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REFLECTIONS

The future is now—it's time to rethink the application of the *Global Warming Potential* to anesthesia

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All volatile anesthetic agents are fluorocarbons and variably potent greenhouse gases (GHG).[1] As a chlorofluorocarbon (CFC), isoflurane also has ozone depleting potential (as does nitrous oxide [N_2O]), while sevoflurane and desflurane, being hydrofluorocarbons (HFC), do not.[1] The global emission of HFCs increased 128% from 1990 to 2005 and is projected by 2030 to increase a further 336% compared with 2005 emissions.[2] The Montreal Protocol is an international treaty agreed upon in 1987 with the primary goal to protect the ozone layer and to reverse the ozone hole over Antarctica.[1] While it is being heralded as a major multinational success, since it has led to the phase-out of CFCs[3] and a subsequent slow recovery of the ozone layer, it has led to an increased use of HFCs, which are also very potent GHGs. The 2016 Kigali amendment to the Montreal Protocol further aims to phase-down those HFCs with a high potential for contributing to global warming.[1] Unfortunately, the field of anesthesia finds itself in a unique position where the release of its CFCs and HFCs has actually increased over time.

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What makes inhalational anesthetics potent GHGs?

A gas in the atmosphere becomes a GHG by absorbing and reflecting infrared radiation (IR) from Earth that would otherwise escape into space. Three properties of the gas primarily determine its potency as a GHG[4]:

1. the atmospheric lifetime (AL) of the gas;
2. how much IR it absorbs during its AL; and
3. whether there are naturally occurring chemical species (like water or carbon dioxide [CO_2]) in the atmosphere that would absorb the same wavelength of IR. The fewer naturally occurring species there are, the more potent the GHG.

All three criteria play a role in determining the potential of a gas in the atmosphere to contribute to global warming. Chlorofluorocarbons and HFCs fulfill all three criteria and have global warming potentials ranging into thousands of times as much as CO_2.[1] Volatile anesthetics mainly fulfill the third criterion above, since they absorb IR in what is known as the atmospheric window—a bandwidth of IR in which naturally occurring absorption is very low.[5] Nitrous oxide mainly fulfills the first criterion in having a very long AL.[1]

How do we measure the environmental impact of inhalational anesthetic agents?

The most commonly used metric to do so is the *Global Warming Potential* (GWP). This metric calculates how much heat a gas will trap over a time horizon (TH) compared with a reference gas (which is usually CO_2).[1] The two commonly used THs are 100 years and 20 years (giving the specific metrics of GWP_{100} and GWP_{20}, respectively). A detailed explanation of GWP and how to calculate it can be found in the Electronic Supplementary Material (ESM) eAppendix 1.

The Kyoto Protocol is an international treaty (signed in 2005) that commits its signatories to reducing GHG emissions.[1] Ever since its adoption in the Kyoto Protocol, the GWP_{100} is considered to be the standard metric for comparing GHG. Nevertheless, it is important to note that GWP_{100} was mainly devised to make policy decisions and has some disadvantages when used to compare individual anesthetic agents. There is a high degree of uncertainty associated with the values of the variables used in its formula, especially when calculating the reference gas CO_2.[1] Since then, many publications have discussed the environmental impact of inhalational agents and have measured their impact using the GWP[5-12] at other specific time points to compare and contrast their environmental impact.

Global Warming Potential is usually only considered at a single time point or at the two aforementioned time point(s) and better methods are needed for comparing species with particularly short lifetimes. Shine argues for the sole use of GWP_{100} over GWP_{20}, the latter having been used by some authors.[10] We challenge the argument that one single metric should be used to compare different emissions, and that one "cannot pick and choose to emphasize or de-emphasize their impact". Rather than considering a single metric, examining the impact curves at various time points from one year to 100 years may facilitate understanding of the GWP impact and thus aid in making practice choices. Accordingly, we have calculated the GWP values at time points from 1 to 100 years and have plotted the values along a curve (Fig. 1a). The numerical values can be found in eAppendix 2 in the ESM.

Since GWP compares 1 kg of species with the others, and thus does not represent that inhalational agents are used in clinically different concentrations, we calculated the carbon dioxide equivalency (CDE) for all inhalational agents at different time points at 1 minimum alveolar concentration (MAC) and identical fresh gas flows (FGF) using the method previously reported by Ryan *et al*.[6] The following were used: isoflurane at 1.2% volume percent, sevoflurane at 2%, desflurane at 6%, and N_2O at 66%. Nitrous oxide was calculated in clinically used concentration instead of at 1 MAC (as that would be 104%). We chose a FGF of 0.5 $L{\cdot}min^{-1}$ for all inhalational agents, and assumed a lack of metabolism or other degradation and an uninterrupted delivery of the inhalational anesthetic in steady-state conditions. A FGF of 0.5 $L{\cdot}min^{-1}$ is minimal flow and so represents a baseline impact. This will increase if higher FGFs are used. To know the CDE at various time points, the product of anesthetic usage (g/h) and GWP was obtained and plotted to obtain the graphs. The CDE curve is presented in Fig. 1b and the numerical values are in eAppendix 2 (the formulas used for calculation are in eAppendix 1).

To further compare the CDE between individual species, ratios of CDE were calculated for desflurane, isoflurane, and N_2O compared with sevoflurane. The rationale for using sevoflurane was its lower GWP compared with other agents. The curve with the ratios is shown in Fig. 2. From the curves, it is apparent that GWP values for sevoflurane and isoflurane are very close and look to have approximately similar impact over time, while desflurane has by far the largest impact of all inhalational agents (Fig. 1a). This is even more apparent when comparing CDE in clinically used dosing (Fig. 1b). Nitrous oxide becomes and remains the second most impactful agent at around ten years. By 20 years, the impact, particularly for sevoflurane and for isoflurane, has dropped off because of the shorter AL. As shown in Fig. 2, the impact of desflurane in relation to sevoflurane increases over time, as is also the case with N_2O. The impact of isoflurane and sevoflurane remain approximately equivalent over time.

The application of GWP to anesthesia

Our calculations show that all volatile anesthetics have maximum environmental impact within their AL and that this impact decreases rapidly over time. This is a typical pattern for what is called a near-term climate forcer (NTCF), which is a climate forcer with an AL of ten years or less. As the only non-volatile inhaled anesthetic, N_2O has an almost constant impact in our calculations because of its long AL. Irrespective of the time frame, desflurane continues to have a higher and prolonged environmental impact in terms of GWP. This becomes even more pronounced when we consider CDE, since desflurane and N_2O are used in much higher concentrations than sevoflurane and isoflurane and have a far longer AL.

When looking at the atmospheric impact of inhalational anesthetics, it is important to apply the concept of flow and of stock pollutants. A flow pollutant has a short lifetime, so if the amount released remains constant, the pollution created will remain constant at the level of release. A stock pollutant has a long lifetime and will thus cumulate with ongoing release. All three volatile agents are flow pollutants. Looking at their 100-year impact is essentially downplaying their impact in the near future. Nitrous oxide has an AL of over 120 years and is a stock pollutant.

While we agree with Shine[10] that GWP_{100} may be suitable to set emission goals for countries under a "basket of gases" approach, we disagree that it should be "the preferred choice" when comparing inhalational anesthetics. The curves of GWP and CDE are better than a single GWP value for understanding the environmental impact of inhaled agents. Using a single GWP value to

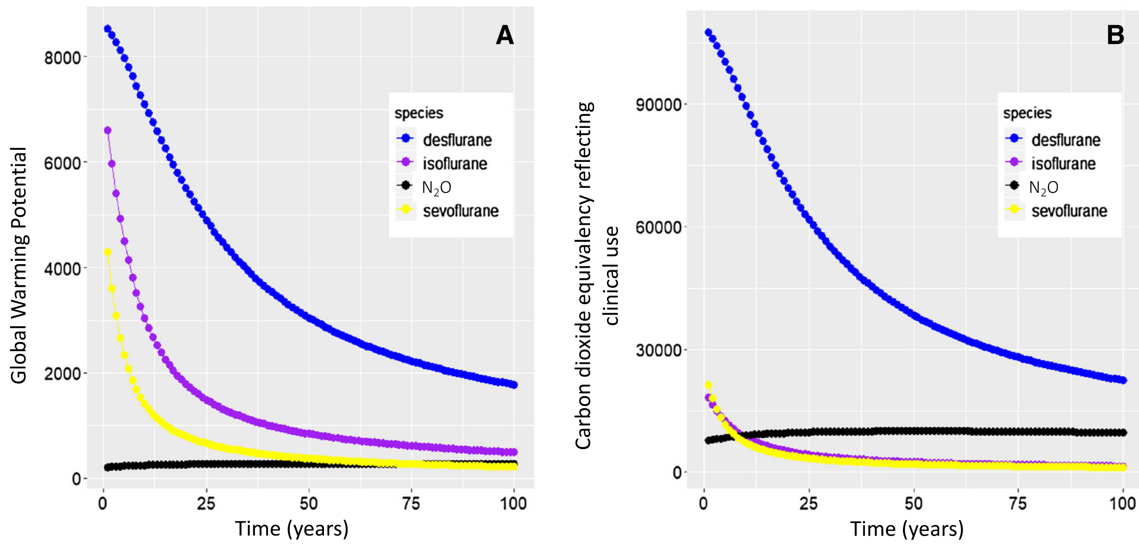
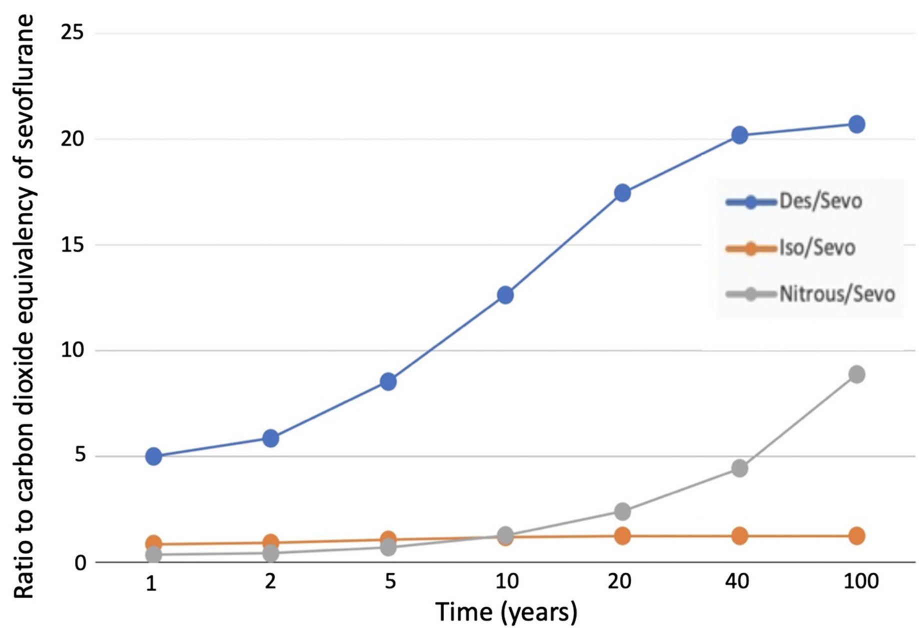


Fig. 1 A) Global Warming Potential of anesthetic gases. B) Carbon dioxide equivalency reflecting clinical use at 0.5 $L \cdot min^{-1}$ fresh gas flow

Fig. 2 Carbon dioxide equivalency ratio of sevoflurane



compare different gases makes everything deceptively convenient, but neglects that this is only a single reference value from a time curve. There is also merit in the different assessment of volatile anesthetics compared with N_2O, since mitigation of NTCF would favourably impact both air quality and climate on a 30-year timescale.[13] While volatile anesthetics do not impact near-term climate as much as other NTCFs such as methane, black carbon, or tropospheric ozone, the projected increases in all HFC may pose a significant GHG burden by the middle of the century.[14]

There are a few additional points to consider when analyzing GWP and hence the CDE. Firstly, the Intergovernmental Panel on Climate Change—which is the United Nations' body for assessing the science related to climate change—estimates approximately 18-26% inaccuracy within GWP, since the absolute GWP of CO_2 in particular is inaccurate because of the many different methods contributing to its atmospheric elimination.[1] Secondly, the numbers used to calculate the GWP of individual gases keep changing with balance shifts of emissions, natural sinks, and new data. Hence the GWP values of all gases are subject to change with time. Thirdly, GWP values are calculated assuming a pulse emission of a gas with a long AL, or when the emission rates remain constant over time for NTCF. For anesthesiologists, the

Table Driving equivalents of inhalational anesthetic agents at different FGFs using GWP_1

Agent*	0.5 L·min^{-1} FGF	1 L·min^{-1} FGF	2 L·min^{-1} FGF
Sevoflurane 2%	783 km	1,566 km	3,132 km
Isoflurane 1.2 %	667 km	1,334 km	2,668 km
Desflurane 6%	3,924 km	7,849 km	15,698 km
Nitrous oxide 66%	279 km	558 km	1,116 km

*Seven hours of use to reflect one day of surgery. FGF = fresh gas flow; GWP_1 = Global Warming Potential at one year

most important thing to consider is to not emit pulses of inhalational anesthetics. Also, there is no foreseeable end to the use of the current anesthetics. The use of volatile anesthetics has steadily increased over the past few decades and this is expected to continue in the coming years[15]—especially in the developing world because access to healthcare is increasing. Thus, with continuous output, anesthesiologists are operating at the front end of the curve: when volatile agents have maximum impact on the climate. If the ultimate goal is to mitigate global warming in the near and intermediate future, anesthesiologists cannot afford to consider GWP_{100} values, which apply only to the future and consider only the residual effect of a species long since eliminated. The GWP_{20} and GWP_{100} numbers will gain relevance only when current inhalational anesthetic agents have been discontinued. If anesthesiologists use the GWP metric for comparison or for quantification, they should use GWP for one year (GWP_1).

To illustrate the impact of inhalational agents, various authors have calculated driving equivalencies using either GWP_{20} or GWP_{100} values.[7,16-18] The Table is a calculation of driving equivalencies for one day's use (i.e., seven hours of anesthetic delivery) of inhalational agents used at 1 MAC (though with N_2O at 66%) and variable FGF; GWP_1 was used for the calculations. Desflurane used at 2 L·min^{-1} FGF for seven hours has the same impact as driving a car from the northernmost point of continental Europe accessible by car (North Cape, Norway) to the southernmost city in Africa (Cape Town, South Africa)—a 211-hr drive (according to Google Maps).

While most of the world has agreed to cut down the usage of HFC via the Kigali Agreement, such a goal will be difficult to achieve for the specialty of anesthesia until non-greenhouse alternatives can be adopted to practice. Hence, it may be wise to adopt the use of an anesthetic agent with the least environmental impact, currently sevoflurane or isoflurane (as easily shown through our calculations). Sevoflurane and isoflurane also have the shortest AL, which makes them better suited as flow pollutants.

While GWP_{100} was developed as a metric for making policy decisions, it does not help anesthesiologists understand the true impact of inhalational anesthetics. This is why we believe it is important to shift the focus away from a single metric at a single time to considering what inhalational agents do at different time points over a longer period of time. When using an inhalational agent intraoperatively, the consideration should not be "what will this mean to the planet in 100 years?" Instead, the consideration should be the strongest impact and not the impact when it starts to reduce. As a physician body, anesthesiologists can also advocate for mandatory reporting on the use of inhalational agents. A method to control the release of GHG into the atmosphere is the two-pronged (or two-basket) approach.[19,20] It proposes to set a cumulative emissions limit for long-lived gases as well as a maximum future rate of emissions for short-lived gases. This is perfectly applicable to anesthesia, since all inhalational agents belong in one of the two categories.

Our tables and graphs can help anesthesiologists make conscious decisions for or against the use of individual inhalational anesthetics in practice. As a specialty, we have to advocate for industry to continue to search for anesthetics with minimal to no environmental footprint such as xenon.[21] By choosing anesthetic agents with short-term impact such as sevoflurane and isoflurane over those with intermediate-term or long-term impact like desflurane and N_2O respectively, we can ensure a rapidly declining impact of our specialty on the environment until no-impact alternatives are available.

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