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INTEGRATED STUDY MASTER'S THESIS

The Anesthesiologist and Global Climate Change

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1. Abstract

1.1 Introduction

The field of anesthesiology plays a critical role in modern healthcare, ensuring patient safety and comfort during surgical procedures and in the intensive care unit. During the last decade, global climate change has become a major topic for the entire world and affects the world's population severely. This paper examines the relationship between anesthesiology and global climate change, particularly focusing on the effect of inhalational anesthetic gases on the environment. Furthermore, it focuses on operating room practices and sustainability as well as adaptation strategies for anesthesiology practices.

1.2 Methodology

A literature review was performed using the PRISMA flowchart analyzing the effects of anesthesiology on global climate change. This overview highlights the importance of understanding the impact of inhalational gases, their carbon footprint, energy consumption in hospitals and waste generation among 64 references.

1.3 Results and Conclusion

Anesthesiology and global climate change share a connection which is multifaceted and highly relevant today. This literature review has explored the complex relationship between the two topics, revealing significant findings that emphasize the need for sustainable practices in healthcare. Key results include that the healthcare sector is a significant contributor to global greenhouse gas emissions, desflurane and nitrous oxide are potent greenhouse gases with global warming potentials far exceeding that of carbon dioxide and should be replaced by different inhalational anesthetics such as sevoflurane. The implementation of low-flow anesthesia techniques and waste reduction strategies can further mitigate the environmental impact of anesthesiology. Findings highlight the urgent need for the community of anesthesiology to adopt more sustainable practices by implementing evidence-based strategies to reduce emissions and waste.

2. Keywords

Anesthesiology, inhalational anesthetics, climate change, greenhouse gases, waste management and sustainable anesthesia

3. Methodology

The Literature review investigates the correlation between anesthesiology and global climate change. It is organized as a literature review based on the latest literature and publications from articles, journals, international guidelines, forums and studies. The publications investigated were mainly found on the following online publication websites: Pubmed, Google scholar and ScienceDirect. To limit the extent of the review and select the most relevant data, the inclusion criteria include german and english language, and an age of maximum of 5 years between 2019 and 2025. Nevertheless, 5 articles older than five years were used to gather as many perspectives and information as possible.
The selection criteria included reviews, systematic review, practice guidelines, case studies as well as websites and organizations. Keywords that were entered in the different search engines include "anesthesiology", "inhalational anesthetics", "greenhouse gases", "waste management", "climate change" and "sustainable anesthesia". Records were identified from four sources: Google Scholar (n = 1,130), PubMed (n = 2), ScienceDirect (n = 16), and other databases (n = 4), totaling 1,152 records. Before screening, 1,000 records were removed as ineligible by automation tools, and an additional 40 records were removed for other reasons. This left 108 records for screening.
Records were identified from websites (n = 12) and organizations (n = 9), totaling 21 records. No records were removed during this stage.
From the database search: Of the 108 screened records, 20 were excluded. The remaining 88 reports were sought for retrieval, but 20 could not be retrieved. This left 68 reports to be assessed for eligibility.
From other methods: All 21 reports identified were successfully retrieved and assessed for eligibility.
For database records: Of the 68 eligible reports, exclusions included: Reports older than five years (n = 12). Reports not in English or German (n = 13). This resulted in the inclusion of 64 new studies from databases. For other methods: All 21 reports assessed for eligibility met the criteria, with no exclusions. A total of 64 new studies were included in the review.
This flowchart provides a clear overview of the systematic review process, ensuring transparency in study selection.

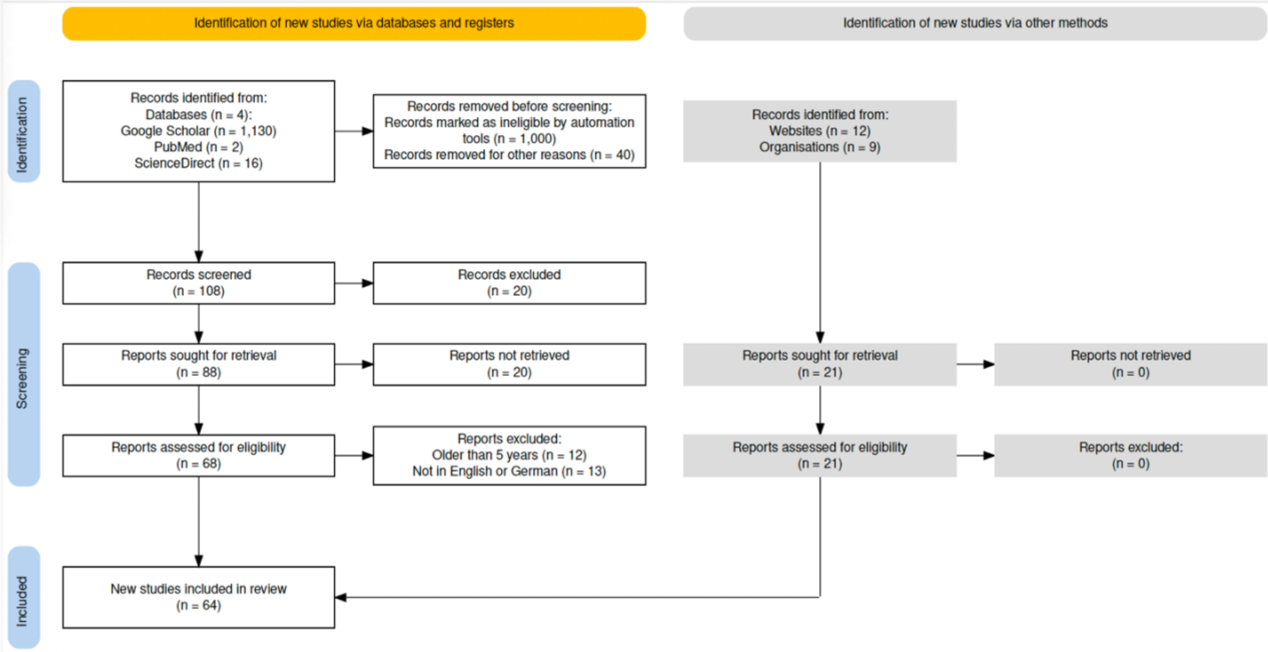


Figure 1- PRISMA 2020 Flowchart

4. Introduction

Global climate change has been a challenge for the entire population for many years now. The earth's surface temperature has increased by about 1°C since the pre-industrial era and is still rising. During the last decade, extreme weather events such as heatwaves, droughts, floods, and storms have occurred more frequently. Due to the melting of polar ice caps and glaciers, sea levels constantly rise. Furthermore, climate change provokes shifts in animal and plant habitats, leading to changes in ecosystems. Even though natural factors like solar activity and volcanic eruptions have an influence on climate, the dominant cause of climate change are human activities.

In 2015 the "Paris Agreement" was adopted by 195 countries, following the goal to limit global warming well below 2°C. In order to achieve this goal, all signatory states committed themselves to a sustainable policy and minimizing their carbon footprint.

According to the World Health Organization (WHO), climate change is a major threat to global health, putting over 250,000 lives at risk per year.

The global health sector is responsible for approximately 5% of greenhouse gas emissions due to high-energy consumption and notably, the use of inhalational anesthetics.

Just as nitrous oxide, chlorofluorocarbons and fluorocarbons, desflurane, sevoflurane, isoflurane are inhalational gases that are classified as greenhouse gases.

To understand the relationship between anesthesiology and global climate change, this paper will first focus on some background information, explaining the greenhouse gas effect, its implications on global health, and the chemistry and utilization of inhalational anesthetics. Elaborating on this topic, the main part of this review will portray the environmental effect of inhalational anesthetics, energy consumption in the hospital, and waste management. Following this, operating room practices and efforts to improve sustainability in the hospital are discussed. Lastly, this review will present adaptation strategies that can be implemented by organizations to reduce their carbon footprint.

4.1 Global Climate Change and its Implications on Global Health

Global climate change is a long-term change in the Earth's climate. It manifests itself primarily in global warming, which has been caused mainly by human activities in recent decades (5).

Three variables determine the earth's energy balance. First is the intensity of solar radiation entering the atmosphere. Secondly, the direct reflection of solar radiation by aerosols in the atmosphere and by bright ice surfaces on the earth's surface (albedo effect), and lastly the emission of infrared heat radiation into space. The most important effect is the third one. This mechanism establishes a stable climate and promotes temperatures on Earth that are compatible with life (8).

The most important causes of climate change are increased greenhouse gases like carbon dioxide, methane, nitrous oxide, and fluorinated gases. They reflect infrared heat radiation from the troposphere back to the Earth which eventually causes global warming (9).

During the last 800.000 years, the physiological CO_2 concentration was measured between 180-280ppm (parts per million). Due to the burning of fossil fuels over the last 50-80 years, it increased to 413 ppm and is the reason for a temperature rise of 1.1°C above pre-industrial levels. Notably, human-induced global warming is currently increasing at a rate of 0.2°C per decade.

Carbon dioxide, methane, nitrous oxide, and fluorinated gases, which make up less than 1% of the mass of the atmosphere, are known as greenhouse gases because of their effect on radiation. Greenhouse gases have the property of allowing the short-wave radiation coming from the sun to pass through the atmosphere unhindered but partially absorbing the long-wave heat radiation emitted by the heated surface of the earth and emitting it in all directions, including towards the earth's surface. This results in a kind of "heat build-up" in the lower atmosphere. Greenhouse gases therefore have a similar effect to the glass panes of a garden greenhouse, from which their name is derived. 66% of the natural greenhouse effect is caused by the water vapor contained in the atmosphere, while carbon dioxide is in second place with approx. 30% (7,8).

The natural greenhouse effect raises the temperature of the earth to +15°C making life possible. Water vapor, which is the most important natural greenhouse gas, absorbs 100% of thermal radiation at wavelengths of around 5.5-7.5 µm and over 22 µm. In some other wavelength ranges, it allows the radiation to pass through completely or partially.

CO_2 partially absorbs in some of these water vapor "windows", such as at 4-4.5 µm and 12-15 µm. At wavelengths around 2.7 µm, CO_2 only absorbs when there is virtually no water vapor in the atmosphere in dry regions. Methane and nitrous oxide cover further wavelength ranges. In contrast to water vapor, carbon dioxide, methane, and nitrous oxide have a much higher longevity causing them to stay inside the atmosphere for many years or even decades (5,6).

Greenhouse gases arise during deforestation, burning fossil fuels, and livestock farming (5,7).

Due to the increased accumulation of these gases in the atmosphere, more heat is trapped inside the atmosphere and is not able to leak back into space which eventually causes global warming (8). The concentration of carbon dioxide has risen to 48% above its pre-industrial level in 2020 (6).

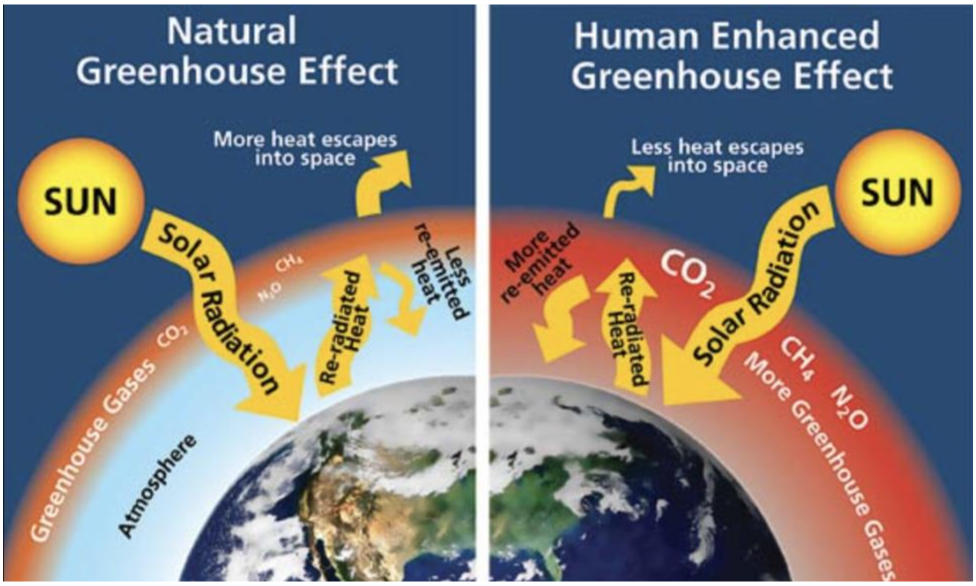


Figure 2- Natural vs. Human enhanced greenhouse effect

In November 2015 the Paris Agreement which is a "legally binding international treaty on climate change ", was adopted by 196 Parties at the UN Climate Change Conference. Its overall objective is to "hold the increase in the global average temperature to well below 2°C above pre-industrial levels" and "to limit the temperature increase to 1.5°C above pre-industrial levels." (12)

To keep global warming below 1.5°C, greenhouse gas emissions need to reach their maximum no later than 2025 and decrease by 43% by 2030 (12). Otherwise, there is only a chance of 66% of not exceeding the so-called tipping elements which include the melting of the polar ice caps and Greenland ice, the deforestation of the Amazonian rainforest, and the thawing of permafrost soils (8).

These tipping elements will lead to self-reinforcing feedback loops and domino effects which cannot be controlled anymore.

Figure 3- Overview of Paris agreement goals by University of Yale (13)

Climate change is not only damaging our environment but also has a major impact on human health and well-being.
According to the World Health Organization (WHO), weather and climate events like storms, floods, extreme heat, droughts, lack of water, and wildfires can affect health directly or indirectly causing more health emergencies, increasing the risk of deaths, noncommunicable diseases and spread of infectious diseases (9). Furthermore, diseases like malaria, dengue fever, and cholera which are more common in southern regions of the world, will spread to Europe.
Eventually, the physical and mental health of the population worldwide will suffer under these circumstances, possibly provoking wars and putting political systems at risk (8).

4.2 Field of Anesthesiology and its Significance in Healthcare; Types of Anesthesia

The field of anesthesiology is one of the most important and central medical specialties. It began to develop in the early 20th century but only after World War II it was recognized as a medical specialty (1). The areas of responsibility of anesthesia include pain elimination, administration of anesthesia during surgical procedures, and perioperative management. Anesthesiologists play an essential role in the operating room, performing different tasks to ensure patient safety and comfort throughout surgical procedures. They are responsible for preoperative evaluation, intraoperative care, postoperative care, and emergency response. Furthermore, they are leading the anesthesia care team and are among the most responsible colleagues (2).

During surgery, anesthesiologists provide intraoperative care including monitoring of vital signs, pain and consciousness management as well as administration of anesthesia. They monitor and control the patient’s heart rate, breathing, blood pressure, body temperature and fluid balance. Additionally, anesthesiologists ensure safe and suitable conditions for successful surgery by maintaining optimal levels of pain relief and unconsciousness through medications.

Specialists in anesthesiology are proficient in the techniques of general anesthesia and regional anesthesia (partial anesthesia).

General anesthesia and regional anesthesia are two different techniques of pain relief used during medical procedures. Regional anesthesia uses nerve blocks like epidurals, spinalanalgesia, and peripheral nerve blocks in which the patient remains awake and conscious; general anesthesia is used for major surgeries (e.g. heart surgery, appendectomies etc.) (2).

General anesthesia has three different therapeutic effects which include reversible amnesia, immobilization and analgesia (3). These effects are achieved by inhalational anesthetic agents and intravenous agents. The group of inhalational anesthetics include sevoflurane, desflurane, isoflurane and nitrous oxide. They can be administered during clinical stages such as induction, maintenance, emergence and recovery. Particularly during the maintenance phase, inhalational anesthetic agents are given to maintain the surgical stage of anesthesia (4).

Intravenous agents used for anesthesia include propofol, ketamine and etomidate. Propofol is the most used intravenous general anesthetic. Depending on the dosage, propofol can either induce sleep while still maintaining the patient’s own breath work or it can be used at higher dosages to depress respiration and therefore facilitating intubation (6).

Amino amides, including lidocaine and bupivacaine are administered for regional anesthesia.

In addition to traditional anesthesia, the specialty also includes intensive care medicine, emergency medicine, pain therapy and palliative medicine.

5. Anesthetic Agents and their Impact on Global Climate

As described above, climate change is a major threat to the entire population of the world.
The main reason for this is an increased concentration of CO_2 in our atmosphere, causing the human-made greenhouse effect. Since the industrial period, CO_2 concentrations have increased by 50% (15). Burning of fossil fuels like coal, oil, and natural gas in power plants, industry, and transportation are the biggest contributors to this rise. Due to deforestation less trees can absorb CO_2 sufficiently (16,17). The second most important greenhouse gas, methane (CH_4), is released in agriculture and livestock farming (15,16). Furthermore, livestock farming and fertilization set nitrous oxide free, refrigeration systems and air conditioners fluorinated gases (15).

The healthcare sector is a significant emitter of greenhouse gases, particularly in western countries. It is responsible for 5-10% of greenhouse gas emissions specifically due to energy-intensive departments and the use of inhalational anesthetics. In their paper, McGain et al. state that "If global healthcare were a country, it would be the fifth largest carbon emitter on the planet." (18) According to Koch et al., intensive care units and operating rooms contribute to over 50% of a hospital's greenhouse gas emission. 35% of a hospital's greenhouse gas emissions are released during the use of inhaled anesthetics (8).
To reduce the carbon footprint of the healthcare sector, anesthesiologists should focus on addressing key factors that significantly contribute to it. These are particularly the use of inhaled anesthetics, hospital energy supply, and waste management in the operating room.

5.1 Inhalational Anesthetics

The history of anesthesia began during the 19th century with the introduction of nitrous oxide (N_2O), ether, and chloroform. Nitrous oxide was synthesized in 1772 and was used for the first time by Horace Wells, a young dentist, during a tooth extraction (19).
In 1846, the dentist William T. Green Morton demonstrated the first anesthesia with ether at the General Hospital in Boston, Massachusetts. According to Brandt et al., this event marked a new era and is considered as the hour of birth for modern anesthesia (20).
Since then, many inhalational anesthetics have been invented and used during surgical procedures. After 1950, all imported drugs in Europe, except ethyl vinyl ether, contained fluorine. In their research

letter, Vollmer et al. state that halothane was introduced clinically in 1956 and profoundly used between the 1960s and 70s. Isoflurane replaced enflurane in the early 1980s. Today, it is commonly used in veterinary medicine.

The most recently introduced inhalational anesthetics were desflurane in 1992 and sevoflurane in 1993-1995 (21).

Inhalational anesthetics can be divided into two groups: Non-volatile gases (e.g. nitrous oxide) and volatile gases (e.g. desflurane, sevoflurane, isoflurane and halothane). The major difference between those gases are their chemical properties.

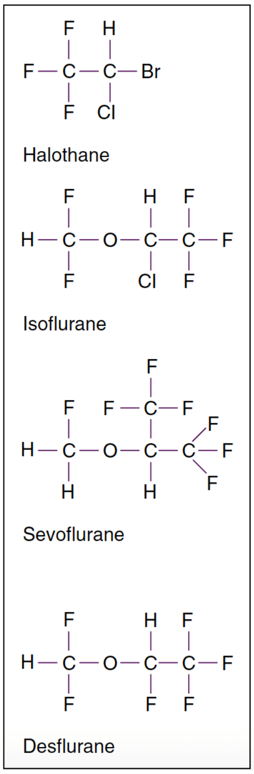


Figure 4-"Molecular structures of potent volatile anesthetics. Halogenated volatile anesthetics are liquids at room temperature. Among the volatile anesthetics, halothane is an alkane derivative, while all others are derivatives of methyl ethyl ether. Isoflurane is the chemical isomer of enflurane". (19)

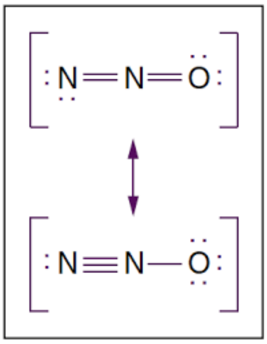


Figure 5- "Molecular structure of nitrous oxide. Nitrous oxide is a linear molecule that exists in two resonance structures. Dots indicate non-bonding electrons". (19)

Nitrous oxide is in gas form at room temperature, whereas volatile gases are liquids at room temperature. They belong to the group of halogens and require vaporizers during administration. Inhalational anesthetics act on the excitatory pathways within the central nervous system. They depress the neurotransmission of acetylcholine on muscarinic and nicotinic receptors, glutamate on NMDA receptors, and serotonin on 5-HT receptors. Furthermore, they intensify inhibitory signals including chloride channels and potassium channels to provide an appropriate level of sedation. Non-volatile agents primarily work on the inhibition of NMDA receptors and glutamate signaling, while volatile agents enhance GABA signaling (22). All inhalational anesthetics have a hypnotic effect. Additionally, halogens stimulate muscle relaxation, bronchodilatation, and amnesia. Nitrous oxide can provide short-term analgesia but does not cause bronchodilatation and muscle relaxation.

According to the Food and Drug Administration (FDA), inhalational anesthetics are indicated for preoperative sedation and perioperative sedation maintenance. Preoperative sedation induces amnesia and anesthesia during surgeries and can be used as a primary or supplementary option. Perioperative sedation maintains anesthesia following initial sedation with intravenous medications like benzodiazepines or propofol.

Additionally, these anesthetics can be used off-label in intensive care units to enhance tolerance of intubation, mechanical ventilation, and various bedside procedures (22).

Anesthetic gases are solely administered via inhalation and rely on multiple factors that determine their therapeutic index. These factors include the minimum alveolar concentration (MAC), alveolar concentration (FA) to inspired concentration (FI), and partition coefficients.

The minimum alveolar concentration is a measure of the potency of inhalational anesthetics. It refers to the proportion of the anesthetic in the inhaled air that achieves adequate pain relief for 50% of patients, ensuring they do not react to highly painful stimuli, such as a surgical skin incision. MAC is inversely proportional to the potency of an anesthetic (potency = 1/MAC) and serves as the ED50 value. The lower the MAC is, the more fat-soluble the anesthetic is. For example, halothane has a high potency due to its high lipid and blood solubility but has a slow induction phase. Contrary to halothane, nitrous oxide has a low potency because of low lipid and blood solubility but a fast induction.

The speed of anesthetic induction is assessed by the ratio of alveolar concentration (FA) to inspired concentration (FI). It operates on a scale from 0 to 1, with the FA/FI ratio approaching 1 as the gas is administered, where 1 represents equilibrium. The speed at which this ratio nears equilibrium reflects the rate of induction.

There are two partition coefficients: Blood-gas coefficient indicates the ratio of anesthetic concentrations in the blood and alveolar space when partial pressures in the two compartments are equal. The higher the blood-gas coefficient, the better the solubility in the blood. The brain-blood coefficient points out the ratio of anesthetic concentration between the brain and the blood when partial pressures remain constant. As with the blood-gas coefficient, the brain-blood coefficient also has a greater solubility in brain tissue if the coefficient is higher (23,24).

For example, nitrous oxide has a minimum alveolar concentration of more than 100%, a blood gas partition coefficient of 0.47, and brain blood coefficient of 1.1. This indicates that this inhalation gas has a very fast induction but low potency. Desflurane on the other hand has a MAC of 6 to 7%, a blood-gas-coefficient of 0.42 and brain-blood-coefficient of 1.3.
Consequently, a greater concentration of desflurane is required to achieve anesthesia compared to more potent agents like isoflurane or sevoflurane which have an MAC of 1,4% and 2%. Due to its low blood-gas partition coefficient, desflurane is favored for its rapid onset and recovery.

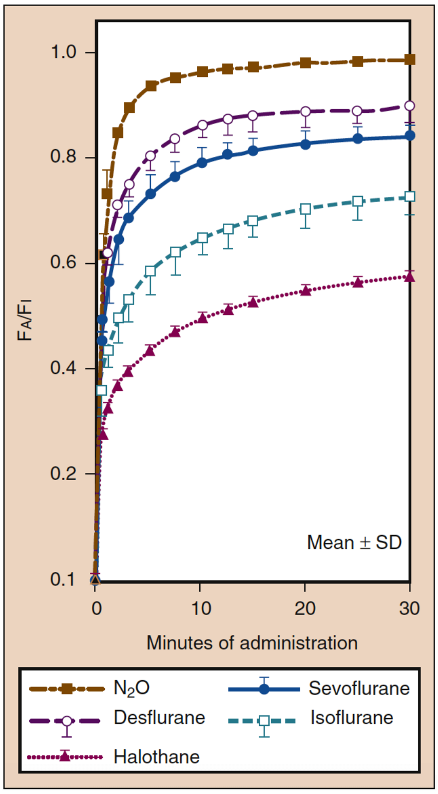


Figure 6- "The rate of induction of anesthesia is paralleled by the rate of increase in the alveolar concentration (Fa)." (25)"

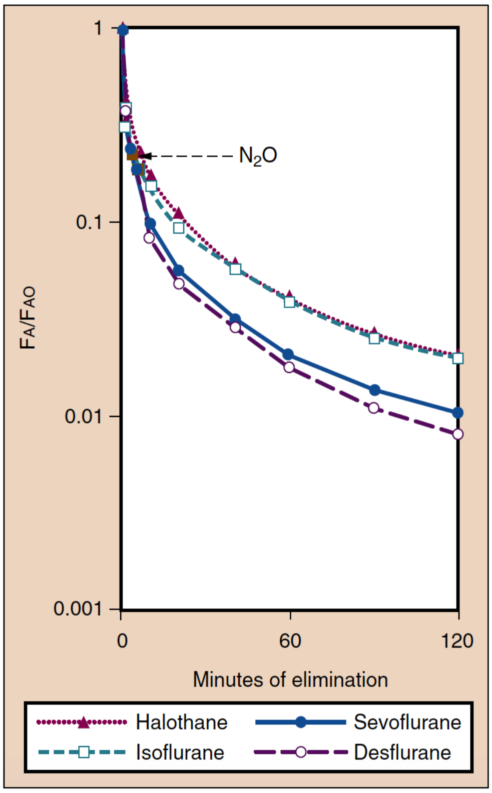


Figure 7- "The rate of induction of anesthesia is paralleled by the rate of increase in the alveolar concentration (Fa)." (25)"

Adverse reactions of these drugs include postoperative nausea and vomiting, risk of malignant hyperthermia (except for nitrous oxide) and postoperative shivering (24).

5.2 Commonly Used Volatile Anesthetics and their Effect on Global Warming

For 180 years inhalational anesthetics have been used for clinical purposes. The global warming potential (GWP) is a commonly used measure to quantify and compare the warming effect of each greenhouse gas (8,26). It is an index that shows how much heat a greenhouse gas can trap in the atmosphere over a specific period of time. Common time scales are 20, 50, or 100 years. These are then labeled GWP20, GWP50, or GWP100. In the Kyoto Protocol, an international agreement linked to the United Nations Framework Convention on Climate Change, GWP 100 is used as the guideline value.

Carbon dioxide is being used as the reference for all GWP calculations and has a GWP of 1, regardless of the time period used (27).

Shorter time horizon GWPs, such as the 20-year GWP, may be more appropriate for assessing the effects of short-lived volatile anesthetics (8,18).

The GWP of each gas depends on its atmospheric lifetime, its spectrum-specific radiation absorption capacity, and the wavelength at which the greenhouse gas absorbs. In their paper, McGain and colleagues state that the atmospheric lifetime of a molecule is determined by the rate at which it is degraded, primarily by the OH radical. The carbon-fluorine (C–F) bond is stronger than carbon-hydrogen (C–H), carbon-chlorine (C–Cl), and carbon-bromine (C–Br) bonds, making it more resistant to the displacement of fluorine atoms by atmospheric OH radicals. For that reason, inhalational anesthetics like desflurane, isoflurane, and sevoflurane have varying lifetimes of 14, 3.2 and 1.1 years (18).

Comparing the wavelength, Koch et al. state that a greenhouse gas is more potent the less it absorbs in the same infrared spectrum of the natural greenhouse gases, water vapor and Co_2 (8).

For instance, methane (CH4) has a GWP up to 30 over 100 years, which means that it is up 30 times more effective at trapping heat than CO_2. Nitrous oxide has a GWP of about 298 for a 100- year timescale and is responsible for the majority of continuing ozone depletion (18,27). 1kg of nitrous oxide captures the same amount of heat over 100 years as 298kg of CO_2 (26).

During the last years, the utilization of volatile anesthetics has increased dramatically and will further rise in the upcoming years due to improved medical care and obsolescence in the western countries leading to more medical interventions and surgeries under general anesthesia. At present, hydrofluorocarbons, desflurane and sevoflurane, chlorofluorocarbon, isoflurane, and nitrous oxide are the most regularly used inhalational anesthetic agents. In 2014, inhalational anesthetics produced a $CO_2{}^{-eq}$ of 3 million tons. Desflurane alone is responsible for over 80% of these emissions.

Even though the Kyoto Protocol banned most halogenated hydrocarbons in 2006, volatile anesthetics are excluded from this contract since they are necessary for medical procedures (8).

As discussed in the previous paragraph, desflurane is a volatile anesthetic with unique characteristics and a significant environmental impact. Clinical characteristics of it include a rapid onset and offset due to low blood-gas and tissue-blood solubilities (5) .

The GWP100 of desflurane is 2540, indicating that it contributes 2540 times more to global warming than an equivalent mass of carbon dioxide. By contrast, sevoflurane has a GWP100 of only 130, while isoflurane has a GWP100 of 510 (28).

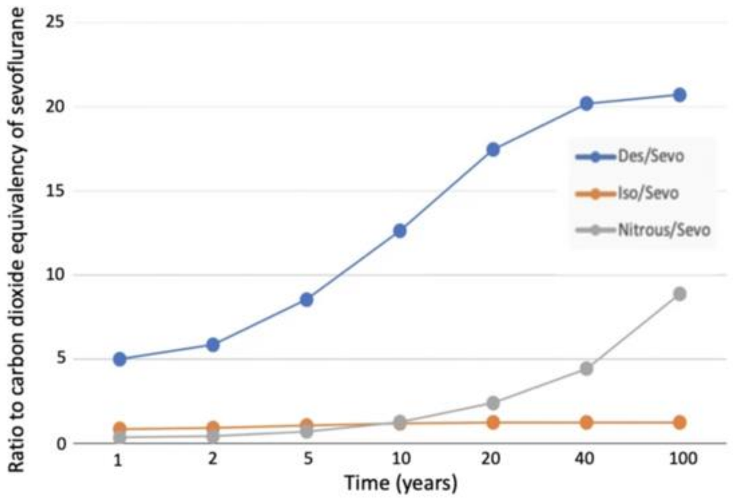
After desflurane, nitrous oxide has the second largest impact on climate change over 100 years and is the "third most climatologically significant greenhouse gas after CO_2 and methane." (8,28) According to McGain et al, nitrous oxide can be used to reduce the amount of other volatile agents needed to deliver one MAC-hour of anesthetic. However, this gas has an atmospheric lifetime of 114 years and a GWP100 of 300. It is estimated that the worldwide anesthetic use of nitrous oxide has a 1 to 3% contribution to global N_2O emissions (18).

In their paper, Özelsel et al. calculated the damaging potency in the first few years after gas emission because the GWP20 and GWP100 do not highlight the damaging effects of these greenhouse gases during the first years after elimination (8,29).

To assess the overall impact of using a specific anesthetic, factors such as fresh gas flow (FGF), where higher flow rates result in more anesthetic being released into the atmosphere, the minimum alveolar (MAC) of the volatile agent, with higher MAC values demanding larger quantities of gas, and the persistence of waste gases released into the troposphere, must be taken into consideration (28).

The review of Van Norman et al. underlines that desflurane carries the highest 'eco-footprint' on a per MAC-hour basis of all the volatile agents when administered in an O2/air admixture:15 times that of and 20 times that of sevoflurane (28,30). According to Hanna and Bryson, one hour of 6% desflurane emits a carbon dioxide equivalent similar to driving 320km (a distance equivalent to driving from Vilnius to Riga) (31). In the publication of Koch and Pecher, it is stated that "a 7-hour anesthesia at a fresh gas flow of 0.5 l/min with 2 % sevoflurane causes a greenhouse gas effect comparable to a 783 km car journey; with 1.2 % isoflurane it is 667 km and with 6 % desflurane 3924 km. Anesthesia with 6% of desflurane and a fresh gas flow of 2L per minute, would correspond to driving from the North Cape, Norway to Capetown, Africa in just seven hours". (8)

Isoflurane, halothane, and nitrous oxide are all ozone depleting substances.
Due to its chlorine atom, isoflurane has an important effect on ozone depletion. As a chlorinated and brominated anesthetic gas, halothane contributes to ozone depletion as well. Notably, it is not used anymore in European countries due to other important side effects including hepatotoxicity (21).



Carbon dioxide equivalency ratio of sevoflurane

Figure 8- "Carbon dioxide equivalency ratio of sevoflurane" (29)

Table 1- Different anesthetics and their characteristics

	Clinical Introduction	Atmospheric Lifetime (Year)	GWP (100 Year)	Radiative Efficiency (mW m^{-2} ppb^{-1})	Abundance[b] (ppt)	Emissions[b] (t yr^{-1})	Radiative Forcing[b] 2014 (mW m^{-2})	Radiative Forcing[b] BAU (mW m^{-2})	Radiative Forcing[b] Growth (mW m^{-2})
Halothane	1956[c,d]	1.0[e]	50[f]	130[g]	0.0092	250	0.0012	0.0011	—
Isoflurane	1981[h]	3.2[i]	510[i]	420[g]	0.097	880	0.041	0.043	0.082
Desflurane	1992[h]	14[j]	2540[j]	450[g]	0.30	960	0.13	0.22	0.35
Sevoflurane	1993–1995[k]	1.1[j]	130[j]	370[g]	0.13	1200	0.047	0.00	0.097

[a]Abundances, emissions, and radiative forcing are global and for 2014. Projections on radiative forcing for the business-as-usual (BAU) and Growth scenarios are detailed in the text and are for 2050.
[b]This work.
[c]*Bovill* [2008].
[d]*Robinson and Toledo* [2012].
[e]*Carpenter et al.* [2014].
[f]*Sulbaek Andersen et al.* [2012a].
[g]*Hodnebrog et al.* [2013].
[h]*Halpern* [1993].
[i]*Sulbaek Andersen et al.* [2010].
[j]*Sulbaek Andersen et al.* [2012b].
[k]*Ball and Westhorpe* [2007b].

„Properties and Results for the Anesthetics Halothane, Isoflurane, Desflurane and Sevoflurane: Greenhouse Warming Potentials (GWPs) are based on a 100 year time frame, and abundances are expressed as dry air mole fractions in parts per trillion (10^{-12})[a]"

5.3 Noninhalational Medication used for Anesthesia and their Carbon Footprint

Propofol is an anesthetic agent which is widely used for the induction and maintenance of general anesthesia, as well as for sedation during medical procedures.
It is a phenol derivative which is poorly soluble in water and contains soybean oil, glycerol, egg lecithin and a preservative. These additives give propofol its milky white consistence.
Propofol acts by potentiating the inhibitory effects of the neurotransmitter gamma-aminobutyric acid (GABA) through GABA-A receptors, leading to sedation and anesthesia. The use of propofol is very popular due to its rapid onset of action and quick recovery times, making it a preferred choice in both surgical settings and intensive care units. Side effects of propofol include drowsiness, pain on injection, and effect on cardiovascular system. It is contraindicated in individuals allergic to eggs, soybeans, or soy products due to its formulation (9,10).

Environmental concerns emerge when considering the use of Propofol and other anesthetic medications, such as lidocaine and acetaminophen. Unfortunately, these environmental effects are very complex and multifaceted but rather unexplored. In contrary to inhalational anesthetics, the potential environmental impacts of medications or metabolites which enter the waste stream are often unknown or not even considered. In their study, Kostrubiak et al., discuss the potential for waterborn pollution and environmental toxicity of total intravenous medications.
Propofol can persist in the environment, especially in water and soil due to its non-biodegradability and is fat soluble. For that reason, it is toxic to aquatic life and can bioaccumulate in organisms. To dispose propofol correctly it is recommended to incinerate it at high temperatures (10).

In contrast to propofol, lidocaine, has a low lipid solubility which makes it less likely to bioaccumulate. However, even though it has a short environmental half-life, it can persist near waste-water release points. Acetaminophen can be very toxic on the human body, but its degradation products can result in environmental toxicity even more than the drug itself. Acetaminophen has a short half-life but due to its constant delivery into the environment, it leads to a pseudo-persistence.
Mitigation strategies which focus on the improvement of waste reduction, management and disposal methods (e.g. incineration of propofol) as well as searching for more environmentally friendly alternatives are inevitable for minimizing the environmental footprint of anesthesiology. Nevertheless, additional research to comprehend and address the effects of certain medications properly must be done in the upcoming years (9,10).

5.4 Strategies to Mitigate the Environmental Impact of Anesthetic Agents

In recent years, anesthesia practice has gained more and more attention due to its notable contribution to global warming and reliance on high-impact greenhouse gases. Therefore, a global consensus statement from the "World Federation of Societies of Anesthesiologists" has been developed by 38 members of the working group in 2021.

The following strategies outline an integrated approach to mitigating the environmental footprint of anesthetic agents while maintaining high standards of patient care.

1. Avoidance of high-impact agents and reduction of nitrous oxide use

To minimize the climate effects of anesthesia, it is essential to limit the use of agents with high global warming potential (GWP), such as desflurane and nitrous oxide. These agents should only be utilized in urgent medical situations where no viable alternatives exist. For routine practice, desflurane can be replaced by alternatives like sevoflurane or isoflurane, which have significantly lower GWP's.

Transitioning from centralized nitrous oxide piping systems to portable tank management can significantly reduce wastage and emissions. Given its substantial atmospheric lifetime and dual contribution to climate change and ozone layer depletion, minimizing nitrous oxide usage is an urgent priority.

The European Union has proposed banning desflurane from January 2026, aligning with the "World Federation of Societies of Anaesthesiologists" consensus that providers should prioritize agents with the lowest environmental impact.(18,32,33)

2. Adoption of Low-flow Anesthesia

Implementing low-flow anesthesia techniques, with fresh gas flow rates below 0.5 L/min, can drastically reduce the volume of inhalational gases used, lowering both costs and environmental harm (34). Turning off fresh gas flows—rather than inhaled anesthetic agents (IAA)—during airway manipulation or disconnection from the circuit is an additional measure to reduce wastage. In their review, Samad et al state that anesthetic machines equipped with end-tidal control functions, further optimize gas usage. Additionally, employing adjunctive techniques, such as the use of opiates, ketamine, or regional anesthesia, can reduce the mean alveolar concentration (MAC) of volatile agents required (35).

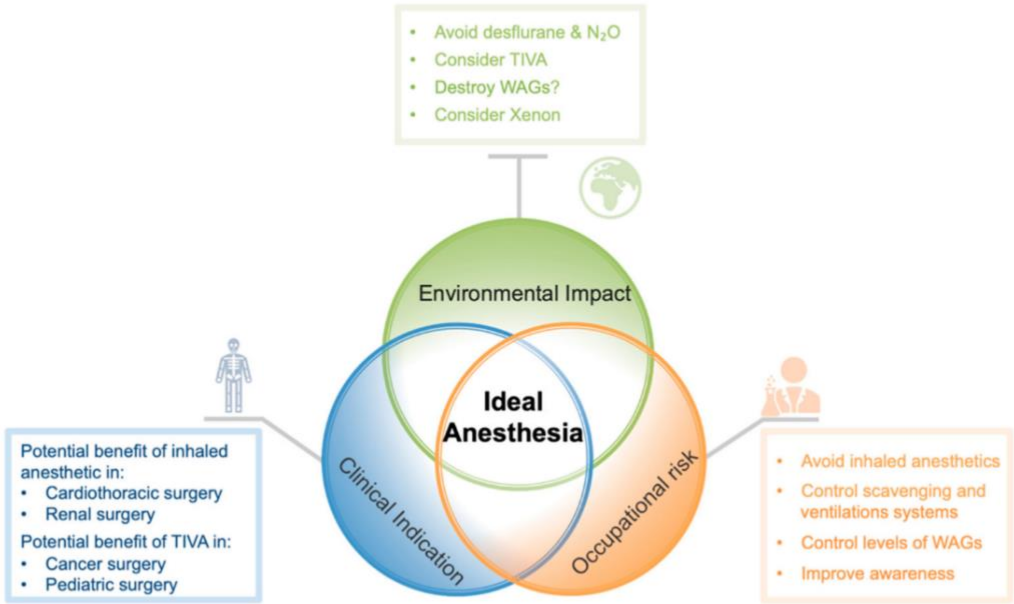


Figure 9- Schemativ view of the three different perspectives in choosing anesthesia technique. Abbreviations: N_2O: Nitrous oxide; TIVA: Total intravenous anesthesia; WAG: Waste anesthetic gas by Gaya da Costa et al. (26)

3. Alternative anesthetic methods

Using alternative techniques, such as total intravenous anesthesia (TIVA) or regional anesthesia, when clinically appropriate, can greatly reduce greenhouse gas emissions. TIVA, particularly with propofol, eliminates reliance on volatile anesthetics that directly contribute to atmospheric greenhouse gases (35). While the life-cycle environmental impact of propofol accounts for emissions from its production and disposal, it is still significantly lower than that of desflurane or nitrous oxide. Research shows that emissions from propofol are approximately one-quarter of those associated with desflurane (36). Nonetheless, addressing wastage - nearly 49% of administered propofol often goes unused - should be a priority to minimize pharmaceutical waste in operating rooms (37).

4. Optimization of anesthetic machines

Enhancing the efficiency of anesthetic machines is an essential approach. Machines equipped with end-tidal control features can significantly reduce the use of inhaled anesthetic agents. Additionally, turning off fresh gas flows during idle periods, such as airway manipulations or circuit disconnections, helps to further limit avoidable emissions (18,34).

5. Use of anesthetic gas filters and recovery systems

The implementation of gas recovery and filter systems represents a promising innovation in sustainable anesthetic practice. These systems can capture and recycle agents like sevoflurane, reducing their environmental impact to levels comparable to propofol (33).

There are two types of filters which are used in the operating room. HEPA filters, are high-efficiency particulate air filters which physically block bacteria and viruses from passing through the anesthesia circuit (38). Heat and moisture exchange filters (HMEFs), enhance comfort of the patient by maintaining moisture levels in inhaled gases through humidification. Typically, they are placed at the expiratory port to prevent contamination and cross-infection between patients.
Importantly, these filters can help significantly in absorption of halogenated inhalational gases like isoflurane and sevoflurane, reducing environmental pollution in operating rooms. However, they must be replaced regularly to avoid obstruction that could lead to inadequate ventilation.
Recovery systems refer to the mechanisms in place for scavenging or removing waste inhalational gases from the operating room environment. Scavenging systems can be differentiated between active and passive systems. Suction is used to remove waste gases from the operating room in active systems, ensuring that excess gases do not accumulate. Passive systems on the other hand, rely on natural airflow and ventilation to disperse waste gases away from the surgical area.
Furthermore, there are two types of interfaces: Open and closed interfaces which either allow waste gases to escape directly into the atmosphere or use valves to contain waste gases within the system until they are safely vented. Open interfaces may pose risks of occupational exposure if they are not managed correctly but can be safer for patients. In contrast, closed interfaces decrease exposure risks for healthcare workers (39). To conclude, anesthetic gas filters and recovery systems minimize the environmental impact of inhalational gases and enhance the safety of both healthcare providers and patients.

6. Optimizing fresh gas flow

Reducing fresh gas flow rates during procedures using agents such as sevoflurane can significantly lower their environmental impact. Although there are concerns about the potential formation of nephrotoxic compounds like Compound A, research has shown that the risk to human patients is negligible (communique sevoflurane).

7. Policy and regulatory support

The guidelines of White et al, which were published in 2022, suggest that institutional and policy support is vital to advancing sustainability in anesthesia practices. Establishing environmental sustainability key performance indicators (KPI) and utilizing digital communication tools can increase awareness and encourage the use of low-impact anesthetic options, such as substituting desflurane with more environmentally friendly alternatives (environmental impact of desflurane) (32).

6. Operating Room Practices and Sustainability

6.1 Energy Consumption and Resource Utilization in the Operating Room

Hospitals are high-energy environments, highlighting the essential need for effective energy management and efficiency in healthcare facilities. Unlike typical buildings, hospitals function continuously, operating 24 hours a day, every day of the year. This constant activity is vital for delivering uninterrupted patient care, but it also leads to significantly higher energy usage. The need for dependable energy is substantial and ongoing, driven by factors such as lighting in various wards and operating rooms, as well as the operation of critical medical equipment that saves lives. To minimize environmental impact and reduce operational costs while also maintaining patient safety and comfort, strategies for energy optimization in operating rooms are crucial.

Moreno et al. have published a research article named “sustainable solutions for thermal energy saving in hospital operating theatres” in 2019. In their paper, they studied and evaluated the annual thermal energy consumption of a conventional operating theatre as well as the installment of a sensible heat recovery system.

Their study shows that sensible heat recovery systems that reuse and recover heat from exhaust air can significantly reduce energy demand. Recirculating 25% of the airflow extracted from the room can lead to a 24.1% reduction in energy consumption.

As the name suggests, heating, ventilation and air conditioning systems (HVAC) have three important functions: heating, ventilation (to renew ambient air and remove bacteria, fungi, and viruses as well as control its temperature), and air conditioning to provide cooling of the room and control humidity of the environment (40). Optimizing these systems to enhance their efficiency is critical. Moreno et al. state, that reducing the supply air volume by 50% while maintaining indoor air quality can lead to substantial energy savings (41).

In their protocol, Chen-Xu et al. underline the importance of Demand-controlled ventilation (DCV) which is a “ventilation control practice that provides the amount of each space based on real-time demand” (40,42). This can be achieved by the implementation of sensors that monitor carbon dioxide levels which adjust ventilation rates based on actual occupancy and air quality needs. Consequently, over-ventilation can be prevented and energy costs reduced (40).

Occupancy-based controls use motion sensors for lighting and HVAC systems which ensure that energy is only consumed when spaces are occupied. According to Chen-Xu et al. this simple adjustment can lead to significant reductions in energy use, especially in areas used intermittently. Regular maintenance and system calibration of HVAC systems can prevent energy wastage and enhance indoor environmental quality which directly benefits patient comfort and safety. In their paper, McGain et al. criticize HVAC systems that exchange room air 20 times per hour in the operating room and 6 times per hour in the intensive care unit. According to the authors, unoccupied Operating rooms do not need this frequent number of air changes since microbiological contamination does not increase either when lowering the fluctuation of air (18). Energy-efficient lighting like LED lighting fixtures decrease energy consumption and extend the lifespan of lighting systems which also reduces maintenance costs. Automated lighting systems can achieve up to a 30% reduction in energy use (43).

Thermal insulation improvements in operating theatres help to maintain optimal indoor temperatures with less energy input, consequently contributing to overall energy savings.

Combined heat and power (CHP), also known as cogeneration is a technology that produces electricity and thermal energy at high efficiencies using a range of technologies and fuels (44). According to Koch et al. CHP plants could generate electricity and heat in a completely CO2-neutral way with a good energy yield if they were converted to run on renewable energy sources like biomass or regeneratively produced hydrogen, etc. (8). Other studies have confirmed that utilizing cogeneration or trigeneration systems, minimize energy losses and reduce overall consumption by 8% to 25% in hospital settings (45).

A major energy consumer in hospitals are water heating systems. These need to be upgraded to high-efficiency water heaters and insulating hot-water pipes can reduce high energy costs in the hospital. Another strategy to promote energy efficiency in hospitals is to conduct regular energy audits which can help identifying areas of high energy consumption and inefficiencies.

Investing in renewable energy sources is a crucial part of energy savings and efficiency. Hospitals should explore various options like solar panels or geothermal systems which offer sustainable energy solutions and reduce reliance on conventional power sources.

Furthermore, hospital staff should be trained and educated on energy-saving practices and incentive programs can help promote sustainability within the hospital (46,47).

These strategies for energy optimization can achieve significant energy savings, reduce operational costs, and most importantly, contribute positively to environmental sustainability while maintaining high-quality standards in operating rooms. A study published by MacNeill et al. compares the carbon footprint of three big hospitals in the US, Great Britain and Canada in 2011.

The results showed that the CO_2^{-eq} emissions for all three clinics were in the range of 3220-5190t CO_2^{-eq} per year. These emissions are attributable primarily to the energy sector (electricity, heating, and air conditioning) and the use of inhaled anesthetics. In contrast to the hospitals in the USA and Great Britain, which use coal as an energy source, the Vancouver General Hospital obtained its energy mostly from hydroelectric power plants, reducing its carbon footprint by a factor of 10. This underlines the fact that hospitals that invest in renewable energy can have a significant impact on a more sustainable and healthy future.

Table 2- CO_2 emissions and hospitals

	Proportionate range of hospital-CO2-emissions (%)	Saving concepts
Anaesthetic use	4-63	No use of desflurane reduces CO2 emissions from 63% to 4%
Energy sector (heating, air conditioning, ventilation, electricity)	17-84	Use of renewable energies reduces CO2 emissions from 84% to 17%
Waste management (household waste, toxic/infectious waste, water consumption, reusable textiles)	12-20	No major differences between three clinics analysed

Share of CO_2 emissions from hospitals and their savings potential. (Based on data from MacNeill et al.; translated from Koch et al. (8,48)

6.2 Healthcare Waste and Management

Over the past decades, the global population has grown significantly leading to an expansion in the healthcare industry and improved access to healthcare services. Consequently, the amount of healthcare waste (HCW) has increased exponentially (49). Factors like location, type of hospital, and patient load play a crucial role in the estimation of waste quantity. According to the World Health Organization, major sources of healthcare waste are hospitals and other facilities, laboratories and research centers as well as mortuary and autopsy centers (50).

In 2020, Anicetus et al. published a study that investigates the quantity of healthcare waste categorically in four different hospitals in Tanzania based on their level and capacity. For fourteen days, non-infectious, sharps, infectious, infectious plastics, and pathological waste were collected and measured. The general waste generation varied from around 298.9kg to 1554.4kg per day in these hospitals, depending on their specialization and work actions (51). Some studies report that in North America about 7.0 to 10.0kg per bed per day are generated while the average of waste in Western European countries lies between 3.0 to 6.0kg per day. The World Health Organization states that 85% of the total amount of waste generated by healthcare activities is general, non-hazardous waste. Hazardous waste material, like infectious, toxic, carcinogen, radioactive, etc. accounts for the remaining 15%. According to the WHO high-income countries generate up to 0.5kg of hazardous waste per hospital bed per day, while low-income countries only produce 0.2kg per day. Notably, low-income countries do not distinguish or properly separate waste into their different categories which is why real quantity is hard to estimate (50).

In their paper, McGain et al. state that a quarter of all hospital waste is generated by operating suites and up to 25% of that from anesthesia (18). Furthermore, 80% of waste material including plastic packaging of surgical instruments and single-use equipment, is collected before the surgery.

To minimize health care waste, there are multiple approaches and strategies which can be implemented. In general, hospitals should focus on the five Rs: "reduce, reuse, recycle, rethink and research" (28).

Waste minimization can be achieved by considering reusable medical equipment instead of disposables. McGain et al. suggest that single-use surgical gowns, hats, and overshoes can be substituted by reusable ones, for example, laundered hats and appropriate footwear. This will not only reduce waste but also maintain hygienic control standards. Additionally, greener packaging and materials should be promoted by hospitals and manufacturers. Recycling plays a vital role in the minimization of waste.

Single-use devices can often be recycled by special companies who clean, retest, and repackage them. According to Van Norman et al. the U.S. Government accountability office has shown that adequately recycled or "remanufactured" materials and devices like surgical staplers, blood pressure cuffs and cardiological catheters are a lot more inexpensive while maintaining the same high standards and quality as new products (18,28). The healthcare plastics recycling council stresses that recycling 11 tons of plastics, paper, etc. from a surgery ward with six theaters, generated approximately 15 tons less CO_2 emissions (120 000km driven) than the production of new plastic materials. According to the council: "Recycling one ton of plastic saves 16.3 barrels of oil, 30 cubic yards of landfill and 5774 kW of energy (enough to power an average US household for 6 months)." (52).

Multiple life cycle assessments (LCAs) have highlighted the significant impact of pharmaceutical and medical devices on health-care related CO_{2e} emissions, revealing that wasted unused supplies offer opportunities for pollution reduction. Improved management of stock levels could help minimize waste, while surplus supplies might be effectively donated. Anesthetists and intensivists can engage in hospital product evaluation committees and incorporate LCA factors into the procurement process, urging manufacturers and suppliers to offer more environmentally sustainable products (18,53,54).

Prevention programmes, for instance "Choosing Wisely" which is an initiative of the American Board of Internal Medicine Foundation, focuses on maintaining and improving clinical care whilst promoting rational resource use. Reducing unnecessary investigations, avoiding medically ineffective operations and critical care admissions, as well as certain medications can significantly minimize the environmental footprint of healthcare (18,55).

In their recommendations to improve environmental sustainability in the operating room and perioperative area by Van Norman et al. it is advocated that pharmaceutical waste like acutely toxic drugs (e.g. epinephrine and nitroglycerin) should be triaged for high-heat incineration. Additionally, drugs, particularly propofol, should not be disposed by entering wastewater or be dumped down the drain. Old electronic equipment should also be recycled by a certified sustainable electronics vendor and should be refurbished for donation. Lithium-ion batteries, lead-acid batteries, and disposable batteries should be recycled. According to Van Norman et al. the strategies to improve environmental sustainability in the operating room and perioperative area, listed in their recommendations are effective and have led to a decrease of 64% CO_2 per case. Notably, 25,000 US dollars of cost savings per month were achieved as well (28).

Table 3- Comparison of medical specialisms and their Hazardous waste contribution and generation

Medical specialisms	HHCW contribution (%)	Rank	Average number of active beds/years	Rank	HHCW generation rate (kg/bed/day)	Rank	HHCW generation rate interval (kg/bed/day)
Internal medicine	16.22	1	346	1	0.87	13	0.77–0.97
Anesthesiology and intensive care	10.09	2	75	7	2.38	3	1.88–3.02
Surgery	9.39	3	151	3	1.10	8	0.77–1.43
Cardiology	8.21	4	145	4	1.00	10	0.94–1.14
Heart surgery	7.18	5	50	11	2.52	2	2.38–2.66
Obstetrics and gynecology	7.15	6	145	4	0.87	13	0.78–1.06
Neurosurgery	5.42	7	30	16	3.20	1	3.15–3.32
Pediatrics	5.31	8	167	2	0.56	15	0.52–0.61
Pulmonology	5.06	9	103	6	0.89	12	0.62–1.40
Urology	4.37	10	50	11	1.55	5	1.36–1.85
Orthopedics	4.16	11	55	10	1.34	6	0.91–1.63
Neurology	3.69	12	63	9	1.04	9	0.91–1.16
Neonatology	3.21	13	NA*	21	NA*	21	NA*
Dermatology	2.63	14	40	13	1.17	7	1.08–1.22
Dentistry	2.27	15	NA**	21	NA**	21	NA**
Oro-maxillofacial surgery	1.90	16	18	19	1.87	4	1.11–2.86
Oncology, oncoradiology	1.20	17	65	8	0.33	18	0.29–0.39
Emergency patient care	0.84	18	15	20	1.00	10	0.07–2.04
Ophthalmology	0.80	19	38	14	0.39	16	0.34–0.44
Otolaryngology	0.70	20	38	14	0.35	17	0.30–0.40
Rheumatology	0.18	21	20	18	0.16	19	0.11–0.27
Psychiatry	0.02	22	22	17	0.01	20	0.01–0.03

NA Not applicable

* The neonatology department does not have patient beds

** In the field of dentistry, the services are typically limited to outpatient care, with no provision for 24 h stays. Therefore, dental department does not have any beds listed in the database

Ranking of medical specialism by percentage of HHCW contribution, active beds, HHCW generation rate and HHCW generation rate interval from 2017 to 2021 at the University of Debrecen Clinical Centre Nagyerdei Campus (UDCC NC) Hungary, Kaposi et al. (56)

The COVID-19 pandemic has significantly influenced waste generation in hospitals and has led to an extreme increase in healthcare waste, particularly infectious medical waste.

Kaposi et al. researched that medical specialties like anesthesiology and intensive care as well as pulmonology, and emergency care generated an extraordinary amount of healthcare waste during the pandemic (56).

The city of Wuhan, China reports that 6 times more medical waste has been generated during COVID-19. In India, there was a 10% increase in medical waste generation, and in Manila, Philippines, 280 tons/day of medical waste have been added to the normal waste generation (57). According to the WHO, 87 000 tons of personal protective equipment (PPE), has been obtained and forwarded to countries in need between March 2020 and November 2021. It is assumed that a major part of this ended up as waste (58).

During COVID-19 existing systems for waste management were overwhelmed with a huge amount of waste leading to illegal dumping and uncontrolled burning of it, especially in regions with limited resources.

7. Case Studies Highlighting Successful Implementation of Sustainable Operating Room Initiatives

In recent last years, the pressure of finding more sustainable and innovative strategies to reduce waste and improve the environmental impact of operating rooms has increased.

Several hospitals and medical centers have implemented new techniques to improve their environmental impact and be a good example for other hospitals and health institutions.

“Greening the Operating Room“, an initiative by Practice Green Health, promotes best practices for sustainability in operating theaters across multiple hospitals. The initiative strives for collaboration between healthcare organizations and successfully sharing strategies and resources for reduction of waste and enhancing efficiency. “Practice Green Health” offers resources to help members develop proactive frameworks for undertaking Greening the OR strategies. Our goal is to provide step-by-step resources that make it simpler for any hospital to design, implement, and measure the success of efforts that reduce energy use, supply costs, and waste generated in the operating room.” (59). Following that, the Cleveland Clinic was able to save more than 4 million US dollars through “Practice Green Health” in 2017.

Inova Fairfax Hospital is a 900-bed trauma 1 community hospital in the USA, which was able to reduce 14% of red bag waste and saved over 200,000 US dollars in waste removal fees. It achieved an 18.6% reduction in regulated medical waste generated by its operating rooms over six months, resulting in savings exceeding 15,000 US dollars. This hospital is a great example which shows that a focused approach to waste management can have significant potential for long-term savings and environmental benefits.

An article published by Stanford Healthcare Magazine introduces strategies that have been implemented throughout the last years which include forming “green teams”, comprising surgeons and anesthesiologists who focus on reducing waste in the operating room. According to the article, changes, such as selecting more sustainable anesthetics and altering surgical practices to minimize waste, were made. The initiative aims to balance patient safety with environmental sustainability with a commitment to educating staff and changing the culture of surgery towards greener practices (60).

The Karolinska University Hospital in Sweden was able to make significant progress in sustainability by eliminating the use of polyvinylchloride products. Their green initiative focuses on reducing environmental impact through careful selection of materials and sustainable practices in their operating rooms (61).

The Green Bavarian Hospital Initiative is a program which was initiated by the Bavarian State Ministry of Health and Care in 2011. It aims to enhance sustainability and energy efficiency of hospitals in Bavaria, Germany and contributes to the state’s goal of becoming climate neutral by 2040. The Regiomed Klinikum Lichtenfels is highlighted as a flagship project within this initiative, showcasing advanced sustainability measures such as triple-glazed windows, heat recovery systems, geothermal energy, and solar integration (62,63).

The Hubertus Protestant Hospital in Berlin, Germany was the first hospital in Germany to receive the “energy-saving hospital” label after successfully reducing its energy consumption by 37% and cutting carbon dioxide emissions by 2,600 tons. Their “green OR committee” focuses on energy efficiency and waste reduction strategies within surgical departments (63).

The Bethesda Hospital in Hamburg, Germany has optimized supply chain logistics to minimize excess materials and waste generation. Their sustainability initiatives play an important role in a larger movement which aims to improve environmental responsibility in healthcare environments.

CUF Tejo Hospitals and Clinics from Portugal, have developed a “greener operating theatre” concept, which addresses the high resource consumption in surgical areas.

By abolishing the highly polluting anesthetic desflurane in favor of sevoflurane, the hospital has actively worked on reducing its carbon footprint. It is estimated that the shift from desflurane to sevoflurane will prevent over 1,000 tons of CO_2 emissions during surgical procedures. Furthermore, the Portuguese hospital has implemented sustainability strategies which include regular carbon footprint assessments and staff engagement in environmental practices (64).

These examples illustrate how hospitals from different countries in the US and Europe are successfully implementing sustainable practices through dedicated green OR committees, focusing on waste reduction, energy efficiency, and environmentally friendly materials to create more sustainable and efficient operating rooms and hospitals.

Table 4- Checklist for adaptation strategies

Topics	Concepts	
Co-operation of all employees	Establish multidisciplinary 'green teams' Disseminate information Offer training	☐ ☐ ☐
Anesthetics	Avoid desflurane and nitrous oxide anesthesia Use low-flow techniques Use TIVA with propofol Use regional anaesthesia	☐ ☐ ☐ ☐
Energy management	Switch to renewable energies Use well-maintained and energy-saving electrical devices Only switch on air conditioning systems in the operating theatre during operating hours Install motion sensors in stairwells/corridors Use LED lamps across the board	☐ ☐ ☐ ☐ ☐
Waste management		
Reduce	Use ventilation tubes for 7 days Use restrictively stocked ready-to-use sets Avoid excess Consider use of pre-filled syringes Select adequate ampoule sizes Use responsible paper printing	☐ ☐ ☐ ☐ ☐ ☐
Reuse	Consider reuse of reusable products Surgical textiles Laryngeal masks Laryngoscopes Medication trays	☐ ☐ ☐ ☐ ☐
Recycle	Develop concepts for the operating theatre Paper/cardboard Plastic Glass Metal	☐ ☐ ☐ ☐ ☐
Rethink	Rethink sustainability concepts of industry partners Healthy cuisine "Divestment"	☐ ☐ ☐
Research	Establish research audits Benchmarking Carry out ecological research projects	☐ ☐ ☐

Mobility	Work-related travel Use public transport/offer job tickets Promote the construction of cycle paths/cycle parking spaces Educational trips Attend local training courses Avoid air travel Offer Teleconferencing/congress streaming	☐ ☐ ☐ ☐ ☐ ☐ ☐

Idea Checklist for the beginning of an ecologic concept at an anesthesiologic department

8. Results and Conclusion

Anesthesiology and global climate change present both challenges and opportunities for the medical community. This thesis has explored the significant environmental impact of anesthetic practices, focusing on the use of volatile anesthetic agents, and their contribution to greenhouse gas emissions. Furthermore, it unfolds operating room practices, waste management and presents sustainable anesthetic practices in the hospital. Findings underscore the urgent need for hospitals to adjust to environmentally friendly alternatives and underline their beneficence.

Inhalational gases, especially desflurane and nitrous oxide, have been identified as potent greenhouse gases with global warming potentials far exceeding that of carbon dioxide. The healthcare sector, including anesthesiology, is a substantial contributor to global carbon emissions, necessitating immediate action to reduce its environmental footprint.
Mitigation strategies have been discussed, including the use of low-flow anesthesia, preference for less harmful anesthetic agents like sevoflurane, and the implementation of capture and recycling technologies for waste inhalational gases. Waste management guidelines including “reduce, reuse, recycle, rethink and research” have been emphasized. The potential for innovation in anesthetic delivery systems and the development of more environmentally friendly anesthetic agents offer promising advantages for future research and development. Education and awareness among anesthesiologists and other healthcare professionals about the environmental impact of their practices are crucial for driving change.

Over the next decades the world is going to be confronted with even more challenges due to climate change which is why anesthesiology is uniquely positioned to set a precedent for sustainability in healthcare. By promoting eco-friendly practices, anesthesiologists can substantially decrease their environmental impact while maintaining excellent patient care standards.

It is crucial that environmental awareness will be emphasized in anesthesiology practice, research and training. This fundamental change will not only support global climate change mitigation efforts but also the field in line with broader sustainable healthcare objectives.

To conclude, the connection and relationship between anesthesiology and global climate change is very complex and many-sided. However, through collaborative action, creative solutions, and a dedication to sustainability, anesthesiologists can be great examples for progressing into a more environmentally responsible healthcare community.

9. References

1. Evolution of Anesthesiology as a Clinical Discipline: A Lesson in Developing Professionalism | Anesthesiology, 3e | AccessAnesthesiology | McGraw Hill Medical [Internet]. [cited 2025 Jan 30]. Available from: https://accessanesthesiology.mhmedical.com/content.aspx?bookid=2152&sectionid=164215839
2. Was macht ein/e Anästhesist/in? » Anästhesie » Anästhesisten im Netz - Ihr Portal für Anästhesie, Intensivmedizin, Notfallmedizin, Schmerzmedizin und Palliativmedizin » [Internet]. [cited 2024 Dec 1]. Available from: https://www.anaesthesisten-im-netz.de/anaesthesie/was-macht-ein/e-anaesthesist/in/
3. Made For This Moment | Anesthesia, Pain Management & Surgery [Internet]. [cited 2024 Dec 1]. General Anesthesia - Definition & Side Effects | Made for This Moment. Available from: https://madeforthismoment.asahq.org/anesthesia-101/types-of-anesthesia/general-anesthesia/
4. Forman SA, Chin VA. General Anesthetics and Molecular Mechanisms of Unconsciousness. Int Anesthesiol Clin. 2008;46(3):43–53.
5. Wolfe RC. Inhaled Anesthetic Agents. J Perianesth Nurs. 2020 Aug 1;35(4):441–4.
6. Common Medications Used In Anesthesia [Internet]. [cited 2025 Jan 30]. Available from: https://www.aegisanesthesiapartners.com/common-medications-used-anesthesia/
7. Bildung B für politische. bpb.de. [cited 2024 Nov 30]. Klima und Klimawandel. Available from: https://www.bpb.de/kurz-knapp/lexika/lexikon-in-einfacher-sprache/286916/klima-und-klimawandel/
8. Koch S, Pecher S. Neue Herausforderungen für die Anästhesie durch den Klimawandel. Anaesthesist. 2020 Jul 1;69(7):453–62.
9. Der natürliche Treibhauseffekt [Internet]. [cited 2024 Nov 30]. Available from: https://www.klimanavigator.eu/dossier/artikel/011967/index.php
10. Causes of climate change - European Commission [Internet]. [cited 2024 Nov 30]. Available from: https://climate.ec.europa.eu/climate-change/causes-climate-change_en
11. What is the greenhouse effect? - NASA Science [Internet]. [cited 2024 Nov 30]. Available from: https://science.nasa.gov/climate-change/faq/what-is-the-greenhouse-effect/
12. The Paris Agreement | UNFCCC [Internet]. [cited 2024 Dec 10]. Available from: https://unfccc.int/process-and-meetings/the-paris-agreement
13. A refresher on the Paris Climate Agreement [Internet]. 2021 [cited 2025 Jan 31]. Available from: https://macmillan.yale.edu/stories/refresher-paris-climate-agreement
14. Climate change [Internet]. [cited 2024 Nov 30]. Available from: https://www.who.int/news-room/fact-sheets/detail/climate-change-and-health
15. NABU - Naturschutzbund Deutschland e.V. [Internet]. [cited 2024 Dec 9]. Ursachen des Klimawandels - NABU. Available from: https://www.nabu.de/umwelt-und-ressourcen/klima-und-luft/klimawandel/06738.html
16. Ursachen des Klimawandels [Internet]. [cited 2024 Dec 9]. Available from: https://www.klimawandelanpassung.at/kwa-allgemein/kwa-ursache
17. Klimawandel aktuell 2023 - Ursachen und Folgen, Prognose - Globale Erderwärmung CO2-Emissionen - Klimaschutz Maßnahmen - Was tun gegen den Klimawandel? - LpB BW [Internet]. [cited 2024 Dec 9]. Available from: https://www.lpb-bw.de/klimawandel
18. McGain F, Muret J, Lawson C, Sherman JD. Environmental sustainability in anaesthesia and critical care. BJA Br J Anaesth. 2020 Nov;125(5):680–92.
19. NYSORA. NYSORA. 2022 [cited 2024 Dec 14]. Inhalative Anästhetika. Available from: https://www.nysora.com/de/An%C3%A4sthesie/inhalierte-An%C3%A4sthetika/
20. Brandt L, Adams HA, Hönemann C. 170 years of ether anaesthesia – an epochal event with a long history. Anästh Intensiv.
21. Vollmer MK, Rhee TS, Rigby M, Hofstetter D, Hill M, Schoenenberger F, et al. Modern inhalation anesthetics: Potent greenhouse gases in the global atmosphere. Geophys Res Lett.

2015;42(5):1606–11.
22. Clar DT, Patel S, Richards JR. Anesthetic Gases. In: StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing; 2024 [cited 2024 Dec 9]. Available from: http://www.ncbi.nlm.nih.gov/books/NBK537013/
23. European Journal of Anaesthesiology | EJA [Internet]. [cited 2025 Jan 31]. Available from: https://journals.lww.com/ejanaesthesiology/abstract/2009/10000/anaesthetic_mechanisms__update_on_the_challenge_of.2.aspx
24. Kreuer S, Bruhn J, Wilhelm W, Bouillon T. Pharmakokinetische/pharmakodynamische Modelle für Inhalationsanästhetika. Anaesthesist. 2007 Jun 1;56(6):538–56.
25. NYSORA. NYSORA. 2022 [cited 2024 Dec 9]. Inhaled Anesthetics. Available from: https://www.nysora.com/anesthesia/inhaled-anesthetics/
26. Gaya da Costa M, Kalmar AF, Struys MMRF. Inhaled Anesthetics: Environmental Role, Occupational Risk, and Clinical Use. J Clin Med. 2021 Mar 22;10(6):1306.
27. US EPA O. Understanding Global Warming Potentials [Internet]. 2016 [cited 2024 Dec 11]. Available from: https://www.epa.gov/ghgemissions/understanding-global-warming-potentials
28. Van Norman GA, Jackson S. The anesthesiologist and global climate change: an ethical obligation to act. Curr Opin Anaesthesiol. 2020 Aug;33(4):577–83.
29. Özelsel TJP, Sondekoppam RV, Buro K. The future is now—it's time to rethink the application of the Global Warming Potential to anesthesia. Can J Anesth Can Anesth. 2019 Nov 1;66(11):1291–5.
30. The Environmental Impact of Inhaled Anesthetics [Internet]. [cited 2024 Dec 12]. Available from: https://www.asahq.org/about-asa/governance-and-committees/asa-committees/environmental-sustainability/greening-the-operating-room/inhaled-anesthetics
31. Hanna M, Bryson GL. A long way to go: minimizing the carbon footprint from anesthetic gases. Can J Anesth Can Anesth. 2019 Jul 1;66(7):838–9.
32. White SM, Shelton CL, Gelb AW, Lawson C, McGain F, Muret J, et al. Principles of environmentally-sustainable anaesthesia: a global consensus statement from the World Federation of Societies of Anaesthesiologists. Anaesthesia. 2022;77(2):201–12.
33. Müller S. Einfluss der Anästhesiegase auf den Klimawandel. Müller Wulf H Einfluss Anästhesiegase Auf Den Klimawandel. 2023 Nov 8;(11–2023):418–27.
34. Samad K, Yousuf MS, Ullah H, Ahmed SS, Siddiqui KM, Latif A. Anesthesia and its environmental impact: approaches to minimize exposure to anesthetic gases and reduce waste. Med Gas Res. 2024 Jun 26;15(1):101–9.
35. Lane SF. The environmental sustainability of propofol use in daily practice. Br J Anaesth. 2020 Jun 1;124(6):e221–2.
36. Sherman J, Le C, Lamers V, Eckelman M. Life cycle greenhouse gas emissions of anesthetic drugs. Anesth Analg. 2012 May;114(5):1086–90.
37. Gasciauskaite G, Lunkiewicz J, Tucci M, Von Deschwanden C, Nöthiger CB, Spahn DR, et al. Environmental and economic impact of sustainable anaesthesia interventions: a single-centre retrospective observational study. Br J Anaesth. 2024 Dec 1;133(6):1449–58.
38. Chellam S, Dalal KS, Toal PV. Use of filters in anaesthesia: Is it warranted? Indian J Anaesth. 2014 Aug;58(4):475.
39. Anesthesia Gas Machine- Scavenging and WAGs [Internet]. [cited 2025 Jan 15]. Available from: https://healthprofessions.udmercy.edu/academics/na/agm/10.htm
40. Chen-Xu J, Kislaya I, Fernandes RM, Carvalho J, Blanco-Rojas BJ, El-Omrani O, et al. Interventions for increasing energy efficiency in hospitals. Cochrane Database Syst Rev. 2024 Mar 5;2024(3):CD015693.
41. Sánchez-Barroso Moreno G, García-Sanz Calcedo J, González AG, Salgado DR. Sustainable solutions for thermal energy saving in hospital operating theatres. Balan MC, Bode F, Croitoru C, Dogeanu A, Georgescu A, Georgescu C, et al., editors. E3S Web Conf. 2019;85:01002.
42. Integrating Health and Energy Efficiency in Healthcare Facilities.
43. Sensgreen. Energy Optimization for Hospitals: 8 Use Cases that Drive Savings [Internet].

Sensgreen. 2024 [cited 2025 Jan 18]. Available from: https://sensgreen.com/energy-optimization-for-hospitals-8-use-cases-that-drive-savings/
44. US EPA O. What Is CHP? [Internet]. 2015 [cited 2025 Jan 29]. Available from: https://www.epa.gov/chp/what-chp
45. Suszanowicz D, Ratuszny P. Energy efficiency improvement in hospital buildings, based on the example of a selected type of hospital facility in Poland. IOP Conf Ser Mater Sci Eng. 2019 Oct;564(1):012129.
46. 15 Strategies to Running Energy Efficient Hospitals - Aemaco [Internet]. 2024 [cited 2025 Jan 20]. Available from: https://aemaco.com/2024/09/01/energy-efficient-hospitals/
47. Key.com [Internet]. [cited 2025 Jan 20]. Energy efficiency in hospitals | Key. Available from: https://www.key.com/businesses-institutions/business-expertise/articles/energy-efficiency-strategies-for-hospitals.html
48. MacNeill AJ, Lillywhite R, Brown CJ. The impact of surgery on global climate: a carbon footprinting study of operating theatres in three health systems. Lancet Planet Health. 2017 Dec;1(9):e381–8.
49. Joneghani NM, Zarrinpoor N, Eghtesadifard M. A mathematical model for designing a network of sustainable medical waste management under uncertainty. Comput Ind Eng. 2022 Sep 1;171:108372.
50. Healthcare waste [Internet]. [cited 2025 Jan 20]. Available from: https://www.who.int/news-room/fact-sheets/detail/health-care-waste
51. Anicetus H, Saria J, Mohamed H. Estimation of Different Categories of Healthcare Waste Generated at Two Different Hospital Categories in Four Hospitals in Dar es Salaam City. J Environ Prot. 2020 Sep 28;11(10):872–88.
52. Communicating Your Hospital Recycling Program Successes and Lessons Learned - Healthcare Plastics Recycling Council [Internet]. [cited 2025 Jan 18]. Available from: https://www.hprc.org/resources/communicating-your-hospital-recycling-program-successes-and-lessons-learned/
53. Environmental Impacts of the U.S. Health Care System and Effects on Public Health | PLOS ONE [Internet]. [cited 2025 Jan 18]. Available from: https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0157014
54. The carbon footprint of Australian health care - ScienceDirect [Internet]. [cited 2025 Jan 18]. Available from: https://www.sciencedirect.com/science/article/pii/S2542519617301808
55. Choosing Wisely: Helping Physicians and Patients Make Smart Decisions About Their Care | Health Care Quality | JAMA | JAMA Network [Internet]. [cited 2025 Jan 18]. Available from: https://jamanetwork.com/journals/jama/article-abstract/1150103
56. Kaposi A, Nagy A, Gomori G, Kocsis D. Analysis of healthcare waste and factors affecting the amount of hazardous healthcare waste in a university hospital. J Mater Cycles Waste Manag. 2024 Mar 1;26(2):1169–80.
57. Jayasinghe PA, Jalilzadeh H, Hettiaratchi P. The Impact of COVID-19 on Waste Infrastructure: Lessons Learned and Opportunities for a Sustainable Future. Int J Environ Res Public Health. 2023 Feb 28;20(5):4310.
58. Tonnes of COVID-19 health care waste expose urgent need to improve waste management systems [Internet]. [cited 2025 Jan 22]. Available from: https://www.who.int/news/item/01-02-2022-tonnes-of-covid-19-health-care-waste-expose-urgent-need-to-improve-waste-management-systems
59. Greening the OR | Practice Greenhealth [Internet]. [cited 2025 Jan 23]. Available from: https://practicegreenhealth.org/topics/greening-operating-room/greening-or
60. Digitale E. Stanford Medicine Magazine. 2023 [cited 2025 Jan 23]. Initiatives aim to make the operating room sustainable. Available from: https://stanmed.stanford.edu/greening-operating-room-sustainability/
61. Lee SM, Lee D. Developing Green Healthcare Activities in the Total Quality Management Framework. Int J Environ Res Public Health. 2022 May 26;19(11):6504.
62. Green HospitalPLUS Initiative – soziale und ökologische Nachhaltigkeit in bayerischen

Krankenhäusern [Internet]. Bayerisches Staatsministerium für Gesundheit, Pflege und Prävention. [cited 2025 Jan 23]. Available from: https://www.stmgp.bayern.de/gesundheitsversorgung/krankenhaeuser/green-hospital-bayern-nachhaltigkeit-bayerische-krankenhaeuser/
63. jessy. Green Hospitals [Internet]. Hospital Magazine - Leading Healthcare Magazine in the Middle East. 2022 [cited 2025 Jan 23]. Available from: https://hospitalsmagazine.com/green-hospitals/
64. EPHA Awards 2023 - Green Hospitals and Social Responsibility [Internet]. UEHP. [cited 2025 Jan 23]. Available from: https://www.uehp.eu/corners/epha-awards-2023-green-hospitals-and-social-responsibility/

Fig.1: https://mrgeogwagg.wordpress.com/2015/06/24/greenhouse-effect-and-anthropogenic-warming/

Fig.2: A refresher on the Paris Climate Agreement [Internet]. 2021 [cited 2025 Jan 31]. Available from: https://macmillan.yale.edu/stories/refresher-paris-climate-agreement

Fig.3: NYSORA. NYSORA. 2022 [cited 2024 Dec 14]. Inhalative Anästhetika. Available from: https://www.nysora.com/de/An%C3%A4sthesie/inhalierte-An%C3%A4sthetika/

Fig.4: NYSORA. NYSORA. 2022 [cited 2024 Dec 14]. Inhalative Anästhetika. Available from: https://www.nysora.com/de/An%C3%A4sthesie/inhalierte-An%C3%A4sthetika/

Fig.5: NYSORA. NYSORA. 2022 [cited 2024 Dec 9]. Inhaled Anesthetics. Available from: https://www.nysora.com/anesthesia/inhaled-anesthetics/

Fig.6: NYSORA. NYSORA. 2022 [cited 2024 Dec 9]. Inhaled Anesthetics. Available from: https://www.nysora.com/anesthesia/inhaled-anesthetics/

Fig.7: Özelsel TJP, Sondekoppam RV, Buro K. The future is now—it's time to rethink the application of the Global Warming Potential to anesthesia. Can J Anesth Can Anesth. 2019 Nov 1;66(11):1291–5.

Fig.8: Vollmer MK, Rhee TS, Rigby M, Hofstetter D, Hill M, Schoenenberger F, et al. Modern inhalation anesthetics: Potent greenhouse gases in the global atmosphere. Geophys Res Lett. 2015;42(5):1606–11.

Fig.9: Gaya da Costa M, Kalmar AF, Struys MMRF. Inhaled Anesthetics: Environmental Role, Occupational Risk, and Clinical Use. J Clin Med. 2021 Mar 22;10(6):1306.

Fig.10: MacNeill AJ, Lillywhite R, Brown CJ. The impact of surgery on global climate: a carbon footprinting study of operating theatres in three health systems. Lancet Planet Health. 2017 Dec;1(9):e381–8.

Fig.11: Kaposi A, Nagy A, Gomori G, Kocsis D. Analysis of healthcare waste and factors affecting the amount of hazardous healthcare waste in a university hospital. J Mater Cycles Waste Manag. 2024 Mar 1;26(2):1169–80.

Fig.12: Koch S, Pecher S. Neue Herausforderungen für die Anästhesie durch den Klimawandel. Anaesthesist. 2020 Jul 1;69(7):453–62.