Anaesthesia 2024 doi:10.1111/anae.16119

Review Article

Inhalational volatile anaesthetic agents: the atmospheric scientists' viewpoint

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Summary

All sectors of society must reduce their carbon footprint to mitigate climate change, and the healthcare community is no exception. This narrative review focuses on the environmental concerns associated with the emissions of volatile anaesthetic agents, some of which are potent greenhouse gases. This review provides an understanding of the global warming potential metric, as well as the concepts of atmospheric lifetime and radiative efficiency. The state of knowledge of the environmental impact and possible climate forcing of emitted volatile anaesthetic agents are reviewed. Additionally, the review discusses how climate metrics can guide mitigation strategies to reduce emissions and suggests present and future options for mitigating the climate impact.

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Accepted: 21 July 2023
Keywords: atmospheric chemistry; global warming potentials; volatile anaesthetics

Introduction

Like all sectors of society, the healthcare community has a responsibility to minimise its impact on climate change. Inhalational volatile anaesthetic agent emissions alone contribute to approximately 3% of a wealthy nation's healthcare-related climate footprint [1]. However, the science underpinning the choices faced by clinicians on how to reduce the impact of peri-operative care is complex. Volatile anaesthetic agents, particularly the halogenated ethers that contain fluorine and chlorine, have been used widely for several decades with great success. Those agents containing fluorine fall under the category known as F-gases, some of which are potent greenhouse gases. There is an ongoing discussion within the European Union regarding restrictions and potential bans on the use of F-gases. Emissions to the atmosphere give rise to four main concerns: stratospheric ozone depletion; photochemical air pollution, such as formation of tropospheric ozone and particles; formation of hazardous degradation products; and climate change. To assess the impacts of individual chemical compounds, knowledge of three physical–chemical properties is essential: the reaction rate coefficient with hydroxyl radicals (which determines atmospheric lifetime); the infrared absorption spectrum; and the complete atmospheric degradation scheme. We employ a photochemical reactor or 'smog chamber system', coupled with Fourier transform infrared detection, to gather the necessary physicochemical data for quantifying atmospheric environmental impacts [2, 3].

Among the volatile anaesthetic agents currently in use, only isoflurane contains chlorine, which can contribute to the catalytic destruction of stratospheric ozone. However, due to its relatively short atmospheric lifetime and declining use, the impact of isoflurane on ozone depletion is minimal [4]. Volatile anaesthetic agents do not contribute to photochemical air pollution. The atmospheric degradation of isoflurane, desflurane and sevoflurane results in the formation of

trifluoroacetic acid, which has negligible environmental effects [5]. While trifluoroacetic acid is resistant to breakdown through biological and chemical processes, it is also a by-product of several chlorofluorocarbon replacements. However, compared with other sources, the production of trifluoroacetic acid from environmental degradation of anaesthetic compounds is expected to be small. Consequently, the primary environmental concern associated with volatile anaesthetic agent emissions lies in their contribution to climate change. This narrative review provides an overview of the current state of knowledge on key parameters required to assess the environmental impact of volatile anaesthetic agents, with a specific focus on their potential contribution to the radiative forcing of climate change. Furthermore, we aim to clarify the complexities behind the numerical values of climate impact parameters. Finally, we discuss potential strategies for reducing emissions.

Data and calculations of global warming potentials

Over the last couple of decades, research using laboratory experiments, modelling and atmospheric measurements, has produced sizable datasets concerning the atmospheric chemistry and environmental impact of volatile anaesthetic agents. Based on these data, quantification of environmental impact is possible. The effect on the climate from atmospheric gases can be evaluated by considering the change in the net atmospheric irradiance ($W \cdot m^{-2}$), that is, the amount of outgoing energy from Earth, at the tropopause (approximately 10 km altitude) caused by a change in an external driver of the climate system (e.g. a change in the concentration of a greenhouse gas, such as desflurane). The change considered normally is based on a 1 parts per billion (ppb) increase in the concentration of the gas in the troposphere and is termed 'radiative efficiency' with units of $W \cdot m^{-2} \cdot ppb^{-1}$. The total number of molecules in one atmosphere of air at sea surface level is approximately 2.46×10^{19} molecules$\cdot cm^{-3}$, which is approximately 25 billion-billion molecules per cubic centimetre. Radiative efficiency tells us what the impact of the gas is 'here-and-now' on the climate system. However, the climate does not change instantaneously. Impacts are manifested over time and metrics that include time-integrated effects are therefore required when evaluating the potential impacts of human activities.

The global warming potential (GWP) is the most widely used climate metric, and it is a relative metric [6]. It is a numerical index, describing the impact of a specific chemical relative to the climate impact of emission of 1 kg of carbon dioxide. The index is useful for assessing the potential climate impact over a certain time horizon, normally 100 years, of the emission of a chemical compound to the atmosphere. The numerical values for the GWPs are strongly dependent on the time horizon chosen for the calculation. Typically, three different periods (20, 100 and 500 years) are used to capture impacts in the short, medium and long term. Chemicals such as volatile anaesthetic agents, which decay considerably faster in the atmosphere than the GWP-reference compound carbon dioxide, have GWPs that decrease markedly for the longer time horizons. We think that given the importance of carbon dioxide in driving climate change, and with its atmospheric lifetime of approximately 100 years, climate impact estimates for the use of volatile anaesthetic agents should be derived using time horizons that capture a significant portion of the total climate impact of carbon dioxide. This is especially relevant if used as part of broader-defined systems assessments, which also include evaluation of emission sources of carbon dioxide (e.g. energy generation or consumption). The United States Environmental Agency, European Environment Agency and United Nations climate protocols use the 100-year time horizon (GWP_{100}) for comparing the impacts of short- and long-lived greenhouse gases. While others prefer to use the GWP impact over 20 years (GWP_{20}) to emphasise the dramatically higher short-term climate consequences, we suggest healthcare greenhouse gas accounting follows the precedence of the US and United Nations treaties with consistency and recommend the use of GWP_{100} [7].

For a time-horizon t′ the GWP is defined as:

$$GWP(x(t)) = \frac{\int_0^{t'} F_x \exp\left(-t/\tau_x\right) dt}{\int_0^{t'} F_{CO_2} R(t) dt} \quad (1)$$

where F_x is the radiative forcing per unit mass of the chemical species x, F_{CO_2} is the radiative forcing of carbon dioxide, R(t) is the response function that describes the decay of an instantaneous pulse of carbon dioxide and τ_x is the response time, that is, the decay of the pulse of compound x assuming it obeys a simple exponential decay curve. The denominator in Equation 1 is also the absolute global warming potential for carbon dioxide. Once the GWP for a particular anaesthetic gas is established, one can obtain the carbon dioxide equivalency for an emission of the gas by simply multiplying the mass of the anaesthetic emitted (in kg) and the GWP of the gas.

Global warming potential is a function of both the radiative efficiency and atmospheric lifetime of the forcing agent. In the equation above, F_x depends directly on the infrared spectrum and indirectly on the atmospheric lifetime of the compound, which in turn fixes the response time, τ_x. Even small modifications in estimation methodologies,

updated values for F_x or τ_x, as well as changes in the radiative efficiency of carbon dioxide combine to recurrent updates in the GWP values, albeit small ones.

The concensus on infrared spectra, atmospheric lifetimes and radiative efficiencies

The infrared absorption spectra and associated absorption cross sections of nitrous oxide, isoflurane, desflurane, sevoflurane and methoxyflurane have been determined with a high degree of confidence [4]. The halogenated ethers absorb strongly within the 'atmospheric window', a certain region (8–14 μm) in the spectrum of the outgoing terrestrial infrared radiation in the Earth's infrared emission spectrum, where gases can be particularly efficient at affecting Earth's radiative balance. Nitrous oxide is a weaker absorber as it has a smaller cross section than the halogenated anaesthetics, and has absorption lines located at slightly higher frequencies outside the atmospheric window. It is nonetheless a strong greenhouse gas, an effect of its long atmospheric lifetime.

Table 1 lists the atmospheric lifetimes of the halogenated anaesthetics and nitrous oxide. Volatile anaesthetic compounds, except nitrous oxide, are all lost from the atmosphere through reaction with hydroxyl radicals, predominantly in the lower troposphere (Table 1). Nitrous oxide undergoes ultraviolet photolytic destruction in the stratosphere. The rate coefficients for the hydroxyl radical reactions have been measured experimentally and documented in the literature over the past four decades [3]. Critical reviews of reported rate coefficients are also performed periodically [8] and, accordingly, a well-founded consensus on the reaction kinetics has emerged [9]. The atmospheric lifetime, τ_x in Equation 1, is defined as the time it takes for the concentration of x to decrease to a factor of 0.368 (i.e. 1/e) of its initial value. For compounds that are

Table 1 Recently published atmospheric parameters and impact index values for nitrous oxide and halogenated volatile anaesthetic agents from the World Meteorological Organization Scientific Assessment Panel (WMO SAP) [11], Intergovernmental Panel on Climate Change Sixth Assessment Report (IPPC AR6) [12], Vollmer et al. [24], Hass et al. [28] and Gulev et al. [29].

Compound	Atmospheric lifetime (years)	Radiative efficiency; $W \cdot m^{-2} \cdot ppb^{-1}$	Global warming potentials, time horizons			Ozone depletion potential	Atmospheric mole fractions	Estimated trifluoroacetic acid formation
			20 years	100 years	500 years			
Nitrous oxide								
WMO SAP 2022 [11]	109	0.0032	273	273*	130	0.017	333 ppb (2020)† [11]	0%
IPCC AR6 2021 [12]	109	0.0032	273	273	130	-	332 ppb (2019)† [29]	
Isoflurane								
WMO SAP 2022 [11]	3.5	0.426	1920	536*	153	0.03	0.15 ppt (2021)‡ [24]	95 (± 3)% [5]
IPCC AR6 2021 [12]	3.5	0.426	1930	539	154	-	0.11 ppt (2021)† [11]	
Desflurane								
WMO SAP 2022 [11]	13.7	0.466	6930	2530*	720	0	0.37 ppt (2020)‡ [24]	3–20% [5]
IPCC AR6 2021 [12]	14.1	0.464	7020	2590	741	-		
Sevoflurane								
WMO SAP 2022 [11]	1.41	0.299	505	140*	40	0	0.24 ppt (2021)‡ [24]	2–95% [5]
IPCC AR6 2021 [12]	1.9	0.308	702	195	55.7	-	0.16 ppt (2021)† [11]	
Methoxyflurane								
Hass et al. [28]	0.15	0.0674	14	4*	1	-	-	0%

*Recommended global warming potentials for use by clinicians. ppb, parts per billion; ppt, parts per trillion.
†Global mean mole fractions.
‡Measured at Jungfraujoch, Switzerland.

well mixed within the atmosphere, the average atmospheric lifetime with respect to reaction with hydroxyl radicals can be estimated based on a simple calculation for a chemical decay through reaction with hydroxyl radicals in the atmosphere (of which there are approximately 1×10^6 molecules·cm^{-3} in the troposphere) [10]. Alternatively, a relative scaling to the atmospheric lifetime of methyl-chloroform due to reaction with hydroxyl radicals (6.1 years) can be used. The latter method has typically been used by the World Meteorological Organization and the Intergovernmental Panel on Climate Change in their simplified atmospheric lifetime calculations [11, 12]. For short-lived species, this simplified calculation method produces atmospheric lifetime estimates with large uncertainties. If the tropospheric lifetime of the species is close to tropospheric transport time scales (approximately 6 months or less), the tropospheric distributions of the species will be non-uniform. For example, the local lifetime for a very short-lived substance like methoxyflurane ($\tau \approx 4$ days) will depend on the location of the emissions and the temporal and spatial variations in the chemical conditions of the atmosphere [13]. As such, the lifetimes listed in Table 1 are estimated average atmospheric lifetimes, and complex atmospheric chemical and transport models would be needed to determine the atmospheric lifetimes more precisely. However, these estimates would not necessarily be more accurate, as assumptions and initial starting conditions, which themselves have associated uncertainties, are preconditions for such model-runs.

Finally, the radiative efficiency (units of W·m^{-2}·ppb^{-1}) of a molecule, which reflects the heat trapping ability of the molecule in the atmosphere, is used in place of F_x in the GWP calculation (see Equation 1). It can be calculated using complicated radiative transfer models but is typically estimated using a simplified method known as the Pinnock curve [14]. Various iterations of this method have been employed, resulting in refinements in spectral resolution (e.g. using the Oslo Line-BY-Line radiative transfer model) and development of lifetime-based radiative efficiencies-correction factors for compounds with lifetimes ranging from very short to long, i.e. $10^{-4} < t < 10^4$ years, as done by Hodnebrog et al. [15]. Recently, the impact of the gas on temperatures in the stratosphere has been further refined by Shine and Myhre and is now incorporated explicitly in the Pinnock curve [16] (Table 1).

Future changes in global warming potentials

Contrary to what might be intuitive, the denominator in Equation 1, the absolute GWP for carbon dioxide, is not a universal constant. The value is affected by the increasing atmospheric mixing ratio of carbon dioxide, pulling GWP in two directions. As emissions of carbon dioxide to the atmosphere continue, the radiative efficiency of carbon dioxide decreases because many of the absorption lines for carbon dioxide are already saturated. At the same time, the fraction of carbon dioxide that remains in the atmosphere also increases with the carbon dioxide mixing ratio, increasing the absolute GWP for carbon dioxide. The absolute GWP can also be calculated using complex line-by-line climate models in ways that include climate-carbon cycle feedbacks [17, 18], or leave those out [19].

In the past, the chosen method has depended simply on the principal application of these numbers. In the article by Hodnebrog et al. [20], the climate-carbon cycle feedbacks are excluded, with an updated impulse-response function [20], an updated radiative forcing calculation [21] and updated carbon dioxide mixing ratio [20], the net result is a slight decrease (12%) in the absolute GWP calculated for carbon dioxide (8.064×10^{-14} W·m^{-2}·year) [20], when compared with the values used earlier. We believe there has been a calculation error for the lifetime of sevoflurane in Hodnebrog et al. [20] and Intergovernmental Panel on Climate Change [12], something we have pointed out elsewhere [22], and this is now included in the latest World Meteorological Organization Scientific Advisory Panel 2022 report [11]. The GWP values are necessarily affected by uncertainties in the compound's lifetime, radiative efficiency and absolute GWP for carbon dioxide. Hodnebrog et al. [20] have estimated these uncertainties for short-lived halogenated greenhouse gases in general, and the uncertainty in the GWPs for isoflurane and desflurane are on the order of 15%, and 25% for sevoflurane and methoxyflurane.

The changing input parameters can lead to consternation and bewilderment in the healthcare community and others working with sustainability assessments. However, the GWP metric input parameters must change due to changes in the atmospheric environment. Fortunately, the range of GWP values reported for volatile anaesthetic agents have varied little over the past decade and indeed less than the estimated GWP uncertainties.

Present environmental impact of anaesthetic agents and emission mitigation strategies

At present concentrations, the impact on the climate from halogenated volatile anaesthetic agents in our atmosphere is small when compared with the major drivers of climate change such as carbon dioxide and methane. Vollmer et al.

[23], reported 2014 global mean mole fractions for halothane, isoflurane, desflurane and sevoflurane in the range of parts per quadrillion–parts per trillion and have since updated these values in a recent research activity report [24]. Based on the radiative efficiency values and global mean mole fractions listed in Table 1, the halogenated volatile anaesthetic agents contribute a total of 0.22 $mW{\cdot}m^{-2}$ to the radiative forcing of the climate. Of this number, desflurane is responsible for 0.18 $mW{\cdot}m^{-2}$ (81%). No atmospheric measurements exist in the literature for methoxyflurane. The effective radiative forcing from nitrous oxide is much larger due to a large atmospheric abundance (long lifetime) and has been calculated as 0.21 $W{\cdot}m^{-2}$ [11]. However, atmospheric concentrations of nitrous oxide are largely driven by the intensification of global agriculture, and the current contribution of nitrous oxide from anaesthesia to the radiative forcing of climate has been estimated at 1–3% of current global emissions of nitrous oxide [25].

Nitrous oxide, isoflurane and methoxyflurane are all ozone depleting substances but due to the relatively short atmospheric lifetimes of isoflurane and methoxyflurane, their resulting impact on ozone depletion is expected to be negligible. The contribution of nitrous oxide to stratospheric ozone depletion is difficult to determine. It depends on the concentration of other greenhouse gases in the atmosphere and degree of halogen loading in the stratosphere and is presently small but predicted to increase in the future [26]. Finally, the atmospheric degradation mechanism for the halogenated volatile anaesthetic agents have been studied using experimental chamber studies [3, 27]. In general, carbonyl and ester type products are the terminal degradation products whose dominant fate (within days–months) in the environment is reaction with hydroxyl radicals, photolysis or uptake into rain, cloud and ocean water, followed by hydrolysis. Small yields of trifluoroacetic acid are expected from the processing of the degradation products. Trifluoroacetic acid does not bioaccumulate nor is it toxic at the low to moderate exposures currently measured in the environment or those predicted in the distant future [5].

There are several ways to mitigate the climate impact from the use of volatile anaesthetic agents. The most obvious way is to look at Table 1 and choose the anaesthetic with the lowest GWP value, if this is acceptable for the medical procedure and the patient. The second is to reduce fresh gas flows, which will require stricter observation of the individual patient. Volatile anaesthetic agents undergo almost no in vivo metabolism. Hence, all used material is eventually emitted to the atmosphere unless it is collected or treated. Presently, there are companies providing collection canisters that will absorb anaesthetic compounds. These canisters are shipped for recycling or destruction of the anaesthetic agents. A more sustainable solution would be to have destruction occurring in connection with the anaesthetic machine near the patient.

Conclusions

We have provided an analysis of the environmental impact of volatile anaesthetic agents, approached from the perspective of an atmospheric scientist. The main environmental concern is the impact on climate change. We hope this review will inspire anaesthetists to consider the optimal balance between risks and benefits for each individual patient. It is important that the healthcare community understands the underlying principles and uncertainties associated with the GWP values.

Acknowledgements

No external funding or competing interests declared.

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