (the formation of compound A)' 5/182 (3%). On whether Et Control was used 132/182 (73%) answered 'true', 21/182 (12%) answered 'false' and 29/182 (16%) indicated that this technique was not available. When asked 'If patient safety is not compromised, I am willing to adapt my anaesthesia technique for the sake of the environment.' 90.7% agreed, 3.8% was neutral and 5.5% disagreed.



Discussion

Our study shows that healthcare emissions of VAs and N₂O in the Netherlands are responsible for 0.07% of the carbon footprint of the entire Dutch healthcare sector.²⁴ The total of 12.2 kilotonne of CO₂-eq emitted is comparable to the annual emissions of about 6,700 passenger cars (116 g CO₂/km, 15,000 km/yr). The primary explanation for these relatively low emissions compared to other countries is the limited use of N₂O and desflurane by Dutch anaesthesiologists and a strong preference for intravenously administered propofol as an anaesthetic.¹⁵ Desflurane, the VA with the highest GWP₁₀₀, was only available in 16% of Dutch hospitals and 83% of anaesthesiologists surveyed answered never to use desflurane. Nitrous oxide was not used by 63% of respondents, the remaining 37% reported using N₂O only in less than 5% of their cases. The intravenous anaesthetic propofol was chosen as the first drug of choice by 70% of survey respondents, with low incidence of side-effects such as postoperative nausea and vomiting (PONV), environmental reasons and fast awakening and discharge times as main reasons. Emission mitigation measures of inhalation anaesthetics such as FGF < 1 l/min and Et Control were already applied by 76% and 73% of respondents, respectively.

The purchased volume of desflurane in the Netherlands in 2019 was 41% of the total amount of VAs, but as a result of its high GWP₁₀₀, desflurane's calculated emissions accounted for 41% of total inhaled VAs emissions. Globally, desflurane's market share in 2019 was 5 times higher (20%) than in our study, accounting for 77% of the total CO₂-eq emitted due to VAs in that year.⁴ Atmospheric measurements also show that 80% of the emissions of VAs in the world stem from desflurane use.³ There is a wide variation in the use of desflurane in different countries. Reported emission rates of desflurane from Austria and Ireland (31% and 40%) match those of our study.²⁵⁻²⁷ However, in Germany and Australia, 77% and 88% of emissions are caused by desflurane, respectively.^{21,28} Although the popularity and use of desflurane has declined in the Netherlands since 2020 due to its environmental impact, this is not the only reason for its limited use reported in our study. Since the introduction of sevoflurane and desflurane in the 1990s, sevoflurane has enjoyed much greater preference among Dutch anaesthesiologists. This was partly because sevoflurane was marketed very aggressively during the introduction period and partly because it did not require the purchase of an expensive vapouriser like the one for desflurane. Furthermore sevoflurane is suitable for inhalation inductions of children, which is not the case for desflurane.

Comparing our data one-to-one with those of Australia and New Zealand, the first thing to note is the difference in the preference for desflurane use. Our survey showed that only 1% of Dutch anaesthesiologist had desflurane as their first choice while in the study by McGain et al 12% indicated this.²¹ Based on the consumption numbers

from that study, the effect of this is that 88% of emissions were caused by desflurane use in Australian situation in 2017. In addition, the volume of inhalation anaesthetics consumed in Australia was 53,250 litres versus 9,827 litres in the Netherlands. So a factor of five larger while the population of Australia is only 1.5 times as big. Assuming that the number of operations in both countries is proportionally equal, it can be inferred that intravenous anaesthesia with propofol is chosen much more often in the Netherlands, which was confirmed by the fact that 70% of the respondents in our study indicated anaesthesia with propofol as their first choice. So because of the preference of Dutch anaesthesiologists for intravenous anaesthesia with propofol and very limited use of desflurane, the calculated emission of volatile anaesthetics in 2019 in the Netherlands (3.9 kilotonne CO₂-eq) was 16% of that in Australia (63.7 kilotonne CO₂-eq) in 2017 which has about 1.5 times as many inhabitants.

With respect to our goal of investigating the potential for reducing healthcare GHG emissions from Dutch anaesthesia practices, 76% of respondents were found to be using FGF < 1 l/min and 73% were using Et Control. Similar numbers were also reported in the French and Australian/New Zealand surveys.^{21,29,30} In a recent worldwide survey among anaesthesiologists however only 49% of the respondents indicated to use FGF < 1 l/min.³¹ Managing FGF is a safe and effective way to reduce waste of inhalation anaesthetics and environmental pollution due to their GHG effect.²² With a minimum FGF of 0.5 l/min (minimal flow), the desired clinical effect can be achieved in patients. Using more than minimal flow results in wastage of inhalation anaesthetics. Since there is a linear relationship between the amount of fresh gas used and the amount of inhalation anaesthetics used reducing FGF is an effective mitigation strategy.^{17,32} Traditionally FGF was set manually, but nowadays ventilators can be equipped with an Et Control function with which the FGF is optimally adjusted according to the requested concentration of VA. In a comparative study of VA consumption with Et Control and manual control, the mean consumption of sevoflurane was 14 ml/h versus 30 ml/h (-53%) and of desflurane 27 ml/h versus 45 ml/h (-40%).²³ Our survey deliberately did not ask about the use of VCT as this technique to capture VAs from the anaesthesia machine outlet was not yet available on the Dutch market in 2019. The use of VCT can reduce the amount of VAs emitted into the atmosphere and VAs can potentially be recovered and reused, which can provide financial savings in addition to environmental gains.³³ This technique has recently become available to the market, but there are mixed results regarding its effectiveness in daily practice. In a clinical study performed on 13 patients 62% - 86% of the delivered desflurane was adsorbed with FGFs ranging from 0.5 - 3 l/min.³⁴ In a recent clinical trial in 80 patients, the median amount of desflurane recaptured was only 52%.³⁵ In 70 bariatric patients utilising minimal flow and Et Control 45% of the administered sevoflurane could be captured with VCT.³⁶ The presented hypothesis that



a significant residual amount of sevoflurane and desflurane was still present in the body after extubation and could thus not be captured seems less probable explanation since a computer simulation study showed that theoretically at least 73% of the administered amount of VA could be recovered and only very small amounts of VAs are exhaled in the first hour after surgery.³⁷ The exact effectiveness of VCT will require further study, but the capture and recycling of VAs offers prospects for reducing environmental pollution from their use. In fact, the modelled use of sevoflurane with low FGF and VCT has a similar carbon footprint to intravenous anaesthesia with propofol.¹⁷

The use of N_2O greatly affects total amount of GHGs emitted by anaesthesia practice worldwide due to its high GWP₁₀₀ and low potency.³⁸ Data from Ireland and Austria show that N_2O can be responsible for more than 80% of emissions from inhalation anaesthetics.^{26,27} Our calculation of 66% for the Dutch situation matches this order of magnitude. This large fraction is despite the fact that the use of N_2O in the Dutch healthcare system has fallen drastically in the past decades. In 2019, it was only 5% of the amount of N_2O emitted in 1990 (RIVM data). This recent decline in N_2O use for anaesthesiologic purposes has also been observed by others.³⁹⁻⁴¹ It is consistent with our survey results showing that anaesthesiologists indicate that N_2O is nowadays only rarely used. Nitrous oxide was initially widely used as an adjuvant to VAs to improve the clinical profile of these agents, but with the arrival of desflurane and sevoflurane in the 1990s, that need has been eliminated. Furthermore, the use of more efficient respirators and the introduction of the intravenous agent propofol during the same period reduced N_2O emissions by anaesthesiologists. Still the impact of N_2O on the total amount of emitted GHGs in our study is responsible for two thirds of total emissions and reducing their emissions should be a priority in mitigating climate impact of inhalation anaesthetics. Even though the clinical use of N_2O by Dutch anaesthesiologists has drastically fallen it is still readily applicable as an analgesic in obstetrics and emergency care. For this application there are not always equally effective alternative pain control methods available. In such cases, it is possible for 71-81% of the administered N_2O to be collected and to be catalytically destroyed at the bedside.⁴² Minimizing wastage of N_2O by routinely checking for leakages in N_2O pipeline systems or even decommissioning N_2O manifolds if possible should be encouraged given the reported significant leakages of N_2O into the atmosphere.⁶ The Royal College of Anaesthetists has issued a consensus statement on the removal of pipeline N_2O in the United Kingdom and Republic of Ireland recommending that given the fact that N_2O is no longer an essential drug in modern anaesthetic practice, N_2O manifolds should be decommissioned as soon as possible and if necessary replaced by point-of-care cylinders.⁴³ Furthermore legislation should ensure that gas residues in N_2O cylinders are destroyed rather than vented into the atmosphere before refilling.⁶

Our results show that Dutch anaesthesiologists prefer to perform their anaesthesia for the most part with intravenous propofol and can do so without the use of desflurane. In contrast, worldwide only 23% of anaesthesiologists indicate that they prefer intravenous anaesthesia and 64% prefer inhalation anaesthesia.³¹ As a result of efforts to make the healthcare sector more sustainable, several countries have reduced desflurane use in recent years. In Scotland, for example, the use of desflurane was completely phased out by 2023, and Australia and New Zealand have seen sharp reductions in its use. However, in Japan and Taiwan, desflurane is the most commonly used VA.⁴⁴ A risk-benefit analysis of desflurane versus sevoflurane regarding clinical, financial and environmental characteristics shows that there are no reasons to prefer desflurane as an anaesthetic agent.⁴⁵⁻⁴⁷ The European Union has issued a proposal with the intention to prohibit the use of desflurane as of January 2026. Given the importance of universally phasing down HFCs, this is a logical choice given the availability of the low-GWP₁₀₀ alternative sevoflurane. However, care must be taken to ensure that sevoflurane remains available to anaesthesiologists. Although intravenous propofol is a good alternative to sevoflurane for many indications, inducing anaesthesia in children with a facemask is a unique feature of sevoflurane. Also Dutch anaesthesiologists indicated choosing sevoflurane for its hemodynamic stability and low risk of awareness. Apart from the clinical differences between propofol and sevoflurane, the administration technique of VAs is completely different from that of intravenous agents. Anaesthesiologists have mastered this technique since the early days with ether, and it is important that the future generation of anaesthesiologists learn and maintain this technique. Furthermore, completely phasing out VAs in the interest of global warming would mean complete reliance on a single agent (propofol) to administer general anaesthesia. During the COVID-19 pandemic, the global shortage of propofol led to a flight to sevoflurane and isoflurane, even patients in the ICU were then kept under anaesthesia with these VAs.⁴⁸

Phasing out HFCs is of great importance given the relatively large impact these agents have as a result of their large GWP₁₀₀s. These agents are mainly used as refrigerants, propellants, foams etc. Given the exuberant global presence of these agents and their relatively short atmospheric lifetime, immediate phasedown can have a major impact on the ultimate global temperature rise.^{49,50} The phasing down of these HFCs is expected to avoid emissions of 8.8 gigatonne CO₂-eq per year by 2050 and potentially providing up to 6-10% of the needed mitigation to stay below 2°C average global temperature.⁵⁰ The share of global HFC emissions from VAs is estimated to be of 9.8 megatonne CO₂-eq in 2050 in a growth scenario (2% increase of emissions per year) of the aforementioned 8.8 gigatonne CO₂-eq which is 0.08%.³ This relatively low impact of VAs does not mean that anaesthesiologists need not worry about the



release of their agents, but can be seen as an argument for allowing the continued use of sevoflurane in particular. In order to minimize the environmental impact, the use of sevoflurane will have to be regulated by, for example, making Et Control and VCT mandatory if this agent is chosen for general anaesthesia.

Limitations of our study are that we were not able to obtain N₂O procurement data from Dutch hospitals as this was apparently too complicated to obtain. Instead, we used data from the national Emission Registration, which may have led to underreporting given that these data are based on voluntary declarations from the largest N₂O suppliers in healthcare. We would have liked to obtain purchase data of propofol, however, the problem is that propofol is used not only for general anaesthesia, but also for ICU sedation and procedural sedation, among others. The population of our survey might be skewed by the relatively large number of young respondents. It is possible that our results are influenced by this and that more propofol and N₂O is used by this group. However, our procurement data show a similar pattern.

Conclusion

Our study shows the modus operandi of Dutch anaesthesiologists have resulted in relatively limited greenhouse gas emissions from inhalation anaesthetics. A preference for intravenous propofol and very little desflurane and N₂O use results in a carbon footprint that is equal to the annual emissions of about 6,700 passenger cars. However, there is definitely room for improvement. Implementation of strategies to reduce clinical use and wastage of N₂O, complete elimination of desflurane for general anaesthesia and mandatory use of Et Control and VCT when using sevoflurane can make the insurmountable GHG emissions from anaesthesiologic care acceptable for future generations.

Appendix A.

Supplementary digital content

Survey questions: <https://links.lww.com/EJAIC/A104>

References

1. 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.
2. Charlesworth M, Swinton F. Anaesthetic gases, climate change, and sustainable practice. *Lancet Planet Health*. 2017;1(6):e216–e217.
3. 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.
4. White SM, Shelton CL. Abandoning inhalational anaesthesia. *Anaesthesia*. 2020;75(4):451–454.
5. Sulbaek Andersen MP, Nielsen OJ, Wallington TJ, Karpichev B, Sander SP. Medical intelligence article: assessing the impact on global climate from general anesthetic gases. *Anesth Analg*. 2012;114(5):1081–1085.
6. Liu Y, Lee-Archer P, Sheridan NM, Seglenieks R, McGain F, Eley VA. Nitrous Oxide Use in Australian Health Care: Strategies to Reduce the Climate Impact. *Anesth Analg*. 2023;137(4):819–829.
7. Wong A, Gynther A, Li C, et al. Quantitative nitrous oxide usage by different specialties and current patterns of use in a single hospital. *Br J Anaesth*. 2022;129(3):e59–e60.
8. Feng R, Li Z. Current investigations on global N₂O emissions and reductions: Prospect and outlook. *Environmental Pollution*. 2023;338:122664.
9. Sherman SJ, Cullen BF. Nitrous oxide and the greenhouse effect. *Anesthesiology*. 1988;68(5):816–817.
10. Ishizawa Y. Special article: general anesthetic gases and the global environment. *Anesth Analg*. 2011;112(1):213–217.
11. Seglenieks R, Wong A, Pearson F, McGain F. Discrepancy between procurement and clinical use of nitrous oxide: waste not, want not. *Br J Anaesth*. 2022;128(1):e32–e34.
12. Chakera A, McQuillan R, Waite A, Marchant A. Establishing system waste of piped nitrous oxide: Lothian nitrous oxide mitigation project. *Anaesthesia*. 2021;76(S6):10–88.
13. Gaff SJ, Chen VX, Kayak E. A weighing method for measuring nitrous oxide leakage from hospital manifold-pipeline networks. *Anaesth Intensive Care*. 2024;52(2):127–130.
14. MacNeill AJ, Lillywhite R, Brown CJ. The impact of surgery on global climate: a carbon footprinting study of operating theatres in three health systems. *Lancet Planet Health*. 2017;1(9):e381–e388.
15. 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.
16. Sherman J, Le C, Lamers V, Eckelman M. Life cycle greenhouse gas emissions of anesthetic drugs. *Anesth Analg*. 2012;114(5):1086–1090.
17. Hu X, Pierce JMT, Taylor T, Morrissey K. The carbon footprint of general anaesthetics: A case study in the UK. *Resources, Conservation and Recycling*. 2021;167:105411.
18. Mankes RF. Propofol wastage in anesthesia. *Anesth Analg*. 2012;114(5):1091–1092.
19. Gillerman RG, Browning RA. Drug use inefficiency: a hidden source of wasted health care dollars. *Anesth Analg*. 2000;91(4):921–924.
20. Kostrubiak MR, Johns ZR, Vatovec CM, Malgeri MP, Tsai MH. Environmental Externalities of Switching From Inhalational to Total Intravenous Anesthesia. *Anesth Analg*. 2021;132(5):1489–1493.
21. McGain F, Bishop JR, Elliot-Jones LM, Story DA, Imberger GL. A survey of the choice of general anaesthetic agents in Australia and New Zealand. *Anaesth Intensive Care*. 2019;47(3):235–241.
22. Feldman JM. Managing fresh gas flow to reduce environmental contamination. *Anesth Analg*. 2012;114(5):1093–1101.



23. Singaravelu S, Barclay P. Automated control of end-tidal inhalation anaesthetic concentration using the GE Aisys Carestation™. *Br J Anaesth.* 2013;110(4):561–566.
24. Steenmeijer MA, Rodrigues JFD, Zijp MC, Waaijers-van der Loop SL. The environmental impact of the Dutch health-care sector beyond climate change: an input-output analysis. *Lancet Planet Health.* 2022;6(12):e949–e957.
25. Pichler PP, Jaccard IS, Weisz U, Weisz H. International comparison of health care carbon footprints. *Environ Res Lett.* 2019;14(6):064004.
26. Weisz U, Pichler PP, Jaccard IS, et al. Carbon emission trends and sustainability options in Austrian health care. *Resour Conserv Recy.* 2020;160.
27. Keady T, Nordrum OL, Duffy O, et al. Annual greenhouse gas emissions from inhaled anaesthetic agents in the Republic of Ireland. *Br J Anaesth.* 2023;130(1):e13–e16.
28. Koch S, Samwer C, Rossaint R, et al. Survey regarding routine use of anaesthetic techniques and knowledge of their environmental impact in Germany 2020. *Eur J Anaesthesiol.* 2022;39(3):282–284.
29. Benhamou D, Constant I, Longrois D, Molliex S, Nouette-Gaulain K, Bull A. Use of volatile anaesthetic agents in anaesthesia: A survey of practice in France in 2012. *Anaesth Crit Care Pa.* 2015;34(4):205–209.
30. Tordjman M, Pernod C, Bouvet L, Lamblin A. Environmentally Sustainable Practices in the Operating Room: A French Nationwide Cross-Sectional Survey of Anaesthesiologists and Nurse Anaesthesiologists. *Turk J Anaesthesiol Reanim.* 2022;50(6):424–429.
31. Gonzalez-Pizarro P, Koch S, Muret J, et al. Environmental sustainability in the operating room: A worldwide survey among anaesthesiologists. *European Journal of Anaesthesiology and Intensive Care.* 2023;2(4):e0025–0021–0010.
32. Pierce JMT, Taylor R. Validation of the mathematics in the anaesthetic impact calculator, a smartphone app for the calculation the CO₂ e of inhalational anaesthesia. *Anaesthesia.* 2020;75(1):136–138.
33. Ang TN, Baroutian S, Young BR, Hyland MM, Taylor M, Burrell R. Adsorptive separation of volatile anaesthetics: A review of current developments. *Separation and Purification Technology.* 2019;211:491–503.
34. Janchen J, Bruckner JB, Stach H. Adsorption of desflurane from the scavenging system during high-flow and minimal-flow anaesthesia by zeolites. *Eur J Anaesthesiol.* 1998;15(3):324–329.
35. Hinterberg J, Beffart T, Gabriel A, et al. Efficiency of inhaled anaesthetic recapture in clinical practice. *Br J Anaesth.* 2022;129(4):e79–e81.
36. Mulier H, Struys M, Vereecke H, Rex S, Teunkens A, Kalmar AF. Efficiency of CONTRAfluran in reducing sevoflurane pollution from maintenance anaesthesia in minimal flow end-tidal control mode for laparoscopic surgery. *Anaesthesia.* 2024;79(8):849–855.
37. Dexter F, Epstein RH. Associations Between Fresh Gas Flow and Duration of Anesthetic on the Maximum Potential Benefit of Anesthetic Gas Capture in Operating Rooms and in Postanesthesia Care Units to Capture Waste Anesthetic Gas. *Anesth Analg.* 2023;137(5):1104–1109.
38. Devlin-Hegedus JA, McGain F, Harris RD, Sherman JD. Action guidance for addressing pollution from inhalational anaesthetics. *Anaesthesia.* 2022;77(9):1023–1029.
39. Husum B, Stenqvist O, Alahuhta S, Sigurdsson GH, Dale O. Current use of nitrous oxide in public hospitals in Scandinavian countries. *Acta Anaesthesiol Scand.* 2013;57(9):1131–1137.
40. Uchida K, Yasunaga H, Miyata H, et al. Impact of remifentanyl introduction on practice patterns in general anesthesia. *J Anesth.* 2011;25(6):864–871.
41. Elliott KJ, Pierce JMT. Twelve-year trend in nitrous oxide use at a tertiary institution: striving for a net zero NHS. *Anaesthesia.* 2021;76(12):1667–1668.

42. Pinder A, Fang L, Fieldhouse A, et al. Implementing nitrous oxide cracking technology in the labour ward to reduce occupational exposure and environmental emissions: a quality improvement study(). *Anaesthesia*. 2022;77(11):1228–1236.
43. Anesthetists RCo. Consensus Statement on the Removal of Pipeline Nitrous Oxide in the United Kingdom and Republic of Ireland 2024. <https://anaesthetists.org/Portals/o/PDFs/Position%20statements/Consensus%20statement%20on%20removal%20of%20pipeline%20nitrous%20oxide.pdf?ver=2024-07-25-095247-780×tamp=1721897572977>. Accessed 07–07, 2026.
44. Hu EP, Yap A, Davies JF, Goyagi T, McGain F. Global practices in desflurane use. *Br J Anaesth*. 2023;133(6):1484–1486.
45. Hendrickx JFA, Nielsen OJ, De Hert S, De Wolf AM. The science behind banning desflurane: A narrative review. *Eur J Anaesthesiol*. 2022;39(10):818–824.
46. Shelton CL, Sutton R, White SM. Desflurane in modern anaesthetic practice: walking on thin ice(caps)? *Br J Anaesth*. 2020;125(6):852–856.
47. Meyer MJ. Desflurane Should Des-appear: Global and Financial Rationale. *Anesth Analg*. 2020;131(4):1317–1322.
48. Ferriere N, Bodenes L, Bailly P, L'Her E. Shortage of anesthetics: Think of inhaled sedation! *J Crit Care*. 2021;63:104–105.
49. Xu Y, Zaelke D, Velders GJM, Ramanathan V. The role of HFCs in mitigating 21st century climate change. *Atmos Chem Phys*. 2013;13(12):6083–6089.
50. Zaelke D, Borgford-Parnell N. The importance of phasing down hydrofluorocarbons and other short-lived climate pollutants. *Journal of Environmental Studies and Sciences*. 2015;5(2):169–175.

