




A call for immediate climate action in anesthesiology: routine use of minimal or metabolic fresh gas flow reduces our ecological footprint

Appel à une action climatique immédiate en anesthésiologie : le recours systématique à un débit minimal ou métabolique de gaz frais réduit notre empreinte écologique

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Abstract

Purpose Climate change is a global threat, and inhalational anesthetics contribute to global warming by altering the photophysical properties of the atmosphere. On a global perspective, there is a fundamental need to reduce perioperative morbidity and mortality and to provide safe anesthesia. Thus, inhalational anesthetics will remain a significant source of emissions in the

foreseeable future. It is, therefore, necessary to develop and implement strategies to minimize the consumption of inhalational anesthetics to reduce the ecological footprint of inhalational anesthesia.

Source We have integrated recent findings concerning climate change, characteristics of established inhalational anesthetics, complex simulative calculations, and clinical expertise to propose a practical and safe strategy to practice ecologically responsible anesthesia using inhalational anesthetics.

Principal findings Comparing the global warming potential of inhalational anesthetics, desflurane is about 20 times more potent than sevoflurane and five times more potent than isoflurane. Balanced anesthesia using low or minimal fresh gas flow ($\leq 1 \text{ L} \cdot \text{min}^{-1}$) during the wash-in period and metabolic fresh gas flow ($0.35 \text{ L} \cdot \text{min}^{-1}$) during steady-state maintenance reduces CO_2 emissions and costs by approximately 50%. Total intravenous anesthesia and locoregional anesthesia represent further options for lowering greenhouse gas emissions.

Conclusion Responsible anesthetic management choices should prioritize patient safety and consider all available options. If inhalational anesthesia is chosen, the use of minimal or metabolic fresh gas flow reduces the consumption of inhalational anesthetics significantly. Nitrous oxide should be avoided entirely as it contributes to depletion of the ozone layer, and desflurane should only be used in justified exceptional cases.


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Résumé

Objectif Les changements climatiques constituent une menace mondiale et les anesthésiques volatils contribuent

au réchauffement climatique en modifiant les propriétés photophysiques de l'atmosphère. Dans une perspective mondiale, il est fondamentalement nécessaire de réduire la morbidité et la mortalité périopératoires et de procurer une anesthésie sécuritaire. Par conséquent, les agents volatils demeureront une source importante d'émissions dans un avenir proche. Il est donc nécessaire d'élaborer et de mettre en œuvre des stratégies pour minimiser la consommation d'anesthésiques volatils afin de réduire l'empreinte écologique de l'anesthésie par inhalation.

Sources Nous avons intégré les découvertes récentes concernant les changements climatiques, les caractéristiques des anesthésiques volatils connus, des calculs de simulation complexes et l'expertise clinique pour proposer une stratégie pratique et sécuritaire pour exercer une anesthésie écologiquement responsable en utilisant des anesthésiques volatils.

Constatations principales En comparant le potentiel de réchauffement planétaire des anesthésiques volatils, le desflurane est environ 20 fois plus puissant que le sévoflurane et cinq fois plus puissant que l'isoflurane. Une anesthésie équilibrée avec un débit de gaz frais faible ou minimal ($\leq 1 \text{ L} \cdot \text{min}^{-1}$) pendant la période de mise en route ('wash-in') et le débit métabolique de gaz frais ($0,35 \text{ L} \cdot \text{min}^{-1}$) pendant le maintien à l'état d'équilibre réduit le CO_2 et les coûts d'environ 50 %. L'anesthésie intraveineuse totale et l'anesthésie locorégionale représentent d'autres options pour réduire les émissions de gaz à effet de serre.

Conclusion Les choix responsables en matière de prise en charge anesthésique devraient accorder la priorité à la sécurité des patients et à l'évaluation de toutes les options disponibles. Si l'anesthésie par inhalation est choisie, l'utilisation d'un débit minimal ou métabolique de gaz frais réduit considérablement la consommation d'anesthésiques volatils. Le protoxyde d'azote doit être complètement évité car il contribue à l'appauvrissement de la couche d'ozone, et le desflurane ne doit être utilisé que dans les cas exceptionnels et justifiés.

Keywords climate change · green anesthesia · greenhouse gas emission · inhalational anesthetics · low-flow anesthesia · nitrous oxide

Climate change is considered to be the greatest challenge to our society and is a global threat.¹ Global environmental changes such as climate change, extreme weather events, loss of biodiversity, and air pollution compromise the health and wellbeing of humans.² The implications on global health are already apparent.³ According to the latest prediction by the World Health Organization, there will be

an additional 25,000 deaths per year between 2030 and 2050.⁴

Consequently, there have been worldwide initiatives by governments, nongovernmental organizations, and individuals to promote or implement specific measures to limit the predicted increase in global temperature to 1.5°C. An imperative for the above should also apply to the health sector whose primary duty is to promote and safeguard health. Paradoxically, this sector is one of the largest global emitters of greenhouse gases, with a share of 4.4%.⁵ Anesthesia and critical care medicine significantly contribute to the enormous release of greenhouse gases due to their highly resource-intensive and high-tech working processes.^{6–8}

As a significant source of emissions in the area of perioperative medicine, inhalational anesthetics contribute to the climate crisis by altering the photophysical properties of the atmosphere.^{9,10} Thus, it is necessary to develop and implement strategies to minimize the ecological footprint of anesthesia. Consequently, numerous anesthesiology societies and bodies have published recommendations in the past few years on how anesthesiologists can make their working area more sustainable and greener.^{7,11–13} A Letter to the Editor in this issue of the *Journal* illustrates one example of such initiatives: therein, He *et al.* report on a Greener Gases Starter Pack that the authors developed as part of the Greener Gases project at McMaster University (Hamilton, ON, Canada).¹⁴

In the present article, we focus on inhalational anesthetics and their impact on global warming and climate change. In this context, we review how the use of minimal and metabolic flow during general anesthesia (GA), subject of a Brief Review in the *Journal* a decade ago, reduces overall consumption of inhalational anesthetics, and contributes to lower emissions of greenhouse gases (GHGs).¹⁵ In addition, we discuss alternative anesthesia techniques along with their life cycles and environmental impacts, such as total intravenous anesthesia (TIVA) and locoregional anesthesia (LRA).^{16,17}

Greenhouse gases and the global warming process

The term “atmosphere” refers to the totality of all layers that surround our Earth's surface as a gaseous envelope. In total, the atmosphere is divided into five different layers. For the purpose of the present discussion on the processes of global warming, we will focus on the following three layers: 1) the troposphere, up to 10,000 km; 2) the stratosphere, between 10,000 and 50,000 km; and 3) the mesosphere, beyond 50,000 km.

The GHGs defined and regulated by the Kyoto Protocol 1997 are carbon dioxide (CO_2); methane (CH_4); nitrous oxide (N_2O); and fluorinated gases such as hydroxyfluorocarbon (HFC), perfluorocarbon (PFC), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3).

Among the fluorinated gases are also the commonly used inhalational anesthetics desflurane, isoflurane, and sevoflurane. The global warming potential (GWP) of GHGs represents a common unit to measure absorption of energy in a defined period of time. Thus, it enables a comparison of the greenhouse potential of different gases. In general, the time period is set to 100 years. By definition, CO₂ has a GWP of 1. In addition to the radiative effectiveness, the atmospheric lifetime is a second important determinant that influences GWP.^{18,19}

In the atmosphere, natural concentrations of GHGs, clouds, water vapor, and other compounds adsorb and reflect incoming solar radiation back to space as well as outgoing infrared (IR) radiation back to the Earth. The equilibrium of incoming solar radiation and reflection as well as outgoing long wave IR radiation and IR reradiation creates and maintains appropriate living conditions on our planet.

A range of wavelengths through which electromagnetic radiation can pass the atmosphere back into space is called the atmospheric window. Infrared emission through the atmospheric window ranging from 8 to 14 μm plays an important role in regulating the Earth's temperature. It is relatively transparent for IR as only little absorption by naturally occurring GHG occurs.²⁰ Beyond this spectrum, IR radiation is mainly absorbed and reflected by these GHGs. Unfortunately, inhalational anesthetics absorb mainly within this atmospheric window. Hence, they act as GHGs and influence the Earth's radiative balance by altering the IR radiation back to space. This favors the increase in global temperature.¹⁰

Stratospheric ozone depletion

In the stratosphere, there is a cyclic and constant formation and decomposition of ozone, which creates the ozone layer. The ozone layer absorbs ultraviolet (UV) radiation and protects plants, animals, and humans from increased and deleterious UV-B-radiation. This ozone can chemically be destroyed by reactive gases containing halogens such as chlorine and bromine. Halogen source gases are emitted at the surface and convert to reactive halogen gases by strong UV radiation in the stratosphere. In a catalytic cycle reaction, they initiate the breakdown of ozone and are reformed each time. Due to its extreme stability, one chlorine atom can thereby destroy thousands of ozone molecules before it is inactivated.²¹

Studies have shown that the depletion of stratospheric ozone changes the temperature in the southern troposphere. The resulting stronger winds heighten the ventilation of deep ocean water, increasing the surface water concentration of CO₂. This mechanism limits the oceans' capacity to take up and store further CO₂ emissions and, in

addition, increases the acidification of oceans, which has a negative impact on marine biodiversity.²²

Tropospheric nitrous oxide cycle

In the troposphere, there is a cycle of decomposition and formation of ozone catalyzed by nitrous oxides. The cycle is influenced towards increased formation of ozone by increasing emission of carbon monoxide (CO), N₂O, and other volatile organic compounds. Increasing the concentration of ozone in the troposphere contributes to the greenhouse effect. Thus, from anesthetic HFCs to N₂O, anesthetic procedures can and do contribute to anthropogenic climate change on multiple levels.

“Green” inhalational anesthesia

The health and wellbeing of patients does not depend solely on the quality of health services but also on the condition of the Earth's ecosystem. Nowadays, anesthesiologists are also challenged to consider ecological and sustainable aspects while promoting the health of their patients such as when deciding on the best way to administer GA.

General anesthesia and the choice of inhalational anesthetics

General anesthesia can either be provided as inhalational anesthesia, balanced anesthesia, or TIVA. While TIVA typically is based on a continuous intravenous application of propofol, inhalational anesthesia is delivered using an inhalational anesthetic for induction as well as for maintenance. Balanced GA is delivered using an intravenous hypnotic for induction, and maintained with a volatile inhalational agent such as sevoflurane, desflurane, isoflurane, or halothane, with or without N₂O as a carrier gas.

In a 2012 French study, 72% of anesthesiologists performed GA as a combination of intravenous induction and either desflurane (48%) or sevoflurane (24%). Total intravenous anesthesia was only performed in 17% of the cases. In 8% of cases, the induction technique was not specified, and in 2% of cases, an inhalational induction was performed.²³ In contrast, in a 2013 Scandinavian study, only 48.9% of anesthesiologists performed GA maintained with inhalational anesthetics, whereas 51.1% performed TIVA. In 11.9% of these GAs, N₂O was used as carrier gas or coanalgesic.²⁴

A 2019 environmental survey by the American Society of Anesthesiologists' Committee on Equipment and

Facilities found that sevoflurane was chosen by 66.4% of participating anesthesiologists (1,215/1,829; 95% confidence interval [CI], 64.2 to 68.6), whereas desflurane was chosen by 22.3% (408/1,829; 95% CI, 20.4 to 24.3).²⁵

Inhalational anesthetics and their characteristics

Isoflurane, sevoflurane, and desflurane are halogenated ethers containing an oxygen atom that connects two fluorinated alkyl groups. Containing chlorine, isoflurane belongs to the chlorofluorocarbons (CFCs).^{26–29} These volatile inhalational anesthetics are liquid at room temperature and act through modulation of various membrane-associated proteins. For example, they amplify inhibitory postsynaptic potentials of γ -gamma-aminobutyric acid type A (GABA_A) and glycine receptors, and decrease N-methyl-D-aspartate (NMDA) and α -amino-3-hydroxy-5-methyl-4-isoxazolepropionic acid (AMPA)-related excitatory postsynaptic potentials.^{30,31} Furthermore, they bind to nicotinic acetylcholine receptors, blocking the channel pore. By perturbing lipid rafts of cell membranes, they activate phospholipase D2. Consecutive activation of two-pore domain K⁺ channels causes reversible loss of consciousness.³² Nitrous oxide, in turn, is a colorless nonflammable gas that stimulates cerebral GABA receptors and inhibits spinal NMDA receptors.³³

Inhalational anesthetics and their environmental impact

In addition to the clinical and pharmacological properties of inhalational anesthetics, it has become increasingly evident that their environmental toxicity and sustainability characteristics have to be considered as well. In 2014, inhalational anesthetics accounted for worldwide emission of approximately 3 Mt CO₂e. Regarding N₂O, anthropogenic sources contributed 43% of the total N₂O emission of about 7.3 Tg per year, 1–4% of which originated from medical sources.^{20,34} Currently, inhalational anesthetics are emitted directly and unchanged from anesthesia machine-scavenging systems

into the atmosphere. They influence the radiation balance of the Earth's atmosphere negatively by intensifying IR absorption in the IR atmospheric window, affecting terrestrial regulation of temperature. In fact, they impede heat release back into space not only within but also outside the atmospheric window.⁶ The extent of this detrimental effect largely depends on molecular weight, specific type of halogen, and its atmospheric lifetime (Table 1).³⁵

As stated above, isoflurane is a CFC. Chlorofluorocarbons as well as N₂O (cf. above) contribute to ozone depletion in the stratosphere.¹⁰ In contrast, desflurane and sevoflurane have no ozone-depleting effect because of their complete fluorination.³⁶ Nevertheless, comparing the GWP of inhalational anesthetics, desflurane is about 20 times more potent than sevoflurane and five times more potent than isoflurane.

The GWP of inhalational gases is determined by their atmospheric lifetime and their effectiveness at absorbing and emitting IR radiation, called “radiative efficiency.” The high GWP of desflurane is mainly due to its longer atmospheric lifetime of 14 years compared with 3.2 years for isoflurane and 1.1 years for sevoflurane. Additionally, desflurane has the highest radiative efficiency.¹⁹ It is important to notice that desflurane has a higher minimum alveolar concentration at 1 atm required to prevent 50% of subjects from moving in response to a noxious stimulus (MAC₅₀) than sevoflurane and isoflurane (6.6 vol% vs 1.8 vol% and 1.2 vol%, respectively).³⁷ Thus, higher concentrations are required to deliver the same clinical effect.³⁸ In 2014, desflurane accounted for 80% of the CO₂e emission related to inhalational anesthetics.⁶

To assess the life-cycle GHG emissions of inhalational anesthetics, it is important to consider the waste anesthetic gas emissions as well as the upstream environmental impact including manufacturing, transportation, packing, and drug delivery.^{16,39} Desflurane has not only the highest waste anesthetics gas emissions but also the largest nonwaste anesthetics gas emissions. The comparatively high emissions are mainly caused by manufacturing processes and electricity for volatilization during drug delivery.³⁹ As shown by Richter *et al.*, reduced use of desflurane in clinical practice significantly decreases the

Table 1 Environmental characteristics of inhalational anesthetics^{10,38}

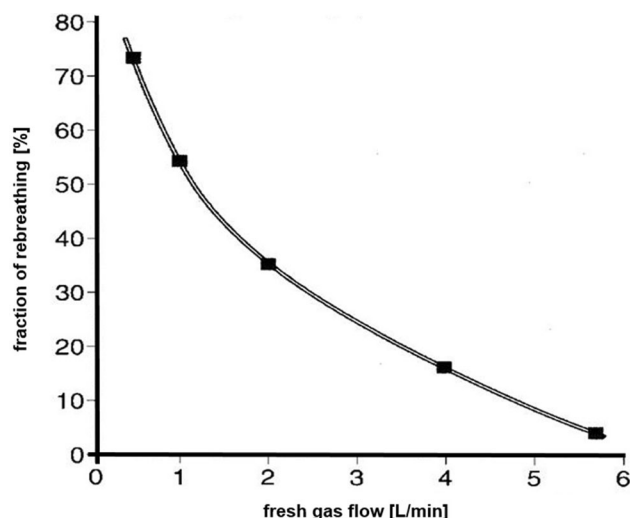
	Isoflurane	Sevoflurane	Desflurane	Nitrous oxide
Lifetime (yr)	3.2	1.1	14	114
GWP100	510	130	2,540	300
GWP20	1,800	440	6,810	290

GWP100 = 100-year global warming potential; GWP20 = 20-year global warming potential

Table 2 Classification of anesthesia according to fresh gas flow for a 40-yr-old, 80-kg male patient

FGF	Classification
> 1.0 L·min ⁻¹	High flow
1.0 L·min ⁻¹	Low flow ⁴⁰
0.5 L·min ⁻¹	Minimal flow ⁴¹
0.35 L·min ⁻¹	Metabolic flow
= $\dot{V}O_2$ (L·min ⁻¹)	Quantitative ^{42,43}

FGF = fresh gas flow; $\dot{V}O_2$ = total consumption of oxygen in L·min⁻¹

**Fig. 1** Fraction of rebreathing (in %) depending on fresh gas flow (modified from Baum⁴⁵ in Hoenemann & Mierke⁴⁶)

emission of CO₂e due to waste anesthetics gas emissions.⁴⁰ In contrast, a compensatory increase of isoflurane consumption should be avoided as it contributes to ozone depletion in the stratosphere and, therefore, counterbalances the positive effect.¹⁰

Making responsible choices with regard to the use of inhalational anesthetics during GA represents a cost-effective and quickly implementable strategy for reducing the CO₂e footprint of anesthesia practice.¹⁸

Low-, minimal-, and metabolic flow anesthesia

According to Baum,⁴⁵ low-, minimal-, and metabolic flow anesthesia is defined by the part of rebreathing and not the absolute level of fresh gas flow (FGF) (Table 2^{41–44}). With decreasing FGF, rebreathing fraction increases (Fig. 1).^{45,46} The part of rebreathing depends on the oxygen consumption ($\dot{V}O_2$) of the patient, FGF, and the volume of the anesthesia workstation's circle system. Oxygen consumption can either be calculated using Fick's formula if cardiac output (CO, in L·min⁻¹) and arterial and venous

oxygen content are known, or it can be estimated using Brody's formula.^{47,48} Accordingly, a healthy 40-yr-old, 80-kg male patient with normal CO consumes about 260 mL oxygen per minute. Contemporary anesthesia machines calculate and display patients' real-time $\dot{V}O_2$ based on the partial pressure differences of inspiratory and expiratory oxygen. Therefore, FGF can be decreased to $\dot{V}O_2$ to reduce waste anesthetic gas to a minimum and to save inhalational anesthetics as well as medical gases.

Contemporary anesthesia workstations with target-controlled concentrations of inspired oxygen and expiratory inhalational anesthetic allow for quantitative anesthesia in a closed-circuit system.⁴³ Switching from conventional fresh gas mode to an electronically controlled mode such as “auto control” (Zeus IE®, Drägerwerk AG & Co. KGaA, Lübeck, Germany), “end-tidal control” (Aisys CS²®, General Electric Company, Boston, MA, USA), or “automated gas control” (FLOW-i®, Maquet, Solna, Sweden) is associated with lower consumption of inhalational anesthetics, costs, and GHG emissions.⁴⁹

In general, anesthesia systems and their components can be safely used with FGFs ≤ 1 L·min⁻¹ under the following conditions: 1) little systemic leakage; 2) mandatory measurement of inspiratory and expiratory concentration of oxygen, carbon dioxide, and inhalational anesthetics; and 3) presence of an integrated carbon dioxide absorber. It is important to prevent accidental dry-out of the carbon dioxide absorber and to use it according to the manufacturers' instructions and recommendations.⁵⁰

Intraoperative consumption of inhalational anesthetics

The overall consumption of inhalational anesthetics depends on several factors such as patient age, individual agent MAC₅₀, duration of wash-in and wash-out periods, and time from incision to suture.

WASH-IN

After intravenous induction and airway establishment, the inhalational anesthetic is washed in. Kim *et al.* showed that after application of an *iv* induction dose of 2 mg·kg⁻¹ of propofol, depth of anesthesia is maintained for approximately nine to 11 minutes for stand-alone administration of propofol.⁵¹ Nevertheless, as GA is typically induced combining propofol with an intravenous analgesic drug (e.g., an opioid), the additive effects must be taken into account. The validated noxious stimulation response index (NSRI) can be used to predict the probability of responding to a noxious stimulus considering interactions between hypnotic and opioid.^{52,53}

Prediction tools and previews such as SmartPilot View® (Drägerwerk AG & Co. KGaA, Lübeck, Germany) rely on

Table 3 Consumption, global warming potential, and costs of inhalational anesthetics depending on different fresh gas flows during the wash-in period simulating a male 40-yr-old, 80-kg patient using a Primus IE® (Drägerwerk AG & Co. KgaA, Lübeck, Germany) with a total breathing system volume of 8.0 L

Inhalational anesthetic FGF (L·min ⁻¹)	Desflurane				Sevoflurane			
	4.0	1.0	0.5	0.35	4.0	1.0	0.5	0.35
Time to 1.0 MAC ₅₀ (min)	7.72	8.37	18.92	31.53	9.92	8.37	20.47	38.47
Consumption (mL)	13.18	7.21	8.1	9.51	7.59	3.66	4.48	5.89
CO ₂ e (g)	49.04	26.83	30.14	35.39	1.5	0.72	0.89	1.17
CO ₂ e (g·min ⁻¹)	6.3	3.2	1.59	1.12	0.15	0.08	0.04	0.03
Cost (EUR)	4.22	2.31	2.59	3.04	1.82	0.88	1.08	1.41
Cost per minute GA (EUR·min ⁻¹)	0.55	0.28	0.14	0.10	0.18	0.10	0.05	0.04

Simulation was performed with GasMan® (Med Man Simulations Inc., Chestnut Hill, MA, USA).⁵⁴ The emitted CO₂e values were calculated according to Ryan *et al.* by using the latest GWP100 values of the inhalational anesthetics and for 1 MAC hour.^{10,38} A correction factor of 5% was used for sevoflurane due to hepatic metabolism. The average costs per mL of inhalational anesthetic (desflurane: EUR 0.32 and sevoflurane: EUR 0.24) were calculated based on the mean purchase price of three different and independent German hospitals.

FGF = fresh gas flow; GA = general anesthesia; GWP100 = 100-year global warming potential; MAC = minimum alveolar concentration

Table 4 Consumption of inhalational anesthetics during a steady state of 120 min at different fresh gas flows simulating a male 40-yr-old, 80-kg patient using a Primus IE® anesthesia machine (Drägerwerk AG & Co. KgaA, Lübeck, Germany) with a total breathing system volume of 8.0 L

FGF (L·min ⁻¹)	Desflurane				Sevoflurane			
	2.0	1.0	0.5	0.35	2.0	1.0	0.5	0.35
Consumption (mL)	84.85	48.08	29.47	24.28	39.45	24.02	16.14	13.8
CO ₂ e (g)	315.74	178.91	109.66	90.35	7.8	4.75	3.19	2.73
CO ₂ e (g·min ⁻¹)	2.63	1.49	0.91	0.75	0.07	0.04	0.03	0.02
Cost (EUR)	27.04	15.39	9.43	7.77	9.47	5.76	3.87	3.31
Cost per minute GA (EUR·min ⁻¹)	0.23	0.13	0.08	0.06	0.08	0.05	0.03	0.03

Simulation was performed with GasMan® (Med Man Simulations Inc., Chestnut Hill, MA, USA).⁵⁴ The emitted CO₂e was calculated according to Ryan *et al.* using the latest GWP100 values of the inhalational anesthetics and for 1 MAC hour.^{10,38} A correction factor of 5% was used for sevoflurane because of hepatic metabolism. The average costs per mL inhalational anesthetic (desflurane: EUR 0.32 and sevoflurane: EUR 0.24) were calculated based on the mean purchase price of three different and independent German hospitals.

FGF = fresh gas flow; GA = general anesthesia; GWP100 = 100-year global warming potential; MAC = minimum alveolar concentration

validated concepts such as MAC or NSRI. They can facilitate anesthesiologic management as they visualize synergistic effects of inhalational anesthetics, intravenous hypnotics, and analgesics.

Clinical experience suggests that for desflurane, an FGF of approximately 0.7 L·min⁻¹ with the vaporizer set to 18%, and for sevoflurane, a FGF of 0.5 L·min⁻¹ with the vaporizer set to 8% appear to be sufficient to maintain adequate depth of anesthesia during the wash-in period. Decreasing FGF during the wash-in period helps prevent unnecessary deep anesthesia and reduces the consumption of inhalational anesthetics. For both inhalational anesthetics, a decrease of FGF from 4 to 1 L·min⁻¹ decreases the consumption of inhalational anesthetic by

45.3% (desflurane) and 51.8% (sevoflurane), respectively. Consecutively, there is also a significant reduction by approximately 45–50% of CO₂e emission and costs per minute GA (Table 3).⁵⁴

STEADY STATE

After initial wash-in of inhalational anesthetic, at a MAC₅₀ of 0.7 to 1.0, a steady state is reached.

Anesthesia with an FGF ≤ 1 L·min⁻¹ does not only effectively maintain intraoperative conditioning (i.e., heating and moisturizing) of inspired gases⁵⁵ but also saves inhalational anesthetics. The following calculation shows the FGF-dependent consumption of sevoflurane and

Table 5 Ecological impact of inhalation anesthesia with nitrous oxide as carrier gas compared with inhalation anesthesia with only O₂ as carrier gas (-N₂O)

	Desflurane		Isoflurane		Sevoflurane	
Carrier gases	60% N ₂ O/40% O ₂	100% O ₂	60% N ₂ O/40% O ₂	100% O ₂	60% N ₂ O/40% O ₂	100% O ₂
Vaporizer setting	2.4%	6.6%	0.5%	1.2%	0.8%	2.0%
CO ₂ e (g·hr ⁻¹) 100	45,403	70,409	20,976	2,823	20,294	1,235
Ratio +N ₂ O/-N ₂ O	0.65	-	7.4	-	16.4	-

A +N₂O/-N₂O ratio less than 1 implies that the use of N₂O as a carrier gas reduces the emitted CO₂e. The emitted CO₂e values were calculated according to Ryan *et al.* using the latest GWP100 of the inhalation anesthetics and for 1 MAC hour with a fresh gas flow of 1 L·min⁻¹.^{10,38} A correction factor of 5% was used for sevoflurane because of hepatic metabolism. Metabolism is negligible for the other volatile anesthetics.

GWP100 = 100-year global warming potential; MAC = minimum alveolar concentration; +N₂O = inhalation anesthesia with nitrous oxide used as carrier gas; -N₂O = inhalation anesthesia with O₂ only as carrier gas

desflurane during steady state (Table 4). For both inhalational anesthetics, a decrease of FGF from 2 to 0.35 L·min⁻¹ reduces consumption of sevoflurane by 65% and desflurane by 71.4%. This saves approximately 20 EUR^A and 1.1 kg of CO₂e for a two-hour GA.

Routinely reducing fresh gas flow saves inhalational anesthetics, reduces CO₂e emission, and is cost-effective.

WASH-OUT

After completion of surgery, the administration of inhalational anesthetics can be terminated. At this point, there is no significant partial pressure difference between alveolar, blood, and cerebral compartments. To enable effective wash-out of inhalational anesthetics, the inspiratory gases must be cleared from inhalational anesthetics by closing the vapor and increasing the FGF to 4–6 L·min⁻¹. During this period, adequate alveolar ventilation must be ensured, and spontaneous breathing efforts of the patient can be supported until the patient fully recovers.

NITROUS OXIDE AS ADDITIONAL ANESTHETIC

Nitrous oxide has been widely used as a carrier gas during balanced anesthesia, and additionally for analgesia during painful procedures (e.g., in children) or during labor, to address treatment-resistant depression, and as a strategy for preventing chronic postsurgical pain in particular populations.^{39,56,57} Nevertheless, the overall clinical use of N₂O has declined.⁵⁸ Nitrous oxide is emetogenic,⁵⁹

inhibits the methionine synthase irreversibly by inactivating the enzyme's vitamin B₁₂ component, and can cause “diffusion hypoxia.”^{60,61} The ENIGMA-II trial supported the safety of N₂O use in major noncardiac surgery,⁶² but the data remain conflicted.

When N₂O is used as carrier gas instead of oxygen, the end-tidal concentration of halogenated inhalational anesthetics can be decreased, reducing the consumption of inhalational anesthetics.^{39,63} Nevertheless, Baum *et al.* showed that expenses for the use of N₂O—such as technical maintenance for the central gas piping system, antiemetic prophylaxis, and the inhalational anesthetic itself—exceed the additional costs for inhalational anesthetics and intravenous analgesics.^{60,64} Therefore, the reduced consumption of inhalational anesthetics does not result in net savings. Comparing the total CO₂e emission when N₂O is used as a carrier gas, there is a net increase for sevoflurane and isoflurane and a decrease for desflurane (Table 5). Nevertheless, this calculation lacks the negative impact of additional N₂O to the tropospheric nitrous oxide cycle and the resulting ozone-depleting effect.^{39,58}

The renouncement of N₂O as a carrier gas allows for safely performing low-, minimal-, and metabolic flow anesthesia. This enables significant savings of inhalational anesthetics and better conditioning of inspired gases compared with high-flow anesthesia, which is required during the wash-in and wash-out periods if N₂O is used as a carrier gas. Additionally, the negative impact of N₂O on CO₂e emissions and ozone depletion can be prevented.

NEW TECHNOLOGIES TO ABSORB INHALATIONAL ANESTHETICS

The use of technologies for absorbing inhalational anesthetics from the exhausted air represents a future solution to achieve sustainability and to reduce the

^A Based on mean purchase prices of three different and independent German hospitals (cf. Table 4).

ecological footprint of GA.⁶⁵ So far, several different purification systems received a patent grant such as adsorption by charcoal granules or by molecular sieve as well as destruction using gas-phase photochemistry.⁶⁶ For example, Doyle *et al.* showed an effective removal of 1% isoflurane from the exhaled air over a period of eight hours using a silica zeolite hydrophobic molecular sieve adsorbent.⁶⁷ Alternatively, inhalational anesthetics can be destroyed directly by UV light. The advantage of this system is the lack of additional treatment. Since these technologies are currently only used experimentally, further studies and technological development under consideration of ecological aspects are highly needed.⁶⁶ It must be stressed that the efficiency of all these technologies is decreased by the use of high FGFs. Thus, minimal or metabolic flow anesthesia is essential to use these technologies beneficially in the future.⁶⁸

ALTERNATIVES TO INHALATIONAL ANESTHETICS

In addition to the use of technical solutions, the transitions from inhalational anesthesia to alternative techniques such as LRA and TIVA represent another approach to reduce GHG emission.¹¹ Locoregional anesthesia and TIVA can be used equally effectively as inhalational anesthesia if surgery and patient's condition allows it.

Compared with inhalational anesthesia, TIVA reduces the risk of postoperative nausea and vomiting, pain scores after extubation, and duration of in postoperative anesthesia care unit stay; on the other hand, it prolongs the time to respiratory recovery and tracheal extubation.⁶⁹ Nevertheless, performing TIVA instead of inhalational anesthesia has environmental costs of its own because of the increased disposable plastic waste, higher propofol consumption, and consecutively increased wastage rate.^{70,71} Other environmental effects of TIVA are still uncertain.⁷¹ Based on the detection of propofol metabolites in the waste water of hospitals, it is important to stress the aquatic toxicity of propofol.^{70–73} Propofol is excreted almost entirely in its metabolized, inactive form.^{74,75} Thus, it can be assumed that the detected propofol metabolites are primarily caused by improper disposal. Therefore, it is important to implement efficient waste disposal systems before converting to TIVA.

Another alternative to TIVA is LRA. A recent Australian study compared the life-cycle GHG emissions for GA with sevoflurane, spinal anesthesia, and the combination of both during total knee arthroplasty. Interestingly, the carbon footprint was similar for all three anesthetic modalities, albeit determined by several choices. For spinal anesthesia, the emissions were mainly dominated by the electricity consumption for oxygen use and cleaning the reusable equipment. Switching from the

Australian grid (mix mainly dominated by fossil energies) to the European grid (with a larger proportion of renewable energies) decreases the carbon footprint of spinal anesthesia by 40%.⁷⁶ These continental differences stress the importance of defining full life-cycle assessments for different anesthetic approaches in different regions. Future analysis would benefit from datasets for medication synthesis provided by manufacturers.^{17,39}

Strategies for “green” anesthesia

The daily practice of health care professionals is governed by the principle “First, do not harm,” and our first responsibility is to provide safe and effective anesthesia to our patients. Paradoxically, as one of the biggest GHG emitters, health care professionals harm public health.⁵

In the Montreal protocol, the medical use of inhalational anesthetics was declared as “essential” without restrictions. In view of global efforts to reduce the emission of greenhouse and ozone-depleting gases, it can be assumed that inhalational anesthetics will remain a significant source of emissions in the future.^{7,37}

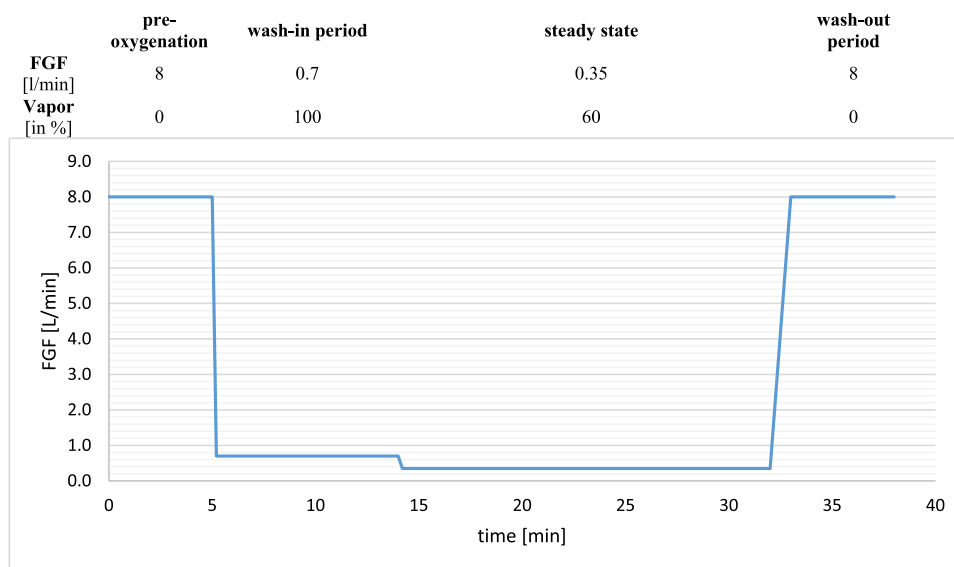
It is important to notice that the health care systems of low- and middle-income countries are confronted with a lack of health care resources and infrastructure, which challenges the provision of safe anesthesia. This lack of resources and infrastructure includes qualified anesthesiologic staff, equipment, and medication as well as basic needs such as continuous medical oxygen, power supply, and clean water.⁷⁷ Moreover, donated equipment cannot be readily maintained and used as expertise and material are missing.⁷⁸ Often, intramuscular application of ketamine or LRA are the only options to perform surgery.⁷⁹ Thus, the perioperative morbidity and mortality rate (PMOR) remains high.⁸⁰

These findings clearly show the global dilemma: paradoxically, high-income countries are challenged to define strategies to reduce anesthesia-related CO₂ emissions, whereas low- and middle-income countries are confronted with the fundamental need to reduce PMOR and simultaneously have to face the consequences of climate change. Nevertheless, on a global perspective, we need to address this gap and it is imperative to develop solutions ensuring safe and sustainable anesthesia in the future.

Responsible choice of inhalational anesthetics

Among the inhalational anesthetics, desflurane has the largest negative ecological impact because of its substantial contribution to radiative forcing. Additionally, high volumes are necessary to maintain GA because of its

Fig. 2 Example of fresh gas flow and vapor setting for “green” metabolic flow general anesthesia



high MAC₅₀ of 6.6%. Therefore, desflurane should be avoided whenever feasible. The responsible choice of inhalational anesthetics during GA, thus, represents a cost-effective and quickly implementable solution to reduce the CO₂e footprint of anesthesia practice.¹⁸

Renouncement of nitrous oxide

Nitrous oxide is a GHG with a long atmospheric lifetime. Accordingly, its use as a carrier gas does not reduce the consumption of inhalational anesthetics except for desflurane. In addition, N₂O contributes a significant amount to ozone depletion. Therefore, N₂O should be avoided entirely as a carrier gas.⁸¹ The use of N₂O as a procedural analgesic should be considered cautiously because of its unfavorable adverse effects, taking into account alternative management including LRA.

Use of minimal or metabolic flow anesthesia

To significantly reduce the consumption of inhalational anesthetics, the lowest FGF applicable should be set. During the wash-in period, we recommend starting with an FGF of 1 L·min⁻¹ until 0.7–1.0 MAC is reached. With increasing clinical experience, the FGF can be reduced further to 0.7–0.5 L·min⁻¹ during the wash-in period. After that, FGF should be reduced to 0.35 L·min⁻¹ until completion of the surgical procedure (Fig. 2). If available, we recommend using target control anesthesia in an automatically controlled mode to reduce FGF and inhalational consumption as much as possible. During GA, disconnections of breathing systems should be avoided to minimize waste of inhalational anesthetics. Prior to the wash-out period, volatile anesthetic administration must be

discontinued and FGF can be increased to 8 L·min⁻¹. We recommend using available prediction tools and previews such as SmartPilot View® (Drägerwerk AG & Co. KGaA, Lübeck, Germany), Navigator Suite (GE Healthcare, Wauwatosa, WI, USA), or Automatic Gas Control (ACG, Maquet GmbH, Getinge Group, Getinge Sweden) to facilitate anesthesiologic management.

Consider alternative anesthesia approaches

The transition to TIVA or LRA represents another alternative to reducing the environmental impact during GA if patient's condition and surgery allow for or favors an alternative anesthesiologic management. The use of TIVA causes additional environmental costs due to propofol and plastic wastage. Nevertheless, the life-cycle carbon emission is lower than in inhalation anesthesia. Life-cycle GHG emissions of LRA mainly depend on the grid mix due to high electricity consumption. In Europe, spinal anesthesia has a smaller ecological footprint than inhalational anesthesia as the European grid mix consists of a larger part of renewable energies. Therefore, it is important to assess the life cycle of anesthesiologic management for different regions to enable a reasonable decision-making process.

Conclusion

Inhalational anesthetics remain essential for safe anesthesia. On a global perspective, it is important to reduce PMOR and anesthesia-related CO₂ emissions at the same time. Responsible anesthetic management choices should prioritize patient safety and consider all available options.

If inhalational anesthesia is chosen, the routine use of minimal or metabolic FGF improves conditioning of inspired gases and reduces the consumption of inhalational anesthetics significantly. In the future, new technologies to absorb and recycle inhalational anesthetics should be implemented to allow for sustainable inhalational anesthesia. Considering the ecological footprint of anesthesia, nitrous oxide should be avoided entirely as it contributes to the depletion of the ozone layer, and desflurane should only be used in justified exceptional cases.

Author contributions Se-Chan Kim and Christian Hönemann designed this review and its main conceptual ideas, Yvonne Dietzler, Miriam Kropf, and Birgit Bette provided measurements and data, Philippe Kruse performed the ecological computations, Marie L. Ruebsam aided in interpreting the results and wrote the manuscript together with Philippe Kruse. All authors provided critical feedback and revised the final manuscript.

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