Anesthesia and its environmental impact: approaches to minimize exposure to anesthetic gases and reduce waste

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Abstract

In today's era of modern healthcare, the intersection between medical practices and environmental responsibility has gained significant attention. One such area of focus is the practice of anesthesia, which plays a crucial role in various surgical procedures. Anesthetics such as nitrous oxide and volatile halogenated ethers (desflurane, isoflurane, sevoflurane) are examples of medical gases that are strong greenhouse gases that contribute to global warming. During medical procedures, most of these anesthetic agents are released into the atmosphere, which exacerbates their influence on the environment. Also anesthesia delivery systems have traditionally utilized high flow rates of gases, leading to not only excessive consumption but also a considerable environmental impact in terms of greenhouse gas emissions. However, the emergence of low-flow anesthesia (LFA) presents a promising solution for achieving emission reduction and cost savings, thereby aligning healthcare practices with sustainability goals. Understanding LFA involves the administration of anesthetic gases to patients at reduced flow rates compared to conventional high-flow methods. This practice requires precision in gas delivery, often incorporating advanced monitoring and control systems. By optimizing gas flow to match the patient's requirements, LFA minimizes wastage and excessive gas release into the environment, subsequently curbing the carbon footprint associated with healthcare operations. Decreasing volatile anesthetic delivery provides safe and effective strategies for anesthesia providers to decrease costs and reduce environmental pollution. Current literature support in favor of LFA represents an area of cost containment and an opportunity to lessen the environmental impact of anesthesia. This article will cover the concept of LFA, the distinctions between low flow and minimal flow, and the potential advantages of LFA, such as those related to patient safety, the environment, and the economy.

Key Words: anesthesia; anesthetic inhalational agents; automated control; climate change; environmental cost; global warming; green anesthesia; low flow anesthesia; rebreathing; sustainable anesthesia

Introduction

Acute care settings rank as the second most energy-intensive industry, following food service facilities, making healthcare a carbon-intensive service. In the United States, it accounts for 8% of all greenhouse gas (GHG) emissions.[1] During perioperative activities, which are especially resource-intensive, operating rooms consume 3 to 6 times more energy than hospitals overall.[2] Numerous scientific studies have demonstrated that all vapors and agents that can currently be inhaled are GHGs that contribute to global warming. However, many anesthesia providers are only vaguely aware of how our field contributes to GHGs and how each gas affects the environment differently. Limiting unnecessary GHG emissions can significantly lessen the detrimental effects on our environment given the prevalence of using inhaled anesthetics.[3] Anesthesia providers must extensively utilize available resources to practice low-flow anesthesia (LFA), as anesthetic gases contribute significantly to environmental pollution.

The goal of LFA is to minimize the waste of inhaled anesthetics that are harmful to the environment.[4] Aside from the economic and ecological advantages, it also offers physiological benefits including maintained heat and humidity, enhanced mucociliary function, and maybe lessened oxidative damage. This is achieved by providing anesthetic gases at lower flow rates.[5] Despite its benefits, anesthesiologists continue to disagree over the use of LFA due to concerns about renal damage and compound A exposure.[6] Studies demonstrating decreased oxidative damage and comparable hemodynamic parameters and recovery durations in obese individuals following laparoscopic surgery[7] support the notion that LFA with sevoflurane can be safe and beneficial. LFA, when combined with patient safety, cost-effectiveness, and environmental factors, offers a promising approach to anesthesiology practice overall.

By learning about each inhaled agent's atmospheric lifespan and global warming potential (GWP) and using these agents responsibly, anesthetists may significantly contribute to the

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reduction of emissions. The aim of this narrative review is to summarize the current knowledge on global warming, anesthesia's impact on the environment, ways to minimize anesthetic gas exposure and waste, alternative options to inhalational anesthesia, and the financial and environmental outcomes of manual *versus* automated end-tidal gas concentration management.

Search Strategy

A systematic search was conducted on PubMed to locate English-language articles published between January 1, 2000 and July 30, 2023, using the search terms "anesthesia" and "greenhouse gas," ensuring the inclusion of recent literature. Of the 48 articles retrieved, 9 were excluded for the lack of relevance to environmental or occupational exposure to inhaled anesthetic gases or their mitigation. The remaining pertinent articles were collected and reviewed, along with an examination of the references cited within them.

Global Warming Theories

The explanation of important terms pertaining to the impact of GHG emissions on global warming will help anesthesiologists comprehend these mechanisms and become knowledgeable about the availability of more environmentally friendly anesthetic alternatives.

GWP is a scale that compares a gas's effect to that of the same mass of carbon dioxide (CO_2) by measuring how much heat it traps in the atmosphere. It is a measurement of the amount of energy that 1 tons of gas emissions will absorb over a specific period, which is typically 100 years, and is denoted by the abbreviation GWP100. This measurement is made in comparison to 1 tonne of CO_2 emissions. Because it is the gas used as the reference, CO_2 by definition has a GWP of 1, regardless of the period used. Consequently, GWP reflects both the length of time a gas spends in the atmosphere and the intensity of its energy absorption.[8]

The term "global warming" describes a sustained rise in the planet's surface temperature.[9] The amount of CO_2 released is known as the "carbon footprint" and is used as a baseline when assessing the GWP of other substances.[9] Radiative forcing is the ratio of the amount of infrared energy radiated back to space to the amount of sunlight (radiation) absorbed into the Earth's internal climate. Since half of the Earth's surface receives sunlight every day, energy is constantly entering the atmosphere. 30% of this sunlight is reflected into space, leaving the remaining 70% for the planet to absorb.[10] When sunlight enters the atmosphere, it causes a phenomenon known as the greenhouse effect, or greenhouse gases (GHGs). Instead of being released back into space, heat is absorbed by GHGs and raises the temperature within the atmosphere.[10] GHGs that trap infrared heat raise temperatures over time by altering the Earth's radiative equilibrium. The greenhouse effect is a naturally occurring phenomenon on our planet and is responsible for regulating the temperature on the Earth. GHGs such as CO_2, methane (CH_4), and water vapor retain some of the radiation that is emitted by the sun on the Earth's surface in the form of heat. The greenhouse effect is fundamental for the maintenance of the ideal temperature for life on the Earth; without the presence of this effect, the average temperature of the planet would be very low and difficult for the survival of many species.

The environmental impact of anesthesia practice is a topic of growing concern, and the GWP of inhalation anesthetics is a term connected to this concern. Each anesthetic has a different infrared absorption spectrum, and this, along with its atmospheric lifetime, determines how much of a GHG it will be. Until that gas breaks down in the atmosphere, it continues to have an impact on the environment. The imbalance is most effectively assessed near the border between the troposphere, the lowest layer of the atmosphere, and the stratosphere, the region with the highest concentration of ozone.[8]

Effects of Ozone on Global Warming

The ozone layer, which is a component of the atmosphere and is situated at a height of 25 km, serves as a solar filter, keeping most ultraviolet (UV) rays from reaching the Earth's surface.[11] When UV radiation interacts with GHGs, it releases free radicals that attack the ozone molecules in the ozone layer. This rarefaction of the gas results in what is known as a "hole in the ozone layer," which exposes the Earth to more UV radiation.[12] In order to prevent permanent harm to the environment and human health, greenhouse gas emissions must be severely curtailed.[13] This decline is concerning consequences on human health. Since it can cause or exacerbate a number of illnesses, the impacts of this decline on human health are concerning and have been the focus of investigations by researchers worldwide.[14]

These findings show serious implications for human health. The quantity of ozone present in the atmosphere directly affects the amount of UV radiation that reaches the Earth's surface. According to Juchem et al.,[15] there is a 2.7% rise in the incidence of nonmelanoma skin malignancies for every 1% decrease in atmospheric ozone, indicating that even little fluctuations in this layer might provide a serious health risk.

The actions on ecosystems affect human health, disease, and well-being. New diseases may emerge, infectious diseases worsen, and chronic non-communicable diseases increase. Current food system may deteriorate leading to more hunger and malnutrition, along with hyper-urbanization, microbial resistance, climate migrations, and conflicts over natural resources.[16]

Anesthesia and Global Impact on Climate or Environment

Climate change is the biggest threat to public health, and minimizing the environmental impact of inhaled anesthetics is crucial. Strategies include avoiding nitrous oxide (N_2O) and desflurane, using intravenous or local-regional anesthesia, and investing in new scavenging technologies. Occupational risks for healthcare professionals from long-term exposure to inhaled anesthetics remain a concern, necessitating regulatory guidelines and improved safety measures. Anesthesia types have an impact on postoperative outcomes, with total intravenous anesthesia showing fewer side effects and growing in preference, especially in pediatric surgery. Ultimately, reducing the use of inhaled anesthetics, particularly desflurane, is essential for mitigating their environmental and health impacts.[17] The ideal anesthesia decision should balance environmental impact, clinical indications, and occupational risk, as illustrated in the accompanying diagram (**Figure 1**).

CO_2 and other GHGs such as N_2O, methane, fossil fuels synthetic GHGs (fluorinated gases), and water vapor, both natural and man-made, contribute to global warming.[10,18] Although the GWP of water vapor has not been properly calculated in the literature, it is the most abundant and potent GHG generated from the natural water cycle (evaporation, condensation, and precipitation). Earth's temperature is regulated by water vapor, which contributes about 60% of the warming effect.[8] The US Global Change Research Program estimates that since pre-industrial times, the atmospheric concentrations of CO_2, methane, and N_2O have increased by about 40%, 150% and 20%, respectively. More than half of the CO_2 rise has happened since 1970.[19]

Halogenated inhalation anesthetics such as isoflurane, desflurane, and sevoflurane have been found in the global atmosphere; in 2014, their mean mole fractions were 0.097 ppt, 0.30 ppt, and 0.13 ppt.[20] In 2014, anesthetics emitted 3.1 ± 0.6 million tons CO_2 equivalent, with desflurane accounting for about 80%.[21] Furthermore, the UK National Health Service was responsible for 2.5% of the greenhouse gas emissions caused by anesthetic inhalation, contributing to the estimated 3.1 million metric tons of CO_2 equivalents of volatile anesthetic gases emitted globally in 2014.[17] Volatile anesthetics exhibit varying GWPs, therefore it is crucial to evaluate and limit their environmental impact.

Recent investigations indicate that the United States healthcare sector contributes to nearly 10% of the total GHG emissions, with hospitals being the primary source. Over the decade spanning 2006 to 2016, GHG emissions associated with healthcare demonstrated a notable increase of 30%.[22] Notably, operating rooms generate 20% to 30% of the entire waste output of hospitals, establishing perioperative services as one of the healthcare sectors with the most substantial environmental impact.[23]

One of the main causes of climate change is the production of GHGs,[24] which includes the discharge of waste anesthetic gases into the atmosphere during surgical operations (**Figure 2**).[25] Although anesthesia gases account for a relatively small proportion of GHGs, a substantial body of research demonstrates the importance of reducing waste anesthetic gas release into the environment to reduce global climate change contributions and associated health risks, as well as personal occupational exposure and risk of adverse effects. According to a 2019 study of global surgery metrics, 266 million surgeries were carried out globally in 2015, with a global median of 4171 operations per 100,000 people.[26] This substantial volume of surgery exposes a variety of healthcare professionals to volatile anesthetics, including anesthesiologists, dentists/dental staff, nurse anesthetists, operating room nurses, operating room technicians/staff, recovery room nurses/staff, and surgeons.[27]

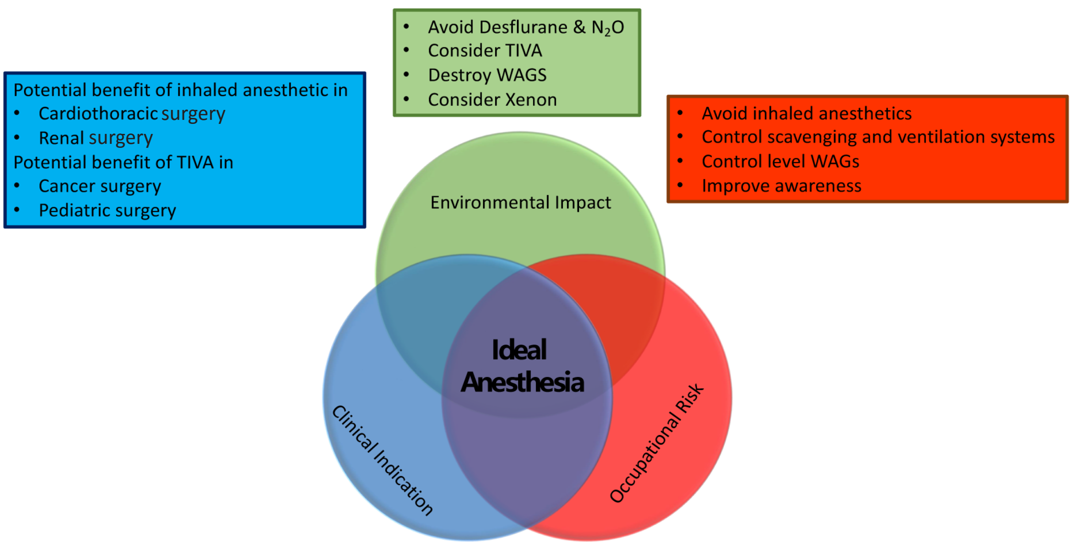

Figure 1 | Schematic view of the three different perspectives in choosing an anesthesia technique.
Reprinted from Gaya da Costa et al.[17] N_2O: Nitrous oxide; TIVA: total intravenous anesthesia; WAG: waste anesthetic gas.

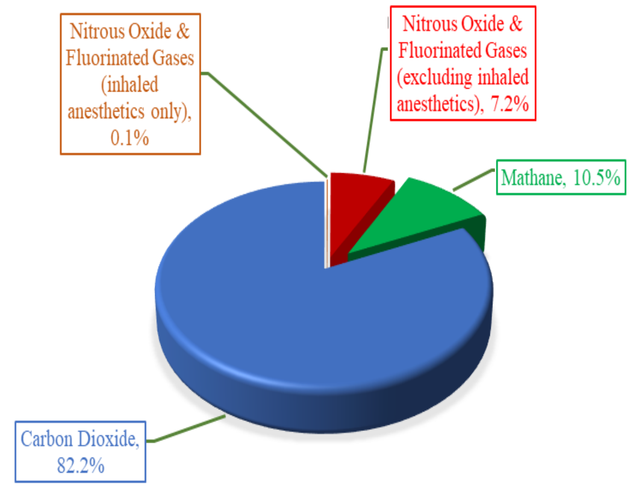

Figure 2 | Composition and contributions to total U.S. greenhouse gas emissions.
The 2012 breakdown of U.S. greenhouse gas emissions, including 4.3% N_2O and 3% fluorinated gases. Inhaled anesthetics (nitrous oxide, desflurane, isoflurane, and sevoflurane) contribute approximately 1% to healthcare sector emissions and 0.1% to total U.S. greenhouse gas emissions (2011–2013). Reprinted from Varughese and Ahmed.[25] N_2O: Nitrous oxide.

Impact of Anesthetic Gases and Climate Change

GHGs like volatile anesthetics, trap energy in the atmosphere by absorbing infrared radiation.[28] Given that the use of these gases is regarded as a medical necessity, volatile anesthetic emissions are not subject to regulation like many other GHGs. They do contribute to global warming, though, and we should not disregard that. The patient only processes less than 5% of the administered volatile anesthetics; the majority are instead released into the atmosphere.[29] Healthcare activities are considered to be responsible for 10% of the nation's GHG emissions in the United States.[30]

The most frequently used volatile anesthetics are N_2O and the highly fluorinated gases sevoflurane, desflurane, and isoflurane, all of which have been linked to climate change in the past decade due to their effects on the photophysical characteristics of the atmosphere.[28] N_2O and halogenated gases with chlorine or bromine, like isoflurane and the outdated drug halothane, can deplete ozone and lessen the ozone layer's ability to shield against UV radiation. Sevoflurane and desflurane are two examples of halogenated gases that harm the climate even though they do not catalytically destroy ozone. Instead, trace amounts of these gases in the atmosphere absorb and reduce outgoing infrared thermal energy, warming the planet.[31]

The majority of volatile anesthetics are eliminated from the body through exhalation while they are being used in clinical settings.[28] N_2O, desflurane, isoflurane, and sevoflurane, for instance, are exhaled unchanged in about 95% of cases.[32] In operating rooms, these substances are usually scavenged from patient breath to minimize occupational exposure. However, these medical waste gases are discharged into the environment as GHGs with little to no additional processing.[3]

Assessing the radiative and atmospheric attributes of specific substances, the GWP provides a measure to quantify how various agents, including GHGs, contribute to climate change.[33,34] A gas's capacity to absorb heat from the atmosphere is measured by its GWP.[35] Regardless of the time period used, CO_2 has a GWP of 1 by definition. The term "CO_2 equivalent" refers to the mass of CO_2 that possesses an equivalent GWP as a given mass of a specific agent.[36] This concept facilitates the comparison of the global warming impact of different gases. The 100-year time frame (100-year GWP) is frequently used to calculate GWP. The chemical formula, 100-year GWP, CO_2 equivalent, and lifetime in the atmosphere of frequently used volatile anesthetics are shown in **Table 1**.[17,31,37]

In contrast to sevoflurane, isoflurane manifests a protracted atmospheric persistence of 3.2 years. Its possession of a chlorine atom renders isoflurane proficient in ozone layer attenuation. Relative to other volatile anesthetics, sevoflurane distinguishes itself with the briefest atmospheric longevity at 1.1 years and a 100-year GWP of 575. However, among all volatile anesthetics, desflurane has the highest 100-year GWP. When compared to sevoflurane and isoflurane, it is also used at higher doses, requiring 3 to 6 times as much to achieve the same level of anesthesia.[38] Desflurane should not be used, given its 14-year atmospheric lifetime, in order to reduce environmental harm.

Table 1 | A comparative analysis of commonly employed volatile anesthetics

Gas	Chemical formula	Lifetime in atmosphere (yr)	100-yr GWP	CO_2 equivalent (kg) for agent in container, correlated with container size	Driving equivalent (km/h)	Ozone depletion potential	Greenhouse warming potential
Isoflurane	$CHF_2OCHClCF_3$	2.6–5.9	350	191 (250 mL)	32–64	√	√
Sevoflurane	$CH_2FOCH(CF_3)_2$	1.1–5.2	575	48 (250 mL)	29		√
Desflurane	$CHF_2OCHFCF_3$	8.9–21.0	1526	893 (240 mL)	377–756		√
Nitrous oxide	N_2O	114	296	1013 (Size E)	95	√	√

Data were derived from Varughese and Ahmed[25] and Gadani and Vyas.[29] "Driving Equivalent" refers to the potency of volatile anesthetics at 1 minimum alveolar concentration-hour (0.6 for nitrous oxide), considering a fresh gas flow rate of 0.5–2.0 L/min. A common industry standard for a size E cylinder of nitrous oxide is approximately 1590 L. CO_2: Carbon dioxide; GWP: global warming potential.

N_2O, owing to its anesthetic properties, minimal alveolar concentration-sparing capability, and analgesic effects, finds widespread application in various medical procedures. Its extensive use has resulted in a notable contribution, ranging from 1% to 3%, to the global emissions of N_2O.[39] It is crucial to recognize that N_2O not only functions as a GHG but also exerts ozone-depleting effects, compromising the ozone layer's protection against harmful UV rays from the sun.[40] Despite possessing a substantially lower 100-year GWP compared to desflurane (296 *vs.* 1526), N_2O exhibits a significant atmospheric lifetime of 114 years. Moreover, in contrast to alternative anesthetics administered at concentrations ranging from 1% to 6%, it is commonly employed at elevated doses, typically ranging between 40% and 60%.[41] This is due to its relatively weak anesthetic potency. Nitric oxide and CO_2, which are GHGs, are also contaminants created during the synthesis of N_2O.[42] This data illustrates that relative to alternative volatile anesthetics, desflurane, and N_2O exhibit notably adverse environmental impacts.

It is imperative to consider the enduring, cumulative influence of inhaled anesthetics on climate change and to actively pursue strategies aimed at mitigating the introduction of these agents into the environment. This remains paramount despite the relatively modest contribution of volatile anesthetics to total GHG emissions (0.1%), especially when juxtaposed with CO_2 (82.2%), as depicted in **Figure 2**.[10,31]

Strategies to Minimize Exposure and Waste of Anesthetic Gases

The practice of anesthesia is a critical aspect of modern medical procedures; ensuring patients undergo surgeries and interventions comfortably and safely. However, the administration of anesthetic gases, while essential, presents challenges in terms of both healthcare worker exposure and environmental impact due to gas wastage. To tackle these issues, a range of strategies have been developed to minimize exposure and reduce the waste of anesthetic gases. These strategies not only prioritize the well-being of medical personnel but also contribute to a more sustainable and environmentally conscious healthcare system (**Figure 3**).

Limited use of volatile anesthetics with high 100-year GWP

The GWP of halogenated anesthetics can reach exceptionally high levels, up to 2000 times that of CO_2. N_2O, isoflurane, sevoflurane, and desflurane all possess higher GWP factors than N_2O, with desflurane exhibiting a GWP factor five times greater than that of N_2O. Despite this, N_2O contributes the most to increased climate impact (99.97%), mainly due to its significantly higher consumption volumes compared to other anesthetic gases.[29]

Exploring the substitution of N_2O with alternative anesthetic gases holds potential benefits, potentially achieving equivalent anesthetic effects with lower usage volumes, although this area remains unexplored. To mitigate the environmental impact of inhaled anesthetics, it is advisable to refrain from using N_2O and minimize unnecessarily high fresh gas flow (FGF) rates.

Desflurane stands out with a significantly longer atmospheric "lifetime" of 10 years compared to 1.2 years for sevoflurane and 3.6 years for isoflurane. Considering the administered flow rates, desflurane demonstrates approximately 26 times the GWP of sevoflurane and 13 times the impact of isoflurane.[29]

Low-flow anesthesia technique

LFA techniques are gaining traction as an effective way to minimize gas exposure and waste. By delivering anesthetic gases at lower flow rates than conventional methods, healthcare providers can significantly reduce consumption. These techniques necessitate careful monitoring and adjustment to maintain patient comfort and safety while conserving valuable resources and minimizing environmental impact.

Low-flow anesthesia can refer to any technique that uses an FG flow that is lower than the alveolar ventilation (**Table 2**).[43] LFA is defined as an inhalation anesthetic technique with total FGFs of less than 2 L/min and at least 50% of expired gases (including unabsorbed inhaled anesthetics and unconsumed oxygen) returning to the lungs after CO_2 is removed from the circle by the CO_2 absorbent in a closed circle system. So less gas is released because more gases are recirculated around a circle system when the FGF is low. This is the only way to achieve the lowest possible emission of scavenged gases.[44]

Figure 3 | Greening the operating room: sustainable anesthesia practices. Created with Microsoft PowerPoint Version 2405. GWP: Global warming potential.

Table 2 | Classification of fresh gas flows

Category	Fresh gas flow	Remark
High flow	> 2 L/min	For basic oxygen consumption, a total fresh gas flow of > 1–2 L/min is more than sufficient; however, this causes unmetabolized gases to be released unfiltered into the atmosphere. There is no gas rebreathing.
Medium flow	1–2 L/min	
Low flow	500–1000 mL/min	The oxygen flow must be increased by 10% of total fresh gas flow if the inspiratory oxygen concentration falls below 30% (and must be decreased by the same amount if N_2O is administered).
Minimal flow	250–500 mL/min	The oxygen flow must be increased by 50 mL of total fresh gas flow if the inspiratory oxygen concentration falls below 30% (and decreased by the same amount if N_2O is administered).
Metabolic flow	About 250 mL/min	Since the absolute minimum amount of oxygen required per minute is 250 mL, oxygen should be the only carrier gas.

Data were derived from Baker[43] and Brattwall et al.[45] N_2O: Nitrous oxide.

As the uptake and metabolism are time-sensitive and numerous factors affect the consumption and production of gaseous components, it is difficult to control the dynamic equilibrium of FG composition. This can only be accomplished by frequently adjusting the gas flow controls. To calculate the uptake of substances like oxygen, N_2O, and volatile agents, complicated equations are used. For the safe conduct of LFA, monitoring inspired and end-tidal concentrations with a gas analyzer is a more accurate and practical method.

Use of volatile agents in low-flow anesthesia

To optimize both financial and environmental benefits associated with the utilization of volatile anesthetics, Edmonds et al.[38] propose maintaining an FGF rate of 0.5 L/min for desflurane and keeping it below 1 L/min when isoflurane is employed. Due to the possibility of compound A-induced kidney injury, they also recommend using sevoflurane at an FGF rate of 1 L/min when the required minimum alveolar concentration hours are less than 2. However, it is important to keep in mind that no evidence of compound A-induced kidney damage that is clinically significant has been found in humans.

Advantages of low-flow anesthesia

LFA offers a range of advantages, encompassing cost savings, the prevention of environmental pollution, and substantial physiological benefits. These physiological advantages include improvements in the flow dynamics of inhaled gases, enhanced mucociliary clearance, preservation of the structural and functional integrity of respiratory tract epithelial cells, augmentation of the heat and humidity of rebreathed gases, retention of moisture in CO_2 absorbent, and preservation of body temperature.[44]

Disadvantages of low-flow anesthesia

Due to a longer time constant of the inhaled agents, a higher consumption of CO_2 absorbent, and a higher risk of hypercarbia and CO_2 rebreathing with frequent exhaustion of absorbers, lower FGF causes a slower induction and emergence.[44,45]

To prevent hypoxic mixtures and anesthetic agent under- or over-dosage, constant attention and frequent flow adjustments are necessary. Sevoflurane should not be used in LFA and should be administered at > 1 L/min flows, according to the U.S. Food and Drug Administration.

To address the potential buildup of unfavorable gases like carbon monoxide, methane, acetone, hydrogen, ethanol, Compound A, argon, and nitrogen during anesthesia, it is recommended to flush the circuit with high fresh gas flows (FGFs) periodically.

The following situations do not lend themselves to LFA techniques[46]:

a) LFA is not well-known to anesthesiologists.
b) With a face mask, short-term anesthesia.
c) Procedures involving gas leakage (such as bronchoscopies-laryngoscopies using a rigid bronchoscope).
d) Patients experiencing intoxication should be administered a total FGF exceeding 1 L/min to ensure a consistent washout effect of alcohol.
e) In order to prevent an unfavorable buildup of acetone in the breathing system, patients in ketoacidosis may experience an increase in their blood levels of acetone during anesthesia.

Automated low-flow anesthesia

Automated LFA techniques, employing devices that restrict FGF and recirculate gases within closed systems, have demonstrated efficacy in reducing volatile anesthetic consumption, minimizing exposure to waste anesthetic gases, and mitigating environmental pollution.[44,47] These techniques utilize proprietary software algorithms to regulate the concentrations of end-tidal anesthetics and inspired oxygen. In a comparative study of manual versus automated control, the automated system significantly reduced GHG emissions by 44%.[48] A study further reveals a notable reduction in desflurane consumption with these automated systems compared to traditional LFA.[49] Additionally, closed filling systems for anesthetic vaporizers maintain waste gas exposure below recommended levels. Anesthetic machines equipped with end-tidal-controlled anesthesia autonomously adjust target concentrations, diminishing the necessity for manual interventions and enhancing overall anesthetic delivery efficiency. In conclusion, automated LFA techniques offer substantial benefits, including significant reductions in waste gas and improved delivery efficiency.

Several automated LFA machines presently available include the Zeus® (Dräger, Lubeck, Germany), the Aisys® (GE, Madison, WI, USA), and the Flow-i® (Maquet, Solna, Sweden).[50] The Zeus employs closed-circuit anesthesia, while the Aisys utilizes minimal flow anesthesia with an FGF of 500 mL/min.

The anesthesiologist first chooses a target O_2%, either inspired (Zeus) or end-expired (Aisys), as well as a target alveolar concentration of inhaled anesthetic. Our automated low flow armamentarium now includes this automated gas control, which helps to reduce anesthetic waste, cost, and pollution while lowering the ergonomic liability of LFA.[50,51] Ventilators without these built-in algorithms can still use LFA techniques.[44]

Advanced scavenging systems

These systems safely interface the anesthesia breathing system with the hospital vacuum or other gas disposal system.[52] Adsorptive separation using various materials, such as activated carbons, zeolites, and metal-organic frameworks, has been identified as a potential solution for removing volatile anesthetics from waste gas streams.[53] Studies comparing operating rooms with and without central scavenging systems have shown that the use of these systems can decrease the concentrations of anesthetics in the air, although they may not always meet internationally recommended exposure limits.[54] Overall, the implementation of central scavenging systems and the development of innovative purification systems are important steps toward reducing occupational exposure to anesthetic gases in operating rooms.

Vaporizer efficiency and modern technology

Modern vaporizers such as the Aladin cassette vaporizer, injection vaporizers, and Anesthetic Converting Device, “AnaConDa” (Sedana Medical, Danderyd Sweden) are designed to minimize waste anesthetic gases in the operating room.[55]

The Aladin cassette vaporizer, integrated with DatexOhmeda S/5 ADU (GE Healthcare, Chicago, IL, USA) and GE Aisys (GE Healthcare) anesthesia machines, delivers set agent concentrations accurately with low FGFs and possesses enhanced safety features. Vaporization systems such as those employed by Maquet and DIVA™ present a capability to rapidly achieve the predetermined end-tidal agent concentration, ensuring minimal wastage and theater pollution. AnaConDa™ represents an integration of a vaporizer with a humidity and moisture exchange filter designed for incorporation into the ventilatory circuit. This system facilitates the administration of a safe sedative dose, either isoflurane or sevoflurane, to patients using existing critical care ventilators. This approach not only reduces the overall quantity of anesthetic required but also safeguards the care environment and healthcare workers from undue exposure to these substances.

These contemporary vaporization technologies offer efficient and cost-effective means for delivering anesthetic gases, concurrently minimizing waste within the operating room. In the evolving landscape of healthcare data analytics, several companies are now offer advanced software solutions for perioperative care and anesthesia data analytics on a breath-by-breath basis, storing it in the Cloud, and analyzing it using advanced algorithms for customer access through a web-based dashboard. This innovative approach aligns with the broader trend of leveraging data analytics to enhance patient care, streamline operations, and drive better outcomes in healthcare settings.

Closed-loop anesthesia delivery systems

This represents an innovative strategy for optimizing gas administration. The approach encompasses the measurement of diverse physiological parameters, including the electrocardiogram waveform, pulse rate, blood pressure, and body temperature, through various sensors placed on the patient’s body. These measured parameters play a pivotal role in governing the administration of anesthesia during major surgical procedures, guaranteeing the maintenance of the desired output level.[56] In essence, these advancements in anesthesia delivery systems, coupled with waste gas treatment devices, collectively contribute to waste reduction and enhanced cost savings within the confines of the operating room.

Comprehensive training and education

It is imperative to educate and offer guidance to healthcare practitioners on the critical significance of limiting exposure to and managing anesthetic gases. Their education and training can be effectively conducted by imparting knowledge on waste segregation, providing customized propofol preparation charts, and administering human factors training sessions. Waste segregation education for anesthesia staff has been shown to improve waste segregation compliance in the operating room, increase waste management knowledge, improve sharps waste bin compliance, and produce cost savings.[57] Customized propofol preparation charts can aid anesthesia professionals in determining the approximate requirement for the duration of a procedure, leading to waste reduction and cost savings for healthcare organizations.[58] Human factors training in the operative environment can teach skills such as behaviors and attitudes, teamwork, communication, situation awareness, and leadership, which can help to improve patient safety in the operating room.[59]

Routine maintenance and calibration

It includes implementing scavenging systems and administrative controls to minimize exposure to waste anesthetic gases.[60] Proper maintenance plans for heating, ventilating, and air-conditioning systems also play a significant role in creating favorable indoor environmental conditions and controlling nosocomial infections.[61] By applying condition-based maintenance techniques, hospitals can improve the working practices of heating, ventilating, and air-conditioning maintenance departments, optimize maintenance plans based on equipment’s remaining useful life and associated costs, and make informed decisions regarding equipment investment.[62] Implementing these maintenance practices and controls can help ensure the safe and efficient use of anesthesia equipment, protecting the health and well-being of healthcare personnel in the operating room.

Waste gas monitoring and safety protocols

Incorporating waste gas monitoring protocols enhances the ability to detect deviations from safe exposure limits. Monitoring helps healthcare facilities promptly identify and rectify any issues that may arise, ensuring the safety of both patients and medical staff. Monitoring systems, such as operating room monitoring systems, can be used to collect data from sensor arrays placed around the operating room. Analyzed data can help identify protocol violations and trigger appropriate responses, such as adjusting heating, ventilating, and air-conditioning equipment or providing visual or audible alerts. Best practices, administrative controls, and engineering controls should be implemented to prevent exposure to waste anesthetic gases.[63]

Institutional environmental responsibility

This involves the implementation of sustainable anesthetic strategies, conducting risk assessments, and conducting technical controls.[64] Sustainable anesthetic strategies involve using LFA regimes and more sustainable alternatives to halogen gases. Risk assessments help in predicting the possible risk to personnel's health and can guide decision-making regarding exposure to anesthetic gases. Technical controls, such as regular inspection of ventilation systems, the use of advanced ventilation systems, and continuous control of anesthesia devices, can help minimize exposure to waste anesthetic gases. Additionally, implementing the 5 R's of waste minimization (Reduce, Reuse, Recycle, Rethink, and Research) in the operating room can reduce the environmental impact of anesthesiology practice and decrease costs.[65]

Research

To lessen the environmental impact of the tools and medications we use, research on green anesthesia is currently being conducted. This involves evaluating the effectiveness of waste segregation education for anesthesia staff in improving waste management practices,[66] rearranging patient care pathways to lessen their carbon footprint,[67] investigating the use of total intravenous anesthesia and its effects on the environment,[65] comparing the environmental and financial impact of disposable versus reusable medical devices in terms of carbon footprint, energy and water consumption, and waste generation,[39] and so on. An understanding of more sustainable anesthetic practices may be gained by initiating or participating in these studies.

Conclusion

The strategies to minimize exposure and waste of anesthetic gases represent a vital step towards creating a safer, more efficient, and environmentally conscious healthcare system. By integrating advanced technologies, emphasizing education and training, and fostering a culture of responsibility, healthcare facilities can achieve significant reductions in both exposure risks for healthcare providers and the environmental footprint of medical procedures. These strategies underscore the potential for positive change within the healthcare industry and its commitment to ensuring the well-being of patients, medical personnel, and the planet. As anesthesiologists, we should play a proactive role both at work and outside of it to support environmental sustainability and improve the world for the coming generations. The review is primarily concerned with the environmental effect of anesthesia, specifically the contribution of anesthetic gases to greenhouse gas emissions. While this is a significant concern, other environmental aspects of anesthesia practice, including as waste management, energy consumption, and resource exploitation, are still not well addressed in the literature.

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