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Global Warming Potential of Inhaled Anesthetics: Application to Clinical Use

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BACKGROUND: Inhaled anesthetics are recognized greenhouse gases. Calculating their relative impact during common clinical usage will allow comparison to each other and to carbon dioxide emissions in general.

METHODS: We determined infrared absorption cross-sections for sevoflurane and isoflurane. Twenty-year global warming potential (GWP_{20}) values for desflurane, sevoflurane, and isoflurane were then calculated using the present and previously published infrared results, and best estimate atmospheric lifetimes were determined. The total quantity of each anesthetic used in 1 minimal alveolar concentration (MAC)-hour was then multiplied by the calculated GWP_{20} for that anesthetic, and expressed as "carbon dioxide equivalent" (CDE_{20}) in grams. Common fresh gas flows and carrier gases, both air/oxygen and nitrous oxide (N_2O)/oxygen, were considered in the calculations to allow these examples to represent common clinical use of inhaled anesthetics.

RESULTS: GWP_{20} values for the inhaled anesthetics were: sevoflurane 349, isoflurane 1401, and desflurane 3714. CDE_{20} values for 1 MAC-hour at 2 L fresh gas flow were: sevoflurane 6980 g, isoflurane 15,551 g, and desflurane 187,186 g. Comparison among these anesthetics produced a ratio of sevoflurane 1, isoflurane 2.2, and desflurane 26.8. When 60% N_2O/40% oxygen replaced air/oxygen as a carrier gas combination, and inhaled anesthetic delivery was adjusted to deliver 1 MAC-hour of anesthetic, sevoflurane CDE_{20} values were 5.9 times higher with N_2O than when carried with air/O_2, isoflurane values were 2.9 times higher, and desflurane values were 0.4 times lower. On a 100-year time horizon with 60% N_2O, the sevoflurane CDE_{100} values were 19 times higher than when carried in air/O_2, isoflurane values were 9 times higher, and desflurane values were equal with and without N_2O.

CONCLUSIONS: Under comparable and common clinical conditions, desflurane has a greater potential impact on global warming than either isoflurane or sevoflurane. N_2O alone produces a sizable greenhouse gas contribution relative to sevoflurane or isoflurane. Additionally, 60% N_2O combined with potent inhaled anesthetics to deliver 1 MAC of anesthetic substantially increases the environmental impact of sevoflurane and isoflurane, and decreases that of desflurane. N_2O is destructive to the ozone layer as well as possessing GWP; it continues to have impact over a longer timeframe, and may not be an environmentally sound tradeoff for desflurane. From our calculations, avoiding N_2O and unnecessarily high fresh gas flow rates can reduce the environmental impact of inhaled anesthetics. (Anesth Analg 2010;111:92–8)

Global warming potentials (GWPs) of airborne chemical compounds are currently under scrutiny as many industries search for replacement compounds that will minimize environmental impact. Inhaled anesthetics, as a group, are recognized greenhouse gases.[1–3] However, because they have been considered "medically essential" and used in relatively small amounts, they have been only cursorily investigated.

The currently available inhaled anesthetics, sevoflurane (Chemical Abstract Service [CAS]: 28523-86-6; $[CF_3]_2CH—O—CH_2F$), desflurane (CAS: 57041-67-5; $CF_3CHF—O—CHF_2$), and isoflurane (CAS: 26675-46-7; $CF_3CHCl—O—CHF_2$), undergo very little in vivo metabolism in clinical use.[4–6] They are exhaled and scavenged by anesthesia machines with little or no additional degradation,[7,8] and usually are vented out of the building as medical waste gases. Most of the organic anesthetic gases remain for a long time in the atmosphere where they have the potential to act as greenhouse gases. Published atmospheric lifetimes range between 1.4 and 21.4 years for sevoflurane and desflurane, respectively.[1,2] Various volatile anesthetics have been calculated to have a range of 1100 (isoflurane)[9] to 3766 (desflurane)[3] times the greenhouse warming potential of carbon dioxide (CO_2). The high warming potentials of the inhaled anesthetics warrant further examination for their implications in anesthesia practice. However, GWP alone is not enough to assess environmental impact of each anesthetic because

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variables, such as potency, differ. Fresh gas flows (FGFs), carrier gases, and potency of the volatile anesthetics determine quantities of each inhaled anesthetic that would be delivered to a given patient, and, therefore, when weighted by the GWP specific to that anesthetic, determine relative impact of individual drugs on the environment.

In this study, we derived GWP values for the volatile anesthetics, sevoflurane, isoflurane, and desflurane, based on current physical chemistry methodology frequently used to establish impact of greenhouse gases, then placed them in the context of clinical anesthesia practice. This information will provide clinicians the opportunity to examine the relative impact of their own practice patterns.

METHODS

Theoretical Background

The contribution of inhaled anesthetics to greenhouse warming can be derived from the infrared absorption spectra and atmospheric lifetimes of the gases. Each gas absorbs infrared radiation uniquely over a range of wavelengths, providing an individual spectral signature or absorption cross-section (infrared absorption spectrum per unit concentration and path length).[10] The integrated absorption cross-section, the integral of the absorption cross-section over a given spectral range, is a convenient measure of how efficiently a given trace gas may affect the earth's radiative balance. A larger integrated absorption cross-section suggests a larger degree of warming of the atmosphere and earth due to the gas in question. This change in the net irradiance in the atmosphere, that is, the difference between the incoming radiation energy and the outgoing radiation energy, in favor of atmospheric warming is referred to as positive "radiative forcing." The lifetime of inhaled anesthetics in the atmosphere is thought to depend almost completely on reaction with hydroxyl radicals and is therefore a relatively well-defined value for each.[11] GWP can then be calculated for each anesthetic by the method described by Pinnock et al.,[12] taking into consideration the radiative forcing over time.

GWP is a measure of how much a given mass of greenhouse gas contributes to global warming over a specified time period.[13] It is a relative scale that compares the contribution of the gas in question to that of the same mass of CO_2. The GWP of CO_2 is, by definition, 1. This allows a standard comparison of GWP between any gas and CO_2, or between 2 gases, such as inhaled anesthetics. Although GWP can be measured over any time horizon, the relatively short atmospheric lifetimes of the potent inhaled anesthetics studied here warrant the use of 20-year time-integrated values (GWP_{20}); most of their impact has occurred within the 20-year timeframe because this is twice as long as the longest potent inhaled anesthetic's lifetime (approximately 10 years for desflurane).‡ GWP_{20} is also a frequently measured time horizon for a large number of gases and allows comparison with other greenhouse gases reported to the Intergovernmental Panel on Climate Change (IPCC). However, nitrous oxide (N_2O) has a longer atmospheric lifetime and its impact is better addressed with the 100-year integrated values (GWP_{100}), also a frequently reported time horizon. These and other time horizons are included in the online supplemental material (http://links.lww.com/AA/A150).

Experimental Method

Infrared Spectrometry

Infrared spectra were obtained of the pure gases in a cell of 10.0 ± 0.1 cm length equipped with windows of CsI. The spectra were recorded in the 4000 to 400 wavenumber region using a Bruker IFS 66v Fourier transform infrared spectrometer (Abbott Laboratories, Limited, Saint-Laurent, Québéc) using a nominal resolution of 1.0 cm^{-1}. Single-channel spectra (background or sample) were recorded averaging 512 interferograms and applying a Boxcar apodization. A Ge/KBr beam splitter was used to cover the spectral region. To ensure optical linearity, a DTGS (deuterated triglycine sulfate) detector was used. The partial pressures of the gases in the cell ranged from 1 to 10 hPa and were measured using an MKS Baratron type 122A pressure transducer with a stated accuracy of ±0.15%. The absorption cross-sections were obtained from the absorbance spectra assuming that the gas was ideal. The samples of isoflurane (Abbott) and sevoflurane (Abbott) were used as received and degassed by several freeze-thaw cycles before use. Desflurane was previously investigated by similar methods in our laboratory.[3]

Details of the determination of atmospheric lifetimes, radiative forcing, and GWP_{20} and other time horizons for the 3 anesthetics are found in the online supplemental material (http://links.lww.com/AA/A150).

GWP Application to Anesthetic Use

The following calculations allow application of the concept of GWP to clinical anesthetic use. First, the amount of anesthetic released into the atmosphere was calculated for a given time period. Next, the quantity of anesthetic was multiplied by the GWP_{20} of each gas. Because, by definition, CO_2 has a GWP of 1, the product of the gas quantity and the GWP_{20} expresses the CO_2 equivalent (CDE_{20}) impact of that gas. The CDE_{20} values of the anesthetic gases may then be expressed as a ratio to compare the relative global warming impact. The CDE_{20} may also be used to compare the impact of quantities of anesthetic use to other types of CO_2-producing activities.

The approximate amount of anesthetic released into the atmosphere was calculated for each of the 3 inhaled anesthetics, desflurane, isoflurane, and sevoflurane, for 1 hour of use (1 minimal alveolar concentration [MAC]-hour). The calculations assumed the following: no degradation or metabolism, delivered amount of anesthetic to approximate 1 MAC for a 20- to 40-year-old adult at steady-state conditions, temperature of 20°C, similar patient variables, and FGF of 0.5 to 2.0 L (except FGF for sevoflurane was kept at 2 L).

$$[60\ \text{min/h} \times \text{FGF (L/min)}] \times 1\ \text{MAC}\ (\%) = \text{Anes gas (L/h)}$$

$$[\text{Anes gas (L/h)}/(24\ \text{L/mol})] \times \text{Anes molecular mass (g/mol)} = \text{Anes (g/h)}$$

‡For 1 kg of anesthetic, the following will remain after 20 years: desflurane, 0.14 kg; isoflurane, 0.004 kg; and sevoflurane, essentially 0. The equation C(t) = C(t = 0) × e to the (−t/L) can be used for any time horizon. C = quantity of anesthetic (kg); t = time horizon; L = lifetime of anesthetic; and C(t = 0) refers to initial quantity of anesthetic.

where Anes = anesthetic drug (desflurane, isoflurane, or sevoflurane); 1 MAC = 6% for desflurane, 1.2% for isoflurane, and 2% for sevoflurane; molecular mass = 168 for desflurane, 184.5 for isoflurane, and 200 for sevoflurane.

The total mass of each inhaled anesthetic was then multiplied by its calculated GWP_{20} to provide a weighted comparison between individual anesthetics and various FGF rates:

$$\text{Anes (g/h)} \times \text{Anes } GWP_{20} = \text{Anes } CDE_{20} \text{ (g/h)}$$

For sevoflurane, calculations were limited to 2 L FGF because there is controversy concerning impact on renal function at lower flows.[14] The CDE_{20} of sevoflurane at 2 L FGF was then used as a reference. Comparison to a second inhaled anesthetic at several different FGF rates was expressed as a ratio (relative CDE_{20}).

Similar calculations for CDE_{20} and CDE_{100} were performed for each of the 3 inhaled anesthetics, assuming 60% N_2O/40% oxygen (O_2) mixture in the FGF. The percent anesthetic delivered of desflurane, isoflurane, and sevoflurane was reduced by 60% to preserve the total of approximately 1 MAC of delivered anesthetic gases (N_2O + volatile anesthetic). For N_2O, a molecular mass of 44 was used, and a GWP_{20} of 289.[15] These calculations assumed no degradation or metabolism, delivered amount of anesthetic to approximate 1 MAC for a 20- to 40-year-old adult at steady-state conditions, temperature of 20°C, similar patient variables, 1 hour of anesthetic delivery, and 2 L of FGF. The CDE_{20} values, with and without N_2O, were compared for each inhaled anesthetic and expressed as a ratio.

RESULTS

Infrared spectra of the anesthetics are reported and illustrated in the online supplemental material (http://links.lww.com/AA/A150). Spectra results and estimated atmospheric lifetimes of the anesthetics were then used to calculate the GWP_{20} of the inhaled anesthetics. Table 1 provides the tropospheric lifetime and GWP_{20} values for sevoflurane, isoflurane, and desflurane. Sevoflurane has the shortest lifetime (1.2 years) and lowest GWP_{20}; isoflurane is intermediate (3.6 years) and desflurane has the longest lifetime (10 years) and highest GWP_{20}. GWPs for other time horizons may be found in the online supplemental material (http://links.lww.com/AA/A150).

The GWP_{20} of each anesthetic was then applied to clinical anesthetic use. Table 2 compares the quantities of 1 MAC each of desflurane, isoflurane, and sevoflurane released into the atmosphere per hour of delivery, and weights each result by the GWP_{20}. The resulting CDE_{20} values allow comparison of the global warming impact of each gas. For equivalent FGF at 2 L/min, isoflurane results in the lowest amount of anesthetic used in grams per hour and desflurane results in the highest because of potency differences. However, for equivalent FGF, when weighted by GWP and expressed as CDE_{20}, sevoflurane results in the lowest CDE_{20}, isoflurane results in twice the sevoflurane CDE_{20}, and desflurane in 26.8 times the sevoflurane CDE_{20}. Desflurane has approximately 26 and 13 times the global warming impact of sevoflurane and isoflurane, respectively, when all are used at 2 L FGF.

Table 1. Tropospheric Lifetime and 20-Year Global Warming Potential of Inhaled Anesthetics

Compound	Lifetime (y)	GWP_{20}
Carbon dioxide[15]		1
Sevoflurane	1.2	349
Isoflurane	3.6	1401
Desflurane	10	3714
Nitrous oxide[15]	114	289

GWP_{20} = 20-year global warming potential.

Table 2. Comparison of Global Warming Impact of Frequently Used Inhaled Anesthetics per MAC-Hour of Use at Various Fresh Gas Flows

FGF (L/min)	Grams/hour	GWP_{20}	CDE_{20} (g/h)	Ratio CDE_{20}
2% sevoflurane				
2	20.0	349	6980	1
1.2% isoflurane				
0.5	2.8	1401	3881	0.6
1	5.5	1401	7762	1.1
2	11.1	1401	15,551	2.2
6% desflurane				
0.5	12.6	3714	46,796	6.7
1	25.2	3714	93,593	13.4
2	50.4	3714	187,186	26.8

MAC = minimal alveolar concentration; GWP_{20} = 20-year global warming potential; CDE_{20} = 20-year carbon dioxide equivalent.

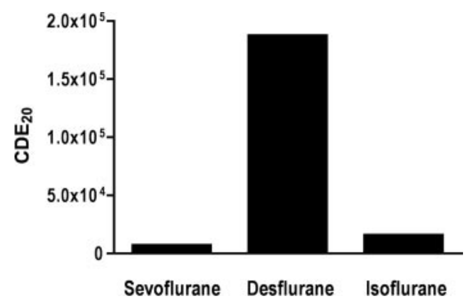

Figure 1. Relative global warming impact of 1 MAC-hour of 3 inhaled anesthetics at 2 L fresh gas flow. CDE_{20} = 20-year carbon dioxide equivalent (in grams).

Table 2 also compares the CDE_{20} values at 1.0 and 0.5 L/min FGF, because isoflurane[16] and desflurane may often be used at lower flows. Compared with sevoflurane at 2 L/min, isoflurane has an approximately equivalent CDE_{20} at 1 L/min. When desflurane at 1.0 and 0.5 L/min is compared with sevoflurane at 2 L/min, the CDE_{20} of desflurane is still 13.4 and 6.7 times higher, respectively. These results illustrate that isoflurane, used at very low flows, has the least global warming impact of the 3 gases, but does not differ much from sevoflurane. Desflurane, at any flow, has a greater global warming impact than either sevoflurane or isoflurane.

The total CDE_{20} difference between the anesthetics for 1 MAC-hour and equivalent FGF is illustrated in Figure 1, again showing that desflurane has a much greater impact than sevoflurane or isoflurane. Because these relationships are linear, this same relative difference will exist at higher flows (as may be used at the beginning of a case to establish a level of anesthesia) or longer periods of use.

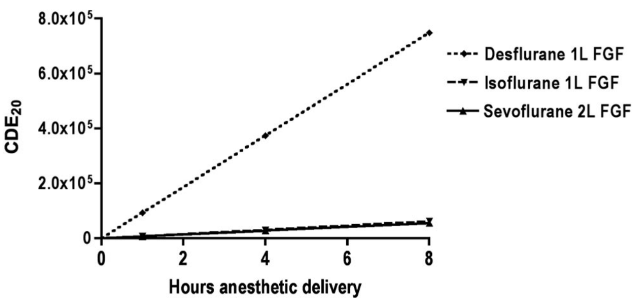

Figure 2. Cumulative impact of 1 MAC inhaled anesthetic over 8 hours at common clinical fresh gas flows. FGF = fresh gas flow (oxygen/air) in liters/minute. CDE_{20} = 20-year carbon dioxide equivalent (in grams).

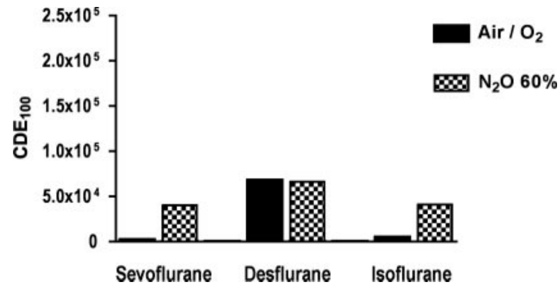

Figure 4. One hour of inhaled anesthetic, delivered with air/oxygen (O_2) or 60% nitrous oxide (N_2O) adjusted to deliver 1 MAC-hour anesthetic at 2 L fresh gas flow. CDE_{100} = 100-year carbon dioxide equivalent (in grams).

Table 3. Comparison of Global Warming Impact of Frequently Used Inhaled Anesthetics, With and Without Nitrous Oxide at 2 L Fresh Gas Flow for 1 MAC-Hour of Anesthetic Delivery

Anesthetic	Carrier gases	CDE_{20} (g/h)	Ratio N_2O/O_2: air/O_2
Sevoflurane			
0.8%	60% N_2O/40% O_2	40,940	
2.0%	Air/O_2	6980	5.9:1
Isoflurane			
0.5%	60% N_2O/40% O_2	44,610	
1.2%	Air/O_2	15,551	2.9:1
Desflurane			
2.4%	60% N_2O/40% O_2	113,022	
6.0%	Air/O_2	187,186	0.6:1

N_2O = nitrous oxide; CDE_{20} = 20-year carbon dioxide equivalent of inhaled drug with air/oxygen (O_2) or inhaled drug + N_2O.

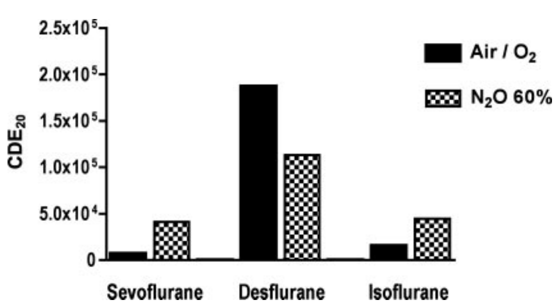

Figure 3. One hour of inhaled anesthetic, delivered with air/oxygen (O_2) or 60% nitrous oxide (N_2O) adjusted to deliver 1 MAC-hour anesthetic at 2 L fresh gas flow. CDE_{20} = 20-year carbon dioxide equivalent (in grams).

Typically, during the bulk of a case, FGFs are kept relatively low. Figure 2 shows the relative global warming impact for cumulative use over 8 hours of delivery of each of the 3 anesthetics at common clinical FGF rates of 2 L/min for sevoflurane and l L/min for both isoflurane and desflurane. Sevoflurane and isoflurane are approximately equivalent and have lower cumulative CDE_{20} totals than desflurane. The difference between 8 hours of sevoflurane and desflurane use is 692,904 CDE_{20} units, or grams CO_2.

Because potent inhaled anesthetics are often delivered with N_2O as a carrier gas, a comparison of the CDE_{20} values of each anesthetic with and without N_2O is shown in Table 3. The relative impact of adding 60% N_2O, and adjusting for 1 MAC of each volatile anesthetic at 2 L FGF is illustrated in Figure 3. For 1 MAC-hour and 2 L FGF, the use of N_2O increases the global warming impact of sevoflurane 590%, the impact of isoflurane 290%, but decreases the global warming impact of desflurane by 40%. The lowest CDE_{20} possible for desflurane is produced with N_2O at 0.5 L FGF; however, this would still be approximately 4 or 7 times greater than using either sevoflurane or isoflurane, respectively, at 1 MAC in air/O_2.

The above results are based on a 20-year time horizon, which is approximately twice the lifetime of the longest lived of the considered potent inhaled anesthetics, desflurane, and thus describes most of the potent inhaled anesthetics' contribution. However, limiting the time frame to 20 years will underestimate the impact of N_2O. Considering a 100-year time horizon (see values in online supplemental material [http://links.lww.com/AA/A150]) instead of a 20-year horizon will not change the CDE ratios for isoflurane compared with sevoflurane carried in air/O_2. For desflurane compared with sevoflurane carried in air/O_2, the CDE ratios will increase only by 16%. However, for anesthetics delivered with N_2O as a carrier gas, the situation is somewhat different. Figure 4 illustrates the relative impact of adding 60% N_2O, and adjusting for 1 MAC of each volatile anesthetic at 2 L FGF for the 100-year time horizon. N_2O has an atmospheric lifetime of 114 years and a GWP_{100} of 298, which is slightly higher than its GWP_{20}.[9] On a 100-year time horizon, the CDE_{100} contribution from N_2O will therefore completely overshadow that of sevoflurane and isoflurane, and equal that of desflurane. The largest difference will be for the shortest-lived anesthetic, sevoflurane, for which the ratio of CDEs with and without N_2O increases from 5.9:1 (CDE_{20}) to 19:1 (CDE_{100}). In addition, although adding N_2O to desflurane lessens the impact of desflurane when viewed with a 20-year time horizon, this apparent improvement has disappeared at the 100-year time horizon (CDE_{100} ratio of 0.99:1).

DISCUSSION

In this study, we derived GWPs, then quantified and compared the global warming impact of inhaled anesthetics within the framework of common clinical anesthesia practice. These calculations illustrate that inhaled anesthetics are contributory greenhouse gases in clinical use, and they vary substantially in their contribution by drug and by

FGF rate. Desflurane has a significantly larger global warming impact compared with sevoflurane or isoflurane, particularly at higher FGF rates or longer delivery times. Sevoflurane and isoflurane are similar to one another, and the gas with the lowest environmental impact depends on FGF rate. N_2O alone, delivered as a carrier gas for volatile anesthetics or as a supplemental anesthetic with IV drugs, can have a relatively large impact. Furthermore, N_2O significantly increases the global warming impact of the combined anesthetic with sevoflurane or isoflurane, but decreases the 20-year impact when combined with desflurane. However, the magnitude of this environmental offset is somewhat deceptive because the full impact of N_2O is only realized on a longer time horizon. Additionally, N_2O, unlike the currently available potent inhaled anesthetics, is destructive to the ozone layer.[15,17] Thus, use of N_2O does not necessarily constitute an environmentally sound tradeoff for the high impact of desflurane and actually contributes an additional type of environmental harm when used with any of these 3 inhaled anesthetics.

This article presents both chemistry data/calculations and anesthetic calculations, each of which has their limitations. The limitations of GWP calculations are essentially governed by available information on the rate constant for the atmospheric degradation reaction by OH radicals. The infrared absorption cross-sections are thought to be accurate within 5%, whereas the atmospheric lifetimes of trace gases are rarely known within better than 25%. This is primarily attributable to uncertainty in the experimental rate constants for reaction between the OH radical and the trace gases. This is also the case with the anesthetics under investigation here. A 25% increase/decrease in the rate constant will result in approximately a 20% decrease/33% increase in the estimated atmospheric lifetimes, and a similar 20% decrease/33% increase in GWP_{20} for sevoflurane. For desflurane, which has a longer atmospheric lifetime, GWP_{20} is less sensitive to a 25% increase/decrease in the OH reaction rate constant and will only result in a 14% decrease/19% increase in GWP_{20}. This degree of uncertainty does not alter the conclusions regarding relative global warming impact of the inhaled anesthetics in clinical practice.

Furthermore, although other measures of GWP appear in both the chemistry and anesthesia literature for some of the anesthetics, methodologies have been inconsistent or incomplete, making comparisons highly questionable. The methodology used in this study is, first, based on experimental results, not estimates. Second, a time horizon is always specified, and third, more representative atmospheric conditions that recognize the enhanced infrared absorption associated with clouds ("cloudy sky conditions") are considered (see online supplemental material for more details [http://links.lww.com/AA/A150]). The articles by Brown et al.[1] and Langbein et al.[2] (and the only article in the anesthesia literature) contain estimates of GWPs in some cases rather than GWPs based on experimental data, do not specify time horizons, and do not consider atmospheric conditions. Neither of these articles' results can be compared with our numbers or similar numbers from IPCC reports, and neither is included in reviews of the atmospheric chemistry literature. The IPCC 2007 report[15] contains values that are relatively close to the values in this study (GWP_{20} = 1100 for isoflurane and GWP_{20} = 3100 for desflurane[18]); however, both numbers are derived assuming atmospheric lifetimes that are too short. In addition, the desflurane value is calculated for "clear sky conditions" (<5% cloud cover). For desflurane, Oyaro et al.[3] used the same methodology as our study, with only a slight adjustment in lifetime accounting for the GWP_{20} difference between 3766 (Oyaro et al.) and 3714 (this study). There are no values in the literature from similar experimental methods for sevoflurane.

The anesthetic calculations ignore metabolism, degradation, and variable FGF rate that occur during a clinical case, because these considerations would have minimal impact on results. There is almost no degradation or metabolism of desflurane[5] and it is minimal for isoflurane.[4] Degradation of sevoflurane, although minimal, may depend on the particular CO_2 absorbent used[7]; metabolism of sevoflurane ranges in studies between 2% and 5%.[4,6,19] The general relationships of these anesthetics to one another and their approximate global warming impact can still be informative and relatively accurate without including these variables.

Because the amount of anesthetic released into the atmosphere is quantified as CDEs expressed in grams, comparisons can extend beyond anesthetic gases. CO_2 burden is a very common comparison for many energy-consuming or climate-related processes, and these calculations could be applied to an overall anesthesia or operating room carbon footprint. Langbein et al.[2] concluded that the influence of inhaled anesthetics on global warming was small, based on 1980s anesthetic use patterns and unclear GWP numbers. However, in the last 30 years, the commercial market for inhaled anesthetics has continued to expand and the predominant drugs have changed. This expanded use along with newer, more clearly specified experimental methods for deriving warming potentials of anesthetics have placed them as greater contributors. Worldwide yearly sales of inhaled anesthetics total in the millions of liters, given that a busy midsize United States (US) hospital might purchase >1000 L of inhaled anesthetic per year.§ Assuming an average 4.78 metric tons of CO_2 emissions/passenger car/year in the US,[20] this would be the equivalent of approximately 100 to 1200 passenger car emissions/year/midsized hospital, depending on which inhaled anesthetics were used. In more personal terms, one 8-hour day, or 8 MAC-hours of desflurane delivery at 1 to 2 L FGF would equal 58 to 116 days of average auto emissions, whereas 8 MAC-hours of sevoflurane (2 L FGF) or isoflurane (1–2 L FGF) would equal about 4.3 or 4.8–9.6 days of auto emissions, respectively. On an hourly basis for the same FGFs (given the US average of 398 g/mile CO_2 emissions) using desflurane equates with driving 235 to 470 miles per hour of anesthetic use, whereas sevoflurane and isoflurane equate with driving 18 and 20–40 miles per hour of anesthetic use, respectively. In the European Union, passenger cars currently emit an average 160 g/km[21] (as opposed to 249 g/km in the US); thus, in the European Union, desflurane equates with

§University of California, San Francisco, with 28 active operating rooms and multiple off-site anesthesia delivery locations, purchased approximately 1270 L of inhaled anesthetic in 1 year.

driving 375 to 750 km per hour of anesthetic use, whereas sevoflurane or isoflurane equate with driving 28 or 31–62 km per hour of use, respectively.

Although we have provided a "yardstick" by comparing anesthetic emissions with auto emissions (a comparison can be made with any type of quantified CO_2 emissions), we have not tried to quantify the worldwide or US anesthetic contribution to the total global greenhouse gas burden. First, not enough information is available at this point to calculate this accurately. Second, it is tempting, but deceptive, to place single contributors to radiative trapping on an absolute scale because every single component contribution will look incredibly insignificant compared with those of H_2O and CO_2. There are a huge number of individual, group, and industry "environmentally preferable practices" that, each taken alone, do not meet the standard of having a big impact, but as a whole, can make a significant difference. It is our intention to show that in many cases it is possible to reduce the anthropogenic impact on the environment by using simple, knowledge-based decisions.

Overall, results from this study suggest several strategies that anesthesiologists can use to minimize their environmental impact when delivering inhaled anesthetics. First, avoid N_2O as a carrier gas unless there is a clinical reason to prefer it. Second, avoid unnecessarily high FGF rates, particularly when using desflurane. However, what constitutes high FGF rates needs to be defined. The optimal (lowest environmental impact) FGF rate has not been established (of course, higher gas flow rates may be necessary at the beginning of a case, and optimal FGF rate does not refer to this initial time period in a case). It would seem that the lowest FGF possible would be best for the environment, because it would minimize anesthetic use. However, because more CO_2 absorbent is used at very low flow rates (which then contribute to operating room waste), the environmental impact relationship between anesthetic use and energy costs associated with absorbent use would need to be investigated. Absorbents containing sodium hydroxide require special disposal because they are very alkaline (see local disposal requirements) and absorbent containers are generally made of disposable plastic material. To accurately assess the environmental impact of various FGF rates, the amount of absorbent used, disposal, transportation, and landfill costs would need to be examined in CDEs. For now, based on the results of the study, reduction of FGF to 2 L/min with sevoflurane (the lowest in common clinical usage currently) and 0.5 to 1 L/min with desflurane and isoflurane would be the best approximations of ideal FGF rates, unless particular anesthesia machine characteristics dictate higher flows. Newer CO_2 absorbents, such as calcium hydroxide, may allow better acceptance of extended use of sevoflurane at FGF rates <2 L/min in the near future,[22,23] further widening the gap between sevoflurane and desflurane. However, real innovation in the area of decreasing environmental impact and the cost of inhaled anesthetics is currently focused on development of systems that avoid release of anesthetic into the atmosphere and allow gas capture for reuse.[24,25]

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