Assessing the Impact on Global Climate from General Anesthetic Gases

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Although present in the atmosphere with a combined concentration approximately 100,000 times lower than carbon dioxide (i.e., the principal anthropogenic driver of climate change), halogenated organic compounds are responsible for a warming effect of approximately 10% to 15% of the total anthropogenic radiative forcing of climate, as measured relative to the start of the industrial era (approximately 1750). The family of anesthetic gases includes several halogenated organic compounds that are strong greenhouse gases. In this short report, we provide an overview of the state of knowledge regarding the impact of anesthetic gas release on the environment, with particular focus on its contribution to the radiative forcing of climate change. (Anesth Analg 2012;114:1081–5)

Research investigating the atmospheric chemistry and environmental impact of halogenated anesthetic gases has been documented in the scientific literature over the past 2 to 3 decades. With the increased focus on concerns relating to global climate change, the breadth of these investigations has expanded considerably over the last few years. In the present work, our discussion is centered on a recent review article entitled "General Anesthetic Gases and the Global Environment," in which Ishizawa[1] addressed the global environmental impacts of anesthetic procedures. Unfortunately, there are a number of errors and misconceptions in the review. To clarify the situation, we reevaluated the key variables needed to access the impact of anesthetic procedures on global climate. Our report has 2 goals: first, to correct the erroneous data, statements, and conclusions in the article by Ishizawa; and second, to present a concise and technically accurate overview of the atmospheric lifetimes, ozone depletion potentials (ODPs), and global warming potentials (GWPs) of inhaled anesthetics for reference by the medical community.

DISCUSSION

Radiative forcing is a measure of the influence a factor has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system, often stated relative to pre-industrial conditions (i.e., the year 1750).[2] Halogenated organic compounds are an important category of greenhouse gases and are responsible for approximately 10% to 15% of the radiative forcing of climate change by long-lived greenhouse gases.[2] Greenhouse gases are compounds that have a significant atmospheric lifetime, and possess infrared absorption bands that overlap with the outgoing radiation from the Earth's lower atmosphere. Gases that absorb strongly in the atmospheric window, the spectral region between approximately 8 to 14 μm (714–1250 cm^{-1}) in the Earth's infrared emission spectrum where absorption by the naturally occurring greenhouse gases is relatively minor, are particularly effective at affecting the Earth's radiative balance. Figure 1 shows the spectrum of outgoing infrared radiation from Earth in this atmospheric window region together with the absorption bands of the halogenated anesthetic gases, halothane ($CF_3CHClBr$), enflurane ($CHFClCF_2OCF_2H$), isoflurane ($CF_3CHClOCHF_2$), desflurane ($CF_3CHFOCHF_2$), and sevoflurane [$(CF_3)_2CHOCH_2F$]. All the anesthetic gases absorb in the atmospheric window region, as illustrated in Figure 1. Emission of infrared radiation through the atmospheric window into space is an important mechanism by which the Earth's temperature is regulated. Because these anesthetic gases possess infrared absorption bands that overlap outgoing radiation inside, as well as outside, the atmospheric window, they can impede the flow of infrared radiation out to space, and hence act as greenhouse gases.

In Ishizawa's[1] abstract, it is stated that "All volatile anesthetics that are currently used are halogenated compounds destructive to the ozone layer." That is not correct. All of the halogenated compounds listed in Ishizawa's[1] Table 1 are greenhouse gases, but of the 3 major halogenated anesthetics currently in use (isoflurane, desflurane, and sevoflurane), only isoflurane contains chlorine, which can contribute to the chlorine-mediated catalytic destruction of stratospheric ozone. Atmospheric oxidation of desflurane and sevoflurane does result in the formation of CF_3 radicals, which add O_2 to give CF_3O_2 radicals followed by reaction with nitric oxide to give CF_3O radicals.[3,4] Several years ago, it was speculated that CF_3O radicals could participate in catalytic ozone destruction cycles[5]; however, experimental studies have subsequently shown that this is not the case.[6,7] The chlorine-containing isoflurane, enflurane, and halothane, with the latter also containing a bromine substituent in addition to chlorine, are all ozone-depleting substances, but halothane is now only in significant use in some developing countries. The ODP is the frequently used index that conveniently compares the effectiveness of 1 mass unit of a substance in destroying ozone with that of CFC-11 (CCl_3F).[8] Because of the relatively short atmospheric lifetimes of both isoflurane, its structural isomer

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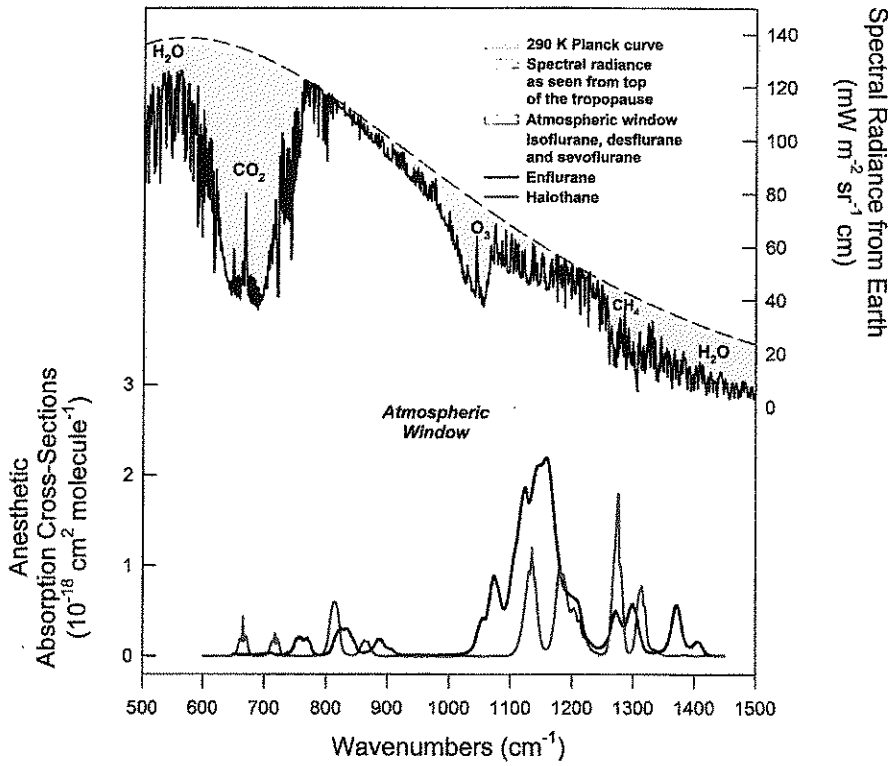

Figure 1. The net upward atmospheric radiance spectrum at the tropopause (personal communication, 2010, R. Beer, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA. Spectral radiance based on Modtran [Spectral Sciences Inc.] atmospheric radiative transfer model calculations), flanked by the ideal Planck function for a blackbody emissions at 290K (black dashed line). The presence of naturally occurring major greenhouse gases in the atmosphere (CO_2, H_2O, O_3, and CH_4) produces attenuation of the outgoing radiation resulting in a nonideal Planck curve. Infrared spectra for halothane (red trace) and enflurane (blue trace), and isoflurane, desflurane, and sevoflurane (gray traces) are shown. These halogenated organic compounds absorb strongly in the atmospheric window region.

Table 1. Summary of Radiative Properties, Atmospheric Lifetimes, and Global Warming Potentials for Nitrous Oxide and the Halogenated Anesthetic Gases

Compound	Atmospheric lifetime (y)	Radiative efficiency (W m^{-2} ppb^{-1})	GWP 20-y time horizon	GWP 100-y time horizon	GWP 500-y time horizon	Ozone depletion potential
Nitrous oxide, N_2O	114[8]	0.00303[8]	289[8]	298[8]	153[8]	0.017[17]
Halothane, $CF_3CHClBr$	1.0[8]	0.165[a]	190[a]	50[a,b]	20[a]	0.4[a,c]
Enflurane, $CHFClCF_2OCF_2H$	4.3[8]	0.447[a]	2370[a]	680[a,d]	210[a]	0.01[a,c]
Isoflurane, $CF_3CHClOCHF_2$	3.2[13]	0.453[13]	1800[13]	510[13]	160[13]	0.01[a,c]
Desflurane, $CF_3CHFOCHF_2$	14[3]	0.469[13]	6810[3]	2540[3]	130[3]	0[a,c]
Sevoflurane, $(CF_3)_2CHOCH_2F$	1.1[3]	0.351[13]	440[3]	130[3]	40[3]	0[a,c]

GWP = global warming potential.

[a] Determined in this work.

[b] Previous literature values were 40[10] and 220[11] with both values converted from HGWP (halocarbon global warming potential) values relative to CFC-12, using GWP (CFC-12) = 10,890.[2]

[c] Estimated using the semiempirical method with fractional halogen release values (describes the fraction of the halogenated gas that has undergone photochemical degradation and released its halogen atoms by some time at a given stratospheric location)[8] for enflurane and isoflurane assumed equal to the average (0.21) for hydrochlorofluorocarbons given in Table 5-1 in the World Meteorological Organization Ozone Assessment Report.[8] Fractional release value for halothane was equated to that for CH_3Br (0.6).

[d] Previous literature values were 440[10] and 870[11], with both values converted from HGWP values relative to CFC-12, using GWP (CFC-12) = 10,890.[2]

enflurane, and halothane, their resulting impact on ozone depletion are comparatively small (Table 1).

Radiative forcing is a metric used to compare the impacts of external drivers of climate change. It is defined as the change in net irradiance (W m^{-2}) at the tropopause caused by a change in an external driver of the climate system. The change normally considered is based on a 1-ppb increase in the concentration of the gas in the troposphere and is termed radiative efficiency with units of W m^{-2} ppb^{-1}. Radiative efficiency is calculated using radiative transfer models of the atmosphere and depends on the strength and spectral position of a compound's absorption bands, atmospheric structure, surface temperature, and the presence or absence of clouds.[2,8] Different gases will act over different time scales. The potential contribution of a greenhouse gas to climate change is frequently assessed through the GWP index, which is a function of both the radiative efficiency and the atmospheric lifetime of the forcing agent. The GWP on a CO_2 equivalent scale for time horizon t′ can be defined as:

$$\mathrm{GWP}(x(t)) = \frac{\int_0^{t'} F_x \exp(^{-t}/_{\tau_x})dt}{\int_0^{t'} F_{CO_2} R(t)dt}$$

where F_x is the radiative forcing per unit mass of species x, F_{CO_2} is the radiative forcing of CO_2, and R(t) is the response function that describes the decay of an instantaneous pulse of CO_2. Furthermore, it is assumed that the decay of the

pulse of compound x assuming it obeys a simple exponential decay curve determined by a response time of τ_x. The denominator in Equation 1 is the absolute GWP for CO_2, which has been evaluated by the World Meteorological Organization as 0.676 W m^{-2} ppm^{-1} for a 100-year time horizon.[8] Knowing the GWP for an anesthetic gas, one can obtain the CO_2 equivalency for an emission of the particular gas by simply multiplying the mass emitted (in kilograms) and the GWP of the gas.

Although GWP is not the only metric available for comparing the impact of climate-forcing agents, GWP is the most widely accepted metric.[8] Values of GWPs can depend markedly on the choice of time horizon in the calculation above. Compounds such as halogenated anesthetics that decay much more quickly in the atmosphere than the reference compound, CO_2, have GWPs that decrease markedly with increasing time horizon. Typically, 3 time horizons (20, 100, and 500 years) are used to capture impacts in the short-, medium-, and long-term. As argued in Wallington et al.,[9] we believe that given the importance of CO_2 in climate change, and with its atmospheric lifetime of approximately a century, climate impact estimates should be derived using time horizons that capture a significant portion of the total impact of CO_2. The United States Environmental Agency, the European Environmental Agency, and the United National Kyoto Protocol all use the 100-year time horizon for comparing the impacts of short- and long-lived greenhouse gases.

Ishizawa's[1] Table 1 presents an overview of the atmospheric lifetimes and the 20- and 100-year GWPs of nitrous oxide, halothane, isoflurane, sevoflurane, and desflurane. Unfortunately, the table contains several errors. Ishizawa cites an atmospheric lifetime and GWP for sevoflurane from the Intergovernmental Panel on Climate Change (IPCC) AR4.[2] However, IPCC AR4 does not contain any information on sevoflurane. Actually, Ishizawa's[1] stated values are for $CH_3OCF_2CF_2CF_3$ [HFE (HydroFluoroEther)-347mcc3], which is not sevoflurane [sevoflurane has the molecular formula $(CF_3)_2CHOCH_2F$]. Furthermore, the atmospheric lifetime for halothane of 7 years given in Ishizawa's[1] Table 1 is not in agreement with the latest World Meteorological Organization assessment of a lifetime of 1 year.[8] Finally, the atmospheric lifetimes listed for desflurane and sevoflurane are based on kinetic studies by Brown et al.[10] and Langbein et al.,[11] and the GWPs for isoflurane, desflurane, and sevoflurane are from Ryan and Nielsen,[12] all of which are erroneous and have been superseded by more recent work.[3,13] As discussed by Calvert et al.,[14] systematic errors in the work of Brown et al. lead to an underestimation of atmospheric lifetimes. As noted by Sulbaek Andersen et al.,[13] there is a typo in the halocarbon GWP expression on page 5 of the supporting information from Ryan and Nielsen,[12] resulting in erroneous GWPs. Ishizawa's[1] Table 1 presents incorrect values of the climate-relevant variables needed to estimate the contribution to the forcing of climate by anesthetic procedures.

To remedy the situation, we have tabulated the most current estimates of atmospheric lifetimes, ODP, radiative efficiencies, and GWP for common halogenated anesthetic gases in Table 1. For completion, the infrared absorption spectra for halothane and enflurane were recorded and used to improve the quantification of the potential impact on climate from halothane and enflurane release to the atmosphere. Although the GWPs of these 2 compounds have been assessed before,[10,11] the previous assessments were based on a single measurement of the infrared absorption spectra and the GWPs were coarsely estimated based on normalizing the integrated infrared absorption cross-sections relative to that of CFC-12 (CF_2Cl_2). This approach does not consider that the actual Planck curve, illustrated in Figure 1, describing the atmosphere's radiative transfer over the spectral region in which halogenated organic compounds absorb, is not an ideal black-body curve, but diverges dramatically because of the spectral overlaps of other radiatively active species (greenhouse gases). The infrared spectra of halothane and enflurane determined in this work are shown in Figure 1 (blue and red traces), and the integrated absorption cross-sections are listed in Table 2. The experimental and theoretical methods used herein are described elsewhere.[13] The measured absorption cross-sections of the anesthetics were weighted by an instantaneous cloudy sky radiative forcing calculated for a model atmosphere with global mean specification of cloudiness and accounting for absorption by CO_2, O_3, and water vapor.[15] Using the spectra for halothane and enflurane shown in Figure 1, we calculated radiative efficiencies for halothane and enflurane of 0.165 and 0.447 W m^{-2} ppb^{-1}, respectively. Using Equation 1 with the radiative efficiencies determined above and the atmospheric lifetimes listed in Table 1 gives GWPs (100-year time horizon) of 50 and 680 for halothane and enflurane. For comparison, the previous 100-year GWP estimations for halothane and enflurane by Brown et al.[10] and Langbein et al.[11] are also included in the footnotes in Table 1.

Table 2. Integrated Absorption Cross-Sections for Halothane and Enflurane at 298 K

Compound	Integrated absorption cross-sections (cm $molecule^{-1}$)		
	Brown et al.[10] (800–1200 cm^{-1})	This work (800–1200 cm^{-1})	This work (650–1500 cm^{-1})
Halothane, $CF_3CHClBr$	5.6×10^{-17}	6.38×10^{-17}	1.22×10^{-16}
Enflurane, $CHFClCF_2OCF_2H$	1.9×10^{-16}	2.04×10^{-16}	2.68×10^{-16}

Referring to the recent study by Ryan and Nielsen,[12] Ishizawa states that "Their study suggests that all the anesthetics (isoflurane, sevoflurane, and desflurane) can have a significant influence on global warming with the greatest influence produced by atmospheric desflurane." We believe this is an overstatement of the conclusions by Ryan and Nielsen. The magnitude of the anesthetic emissions is such that their climate impact is many orders of magnitude less than that of global anthropogenic CO_2 emissions. The inhaled anesthetics released during the approximately 200 million anesthetic procedures performed globally each year globally have a climate impact

that is approximately 0.01%[a] of that of the CO_2 released from global fossil fuel combustion.[13,16] Although we do not want to underestimate the importance of limiting greenhouse gas emissions, the impact of the emission of anesthetics needs to be viewed in perspective. Trapping of used inhaled anesthetics may be warranted, and if the halogenated anesthetics available in the particular therapeutic situation have equal therapeutic worth, doctors could choose the one with the lowest impact on climate. The decision to do so should involve a cost-benefit calculation in which the question is whether switching anesthetics provides the most climate protection in terms of avoided greenhouse gas emissions for the given resources. Assessing the costs is beyond the scope of the present work. The benefits can be assessed using the data provided in Table 1. Exercising care to avoid excessive use of anesthetic gases has the double benefit of reducing health care costs and protecting the environment.

CONCLUSIONS

Ishizawa[1] concludes that "Key criteria that will determine the global environmental impact of alternatives to halogenated anesthetics and nitrous oxide are their atmospheric lifetime, GWP, and ODP. These characteristics should be determined for existing anesthetics, and for any new anesthetic gases before widespread clinical use." We agree that before the large-scale use of any industrial compound, an assessment of the atmospheric chemistry, and hence environmental impact, should be performed. Thorough investigations of the environmental impacts of the anesthetics have now been performed and are summarized in Table 1. Using clinical knowledge of anesthetic potency and resulting flow rate requirements, together with the 100-year GWP values stated in Table 1, allows the anesthesiology community to calculate the CO_2 emissions equivalent (i.e., future climate impact) of each anesthetic procedure.

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[a] Accessing the climate impact of worldwide anesthetic procedures is complicated because no usage or production numbers are publicly available for any anesthetic agents. In Reference 3, we assumed that approximately 200 million anesthetic procedures are performed worldwide on an annual basis. Besides the admittedly large uncertainty in this global procedures estimate, another factor contributing to the overall uncertainty in our CO_2 equivalents estimation for the global anesthetic emissions is that it is based solely on agent specific consumption data from one large United States (US) university hospital, University of Michigan. Here, only limited usage of desflurane occurs. Other hospitals may typically use a mix of anesthetics more biased toward desflurane, which would increase our global anesthetic agent CO_2 equivalent emission rates. With these caveats in mind, proceeding with the assumptions outlined above, we estimated that the annual climate impact, as measured by the 100-year GWP, of global emissions of inhaled anesthetics is equivalent to that from the emission of approximately 4.4 million tonnes of CO_2. The average coal-fired power plant in the US emits 3.85 million tonnes of CO_2 per year whereas a typical passenger car in the US emits 5.1 tonnes of CO_2 per year. Hence, we concluded that global emissions of inhaled anesthetics, when measured by the 100-year GWP, have a contribution to the radiative forcing of climate change that is comparable to that of the CO_2 emissions from 1 coal-fired power plant or approximately 1 million passenger cars.[13] For comparison, the global CO_2 emissions from fossil burning in 2010 have been estimated as 35 gigatonnes (giga = 10^9) of CO_2.[16]

DISCLOSURES

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