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Carbon footprint reduction of the operating room: tools to mitigate the environmental impact of surgical practice

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CARBON FOOTPRINT REDUCTION OF THE OPERATING ROOM

Tools to Mitigate the Environmental
Impact of Surgical Practice



Herman Jan Friedericy

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CARBON FOOTPRINT REDUCTION OF THE OPERATING ROOM

Tools to Mitigate the Environmental
Impact of Surgical Practice

Proefschrift

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*'It is all too easy
when contemplating sustainability
to focus on what we lose
and miss what we gain'*

David Attenborough, (A Life on Our Planet, 2020)

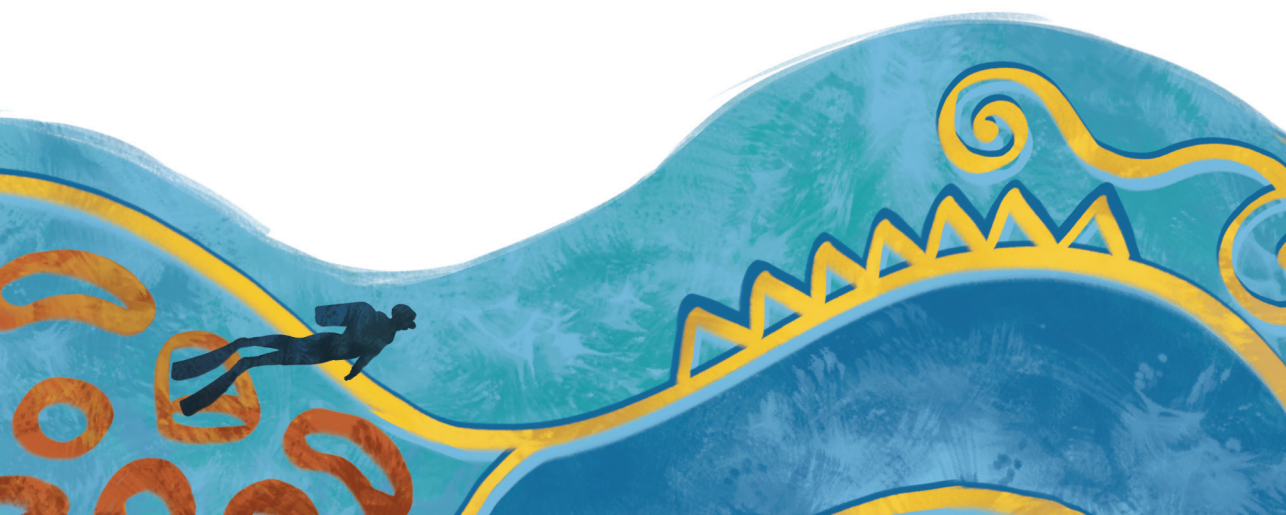
*'Our personal actions are not
a pointless drop in the ocean,
for the simple reason that
their ripple effects can turn into waves.'*

Roman Krznaric, (The Good Ancestor, 2021)

This thesis is dedicated to future generations

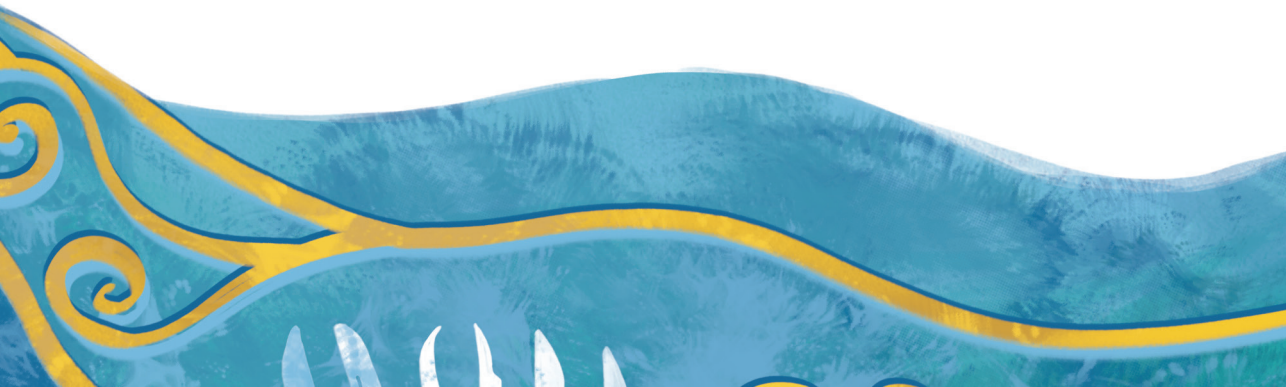
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CHAPTER 1

General Introduction



General Introduction



The era in which we currently live is typically referred to as the Anthropocene, the period of time marked by profound human influences, such as greenhouse gas (GHG) emissions, large-scale deforestation, and the spread of microplastics.¹ Although the term 'Anthropocene' is not officially recognised as a new epoch following the Holocene, it is considered an important transformative event in Earth's history.² It could be said that the Anthropocene began at the end of the 18th century. Analyses have shown that from that time onwards, there was an increase in the GHGs CO₂ and methane found in the air trapped in polar ice.¹ Since the 1950s, humanity's impact on the environment has accelerated, resulting in a dramatic exponential increase in the concentration of GHGs in the atmosphere that has resulted in a near 1.5 °C (above pre-industrial levels) increase of global temperature today.

Climate change is caused by global warming due to GHG emissions, and has major consequences for human well-being. Extreme weather conditions such as heat waves, extreme precipitation, and extreme droughts have undeniable consequences for human health and are increasingly claiming lives and harming people's health worldwide. These weather extremes cause heat-related deaths in vulnerable age groups, such as the very young and the elderly. Extreme drought threatens food and water security and increases the risk of wildfires. Changing climatic conditions are also increasing the risk of transmission of deadly infectious diseases such as dengue and tick-borne diseases (Figure 1).³ Paradoxically, the healthcare sector contributes significantly to GHG emissions such as CO₂ into the atmosphere and is therefore jointly responsible for the negative effects of climate change on public health.

It has recently been determined that the GHG emission of the global healthcare sector is 2.4 gigatonne CO₂-eq, which accounts for 4.4% of the total globally emitted GHGs.⁴ The healthcare GHG emissions per inhabitant across a sample of 36 countries in 2014 was 0.6 tonne CO₂-eq per capita. However, not all countries emit equally; high-income countries such as the United States, Luxembourg, Japan, Estonia, Slovakia, and the Netherlands were at the top of the list with more than 0.85 tonne CO₂-eq per capita. At the low end of the list were Turkey and Mexico with 0.23 and 0.13 tonne CO₂-eq per capita, respectively.⁵

Making healthcare more sustainable

The World Health Organization (WHO) acknowledges that climate change is one of the most serious global health threats of the 21st century and emphasises that decarbonising healthcare systems is essential to both mitigate climate change and protect public health. The WHO advocates, among other actions, that healthcare facilities must be

climate resilient and environmentally sustainable in order to achieve these goals.⁶ In the Netherlands, this ambition has been elaborated in the Green Deal for Sustainable Healthcare. This is an agreement between the Dutch Government and other partners for the implementation of sustainable plans. The Green Deal for Sustainable Healthcare 3.0 targets, among other things, to reduce CO₂ emissions by 55% by 2030 and to be climate neutral by 2050, as well as to reduce the consumption of primary raw materials by 50% by 2030 and maximise circularity in healthcare by 2050.⁷

Operating rooms (ORs), known for their high energy consumption, large consumption of goods, and significant waste generation, offer high-impact opportunities for reducing healthcare emissions. This places them at the heart of strategies for decarbonising hospitals with measures such as energy efficiency, pollution reduction, sustainable waste management and resource efficiency. To decarbonise healthcare efficiently it is important to assess baseline GHG emissions, set targets and monitor progress using universally accepted measurement and accounting methods.⁶

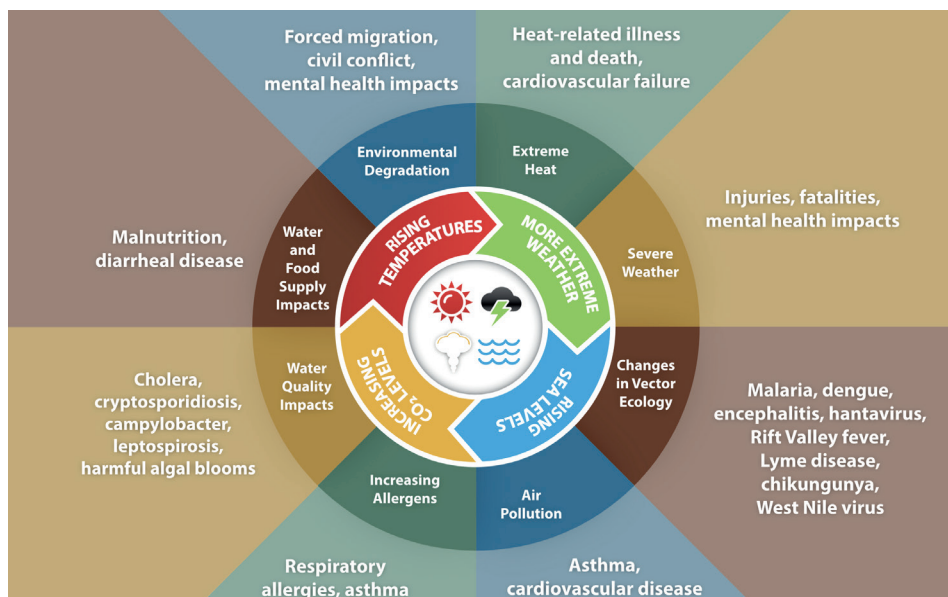


Figure 1. Impact of climate change on human health (Source: US Center for Disease Control and Prevention).



Measuring and accounting carbon emissions

Global warming is caused by an increase in GHGs such as carbon dioxide, nitrous oxide, methane, and fluorinated gases in the atmosphere. Because these gases absorb infrared light, they prevent heat radiation from the earth to space resulting in a rise in temperature (Figure 2).

To quantify the carbon emissions of a product, organisation, or activity, a carbon footprint can be calculated. A carbon footprint is defined as ‘the amount of direct and indirect CO₂ emissions that is caused by an activity, or collected during the life cycle of a product’.⁹ The calculation can be done by means of a life cycle assessment (LCA). With this ‘cradle to grave’ method, the environmental impact during the entire life cycle of a product is calculated from the extraction of raw materials to production, transport, use and waste disposal. Carbon footprint is expressed in CO₂ equivalents (CO₂-eq) which is a unit of measurement that is used to standardise the climate effects of various GHGs. For example, the emission of 1 kg of methane is equal to 25 kg CO₂-eq. Commuting 12.5 km to work in a car producing 170 g CO₂-eq km⁻¹, 5 days a week for 46 weeks a year (5,750 km) produces 1 tonne CO₂.⁸

The ‘Greenhouse Gas Protocol’ is the standard for reporting the carbon footprint of companies and organisations.¹⁰ According to this protocol, GHG emissions are categorised in three scopes: Scope 1 includes direct emissions; Scope 2 includes indirect emissions resulting from the generation of purchased electricity or heat; and Scope 3 includes all other indirect emissions resulting from the production of goods, waste processing and the travel movements of staff and patients (Figure 3).

The carbon footprint of the OR

Research on the carbon footprint of OR complexes shows that there are large absolute and relative differences between hospitals. The most important elements that contribute to the carbon footprint of an OR are: the emissions of inhalation anaesthetics (Scope 1), energy consumption by the heating, ventilation, and air conditioning (HVAC) system (Scope 2) and purchase of goods and the waste production (Scope 3).¹¹

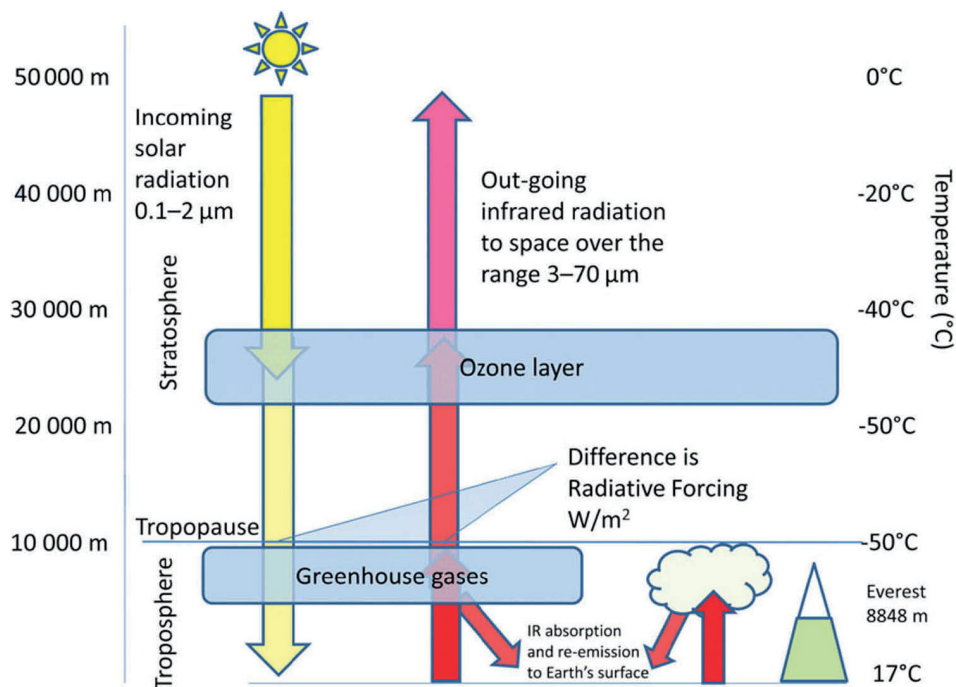


Figure 2. Simplified diagram of the Earth's energy balance. The difference between the incoming and outgoing radiation at the tropopause is called radiative forcing.⁸

Scope 1. Direct emissions due to inhalation anaesthetics.

Inhalation anaesthetics have been used since the first ether narcosis by William Morton in 1846 to induce general anaesthesia for operations. These drugs are potent GHGs that are virtually not metabolised by the body and are vented unchanged via exhaled air into the atmosphere after surgery, where they remain until broken down. Nitrous oxide, for example, remains in the atmosphere for 114 years before decomposition and is a 298 times stronger GHG than CO_2 . The modern volatile inhalation anaesthetic desflurane is even 2,540 times stronger as a GHG than CO_2 and can account for more than 50% of the carbon footprint of OR complexes when used as standard practice by anaesthesiologists.¹¹

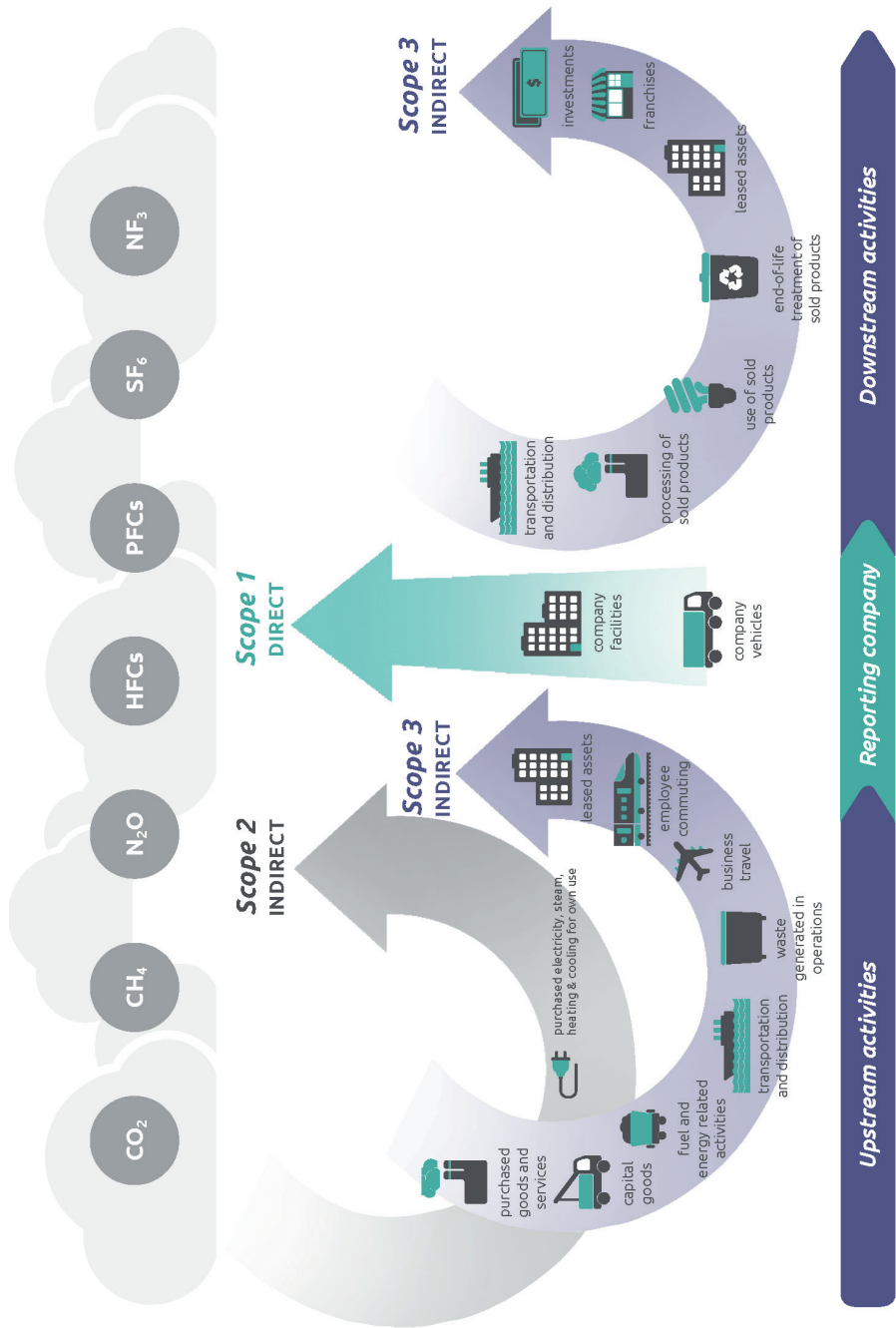


Figure 3. Overview of GHG Protocol scopes and emissions across the value chain.¹⁰

Scope 2: Indirect emissions due to energy consumption by the heating, ventilation, and air conditioning (HVAC).

To prevent airborne contamination of the wound, ORs are equipped with HVAC systems. Frequent and high-quality air filtering reduces the concentration of airborne pathogens from the skin and nasopharynx of those present in the room, thus reducing the chance of airborne contamination of the wound. To ensure good air quality, in practice 20-25 air changes per hour are necessary. It therefore takes a great deal of energy to keep the temperature, humidity and ambient pressure constant. Due to these high demands placed on the air quality inside the OR, 90-99% of the OR complex's energy consumption is due to air treatment.¹¹

Scope 3: Indirect emissions due to procurement of goods and waste generation.

A vast array of supplies is often required to perform operations. These include personal protective equipment, surgical instruments, wound care products, anaesthesia supplies, surgical drapes and towels, and so on. The majority of surgical supplies are currently intended for single use, based on the notion that disposable items are 'safer', more economical, and more convenient to use. Compared to reusable items, disposable items require a considerable quantity of raw materials, and their production, packaging, transport, and disposal generate large amounts of concealed CO₂ emissions, which accumulate throughout the life cycle of the product. Furthermore, the use of these disposables is also responsible for the large volume of waste generated during operations. In a study of three large Western hospitals, the waste from 70,000 operations was measured and averaged 14.5 kg per operation.¹¹

Additionally, but not within the boundaries of this thesis, a part of Scope 3 encompasses emissions resulting from staff, patient, and business travel. A carbon footprint assessment of the National Health Service (NHS) in England estimated this to be 13.5% of all healthcare emissions in 2019.¹²

Aim and outline of this thesis

The aim of this thesis is to investigate how the carbon footprint of ORs can be reduced in order to mitigate the impact of healthcare on the environment, without compromising patient safety. To this end, we will focus on those areas that have a major impact on the carbon footprint of an OR, so-called 'low-hanging fruit'. By addressing these potential quick wins, we aim to contribute to the Green Deal's goal of reducing healthcare-related CO₂ emissions by 55% by 2030.



In Part I, the reduction of major determinants of Scopes 1, 2, and 3 of the OR is investigated: inhalation anaesthetic use, energy consumption due to air treatment and waste generation resulting from widely used sterilisation packaging material for surgical instruments. In addition, the possibility of reducing the carbon footprint of heart valve replacement, a major operation that consumes a significant number of resources, is being investigated.

In Part II, two mitigation tools are developed to quantify carbon emissions and identify hotspots, so that carbon emissions can be reduced efficiently. The first tool works at the micro level (specific operations) and the other at the macro level (OR complexes on a national scale).

Finally, we will discuss the results of Parts I and II of this thesis and twelve practical implications derived therefrom, based on the 10R Framework, a model for transitioning from a linear to a circular economy based on hierarchical measures (Figure 4).¹³ Lastly, we will consider what future steps need to be taken to ultimately move towards a net-zero carbon emission OR by 2050.

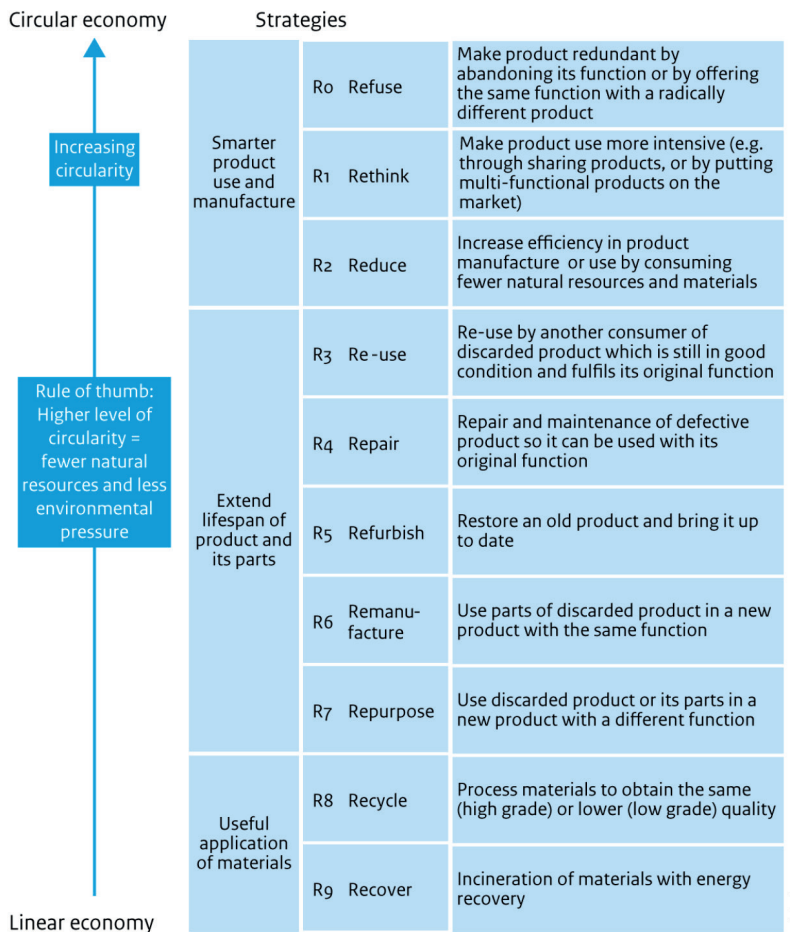


Figure 4. 10R Framework to increase circularity. ¹⁴

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PART I

Investigating Ways to Lower
Carbon Emissions in the OR





CHAPTER 2

Greenhouse Gas Emissions Due to Inhalation Anaesthetics in the Netherlands, Usage Data and a Survey of Preferences Among Dutch Anaesthesiologists

Authors:

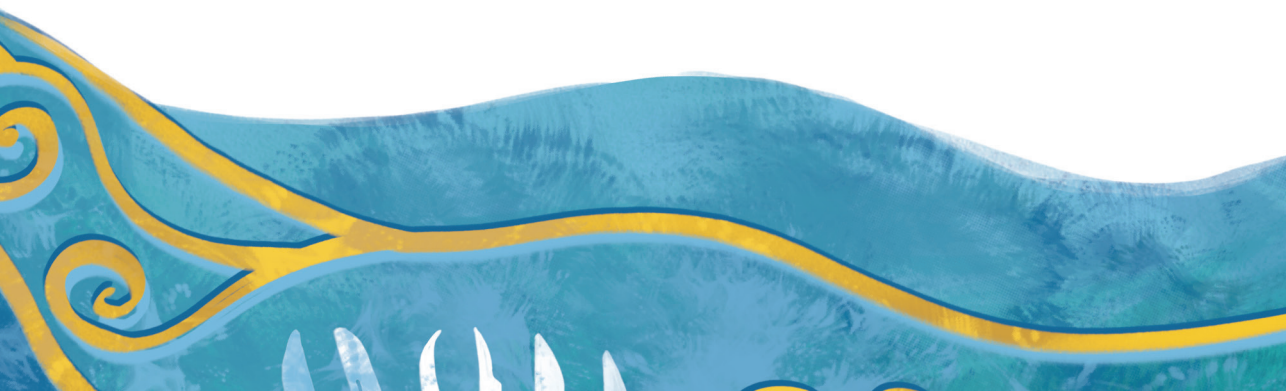
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Abstract

Background: Anaesthetic gases are an important source of greenhouse gas emissions in operating rooms and can attribute significantly to the carbon footprint of a nation's healthcare system.

Objective: To estimate the magnitude of the climate impact of inhaled anaesthetics in the Netherlands. Furthermore, the goal was to assess the preferences of Dutch anaesthesiologists for anaesthesia techniques, and to explore opportunities for reducing greenhouse gas emissions due to anaesthesia practice.

Design: A 2019 bottom-up purchase analysis of inhalation anaesthetics used in all Dutch hospitals was performed and an online survey was conducted among Dutch anaesthesiologists regarding their preferences for anaesthetic agents.

Results: Purchasing quantities of volatile anaesthetic agents were obtained from 61 of the 69 hospital organisations in the Netherlands (response rate 88.4%). A total of 12.2 kilotonne CO₂-eq (0.07% of the Dutch healthcare system) was emitted due to inhalation anaesthetics in the Netherlands in 2019. The volume of volatile anaesthetics purchased in 2019 was 9,178 litres of sevoflurane (93.4%), 404 litres of desflurane (4.1%) and 245 litres of isoflurane (2.5%). The survey in which 182 anaesthesiologists participated demonstrated that propofol was the first drug of choice of 70% of respondents, desflurane was available in 16% of Dutch hospitals and 83% of anaesthesiologists answered never to use desflurane. Nitrous oxide was not used by 63% of respondents, the remaining 27% reported using nitrous oxide only in less than 5% of their cases.

Conclusion: The relatively low emissions of greenhouse gases due to inhalation anaesthetics in Dutch healthcare compared to other countries can be explained by the limited use of nitrous oxide and desflurane by Dutch anaesthesiologists and their strong preference for intravenously administered propofol as an anaesthetic.

Introduction

Modern volatile inhalation anaesthetics (VAs) are inherently potent greenhouse gases (GHG).¹ They belong to the chlorofluocarbons (CFC) and hydrofluocarbons (HFC) that are short-lived climate pollutants (SLCP) with strong radiative forcing characteristics causing global warming. The Montreal Protocol (1987) and the Kigali Amendment (2016) aim to phase out CFCs and HFCs because of their respective ozone-depleting and GHG effects. Inhalation anaesthetics, being pharmaceuticals, have so far been exempted from these legally binding international agreements due to their medical necessity.²

The GHG effect of the globally emitted VAs in 2014 was estimated from atmospheric measurements and amounted to 3.1 million tonne of CO₂-equivalents (CO₂-eq) that year. In a period of 10 years (2004–2014) the atmospheric concentrations of desflurane and sevoflurane more than doubled, which can be explained by their popularity and the increase in the number of operations worldwide.³ Using the same global warming potential over 100 years (GWP₁₀₀), a bottom-up calculation based on the global number of bottles of sevoflurane, desflurane and isoflurane sold in 2019 came to 2.9 million tonne of CO₂-eq, a contribution of 0.01% of total global GHG emissions that year.⁴ Due to its high GWP₁₀₀ of 2540 and relatively low potency, desflurane accounted for about 80% of the total greenhouse effect of modern inhaled anaesthetics, despite accounting for only 20% of the volume sold in 2019.⁴

Nitrous oxide (N₂O) is also a significant GHG (GWP₁₀₀ of 298) but with a much longer atmospheric lifetime (114 years) than the aforementioned SLCP VAs.⁵ Traditionally N₂O was abundantly used as an adjuvant in the administration of older VAs to create a more favourable clinical profile. Nowadays, this technique is less essential with the clinically superior modern VAs. However, N₂O is still widely used in healthcare as an analgesic in obstetrics and emergency medicine.⁶ A breakdown of N₂O use in terms of clinical setting by Wong and colleagues showed that N₂O consumption during childbirth was a factor of 10 higher than during a single surgery (534 L. vs. 48 L.) and that during a paediatric emergency room procedure 61 L. was used.⁷ Today N₂O is the third most important GHG for global warming and accounts for about 7% of all GHG emissions globally. It is emitted for 57% from natural sources and approximately 43% from anthropogenic sources of which two-thirds is due to agriculture.⁸ Rough estimates regarding the share of N₂O emitted by healthcare range from 1–3% of the total annual amount of N₂O emitted globally.^{9,10} Recent reports have shown that a significant proportion of N₂O purchased by hospitals is released unused into the atmosphere. Leaking pipeline manifolds are cited as the main culprit. In addition, there is a residual volume of 1–2% in N₂O cylinders after use which is released into the atmosphere prior to refilling.¹¹ Studies from individual hospitals in the UK and Australia have reported a N₂O wastage percentage between 77–98 based on a discrepancy between purchase and usage data.^{11–13}



Anaesthetic gases are, aside from energy consumption, the most important source of GHG emissions of operating rooms (ORs).¹⁴ In a carbon footprint assessment of the National Health Service (NHS) in England, anaesthetic gases (including N₂O) account for 5% of the total emissions of England's healthcare services.¹⁵ In a carbon footprinting study of three Western academic hospitals it was shown that anaesthetic practice had a significant influence on the GHG emissions caused by VAs. The preferential use of desflurane resulted in a tenfold emission of GHGs due to VAs compared to the hospital in which sevoflurane was the standard of care.¹⁴ Life cycle assessments of anaesthetic drug use also show that the GHG emissions greatly vary with the choice of anaesthetic. Both the use of desflurane and N₂O result in significantly higher GHG emissions for general anaesthesia when compared to sevoflurane. When general anaesthesia is provided with the intravenous drug propofol the GHG emissions are almost negligible.^{16,17} However, other detrimental effects of propofol use on the environment should not be overlooked. Propofol poses an ecological risk if it enters surface water. It is poorly biodegradable and has a high potential for bioconcentration in marine life. Also a large portion of the manufactured propofol is wasted due to regulations for the administration of propofol.^{18,19} Furthermore intravenous drug administration results in large amounts of plastic waste and poses a hazard to drinking water supplies in water-scarce areas due to water pollution.²⁰

The aim of this study was to assess the magnitude of the climate impact of inhaled anaesthetics in the Netherlands, to assess the preferences of Dutch anaesthesiologists for anaesthetic agents and finally, to explore opportunities for reducing healthcare GHG emissions due to anaesthesia practice.

A bottom-up purchase analysis of VAs in all Dutch hospitals was performed by inquiring hospital pharmacists about purchasing data of isoflurane, desflurane and sevoflurane in the year 2019. Data on the use of N₂O in the Dutch healthcare system were obtained from the National Institute for Public Health and the Environment (RIVM). In addition, an online survey was conducted in which Dutch anaesthesiologists and anaesthesiology residents were asked about their preferences for anaesthetic agents and the reasons for them, focusing on side effects, pharmacological factors, environment, costs and practical considerations. In addition, questions were asked regarding the use of GHG emission-saving methods in their daily practice.

Methods

For our survey the Institutional Review Board of the Leiden University Medical Centre ruled that this research proposal (2022-03) does not fall under the Medical Research Involving Human Subjects Act. This research does not meet the criteria because participants are not subjected to procedures or are required to follow rules of behaviour.

As a template, the questionnaire from a survey conducted among Australian and New Zealand anaesthetists was modified and translated into Dutch.²¹ The adapted questionnaire was converted to a digital version using SurveyMonkey (<https://surveymonkey.com>) and to validate, submitted to ten fellow anaesthesiologists in the LUMC for assessment of the readability and comprehensibility of the questions. As a result of this pilot, there was no need to adjust the questions of the survey. In total, the survey consisted of 17 questions that would take less than five minutes to complete (For survey questions see Appendix A. Supplementary data). Questions were formulated to capture preferences by anaesthetic in order of preference. Apart from the three inhalation anaesthetics, respondents could also choose the intravenous anaesthetic drug propofol. Next, the rationale for these preferences was asked. Standard reasons were chosen which respondents could tick as reasons for preferences, in addition to a free-text comment for other reasons. These standard reasons were based on side effects, pharmacodynamic, pharmacokinetic and environmental properties of the agents, costs and practical considerations. In addition, questions were asked regarding the use of techniques on the efficient use of inhalation anaesthetics which can reduce the amount emitted into the atmosphere while achieving the same effect on the patient. These regarded the use of low fresh gas flows (FGF) and the use of automated control of end-tidal inhalation anaesthetic concentration (Et Control).^{22,23} The degree of willingness to adapt their anaesthesia technique for the benefit of the environment was surveyed as well as the demographic data of the participants (years of experience as an anaesthesiologist, type of hospital and its geographic location).

A request for participation in the survey was addressed to all staff anaesthesiologists and anaesthesia residents in the Netherlands. Information regarding the study and a web link to the survey was published in the newsletter of the Dutch Society of Anaesthesiologists (NVA) and in the Dutch Journal of Anaesthesiology (NTvA). Furthermore, the survey was advertised via social media (LinkedIn). The survey was open for six months from 30 June to 30 December 2022. The input data were manually exported from 'SurveyMonkey' to a Microsoft Excel sheet. Percentages and proportions were calculated for all quantitative results.



To obtain purchasing quantities of VAs in 2019, the anaesthesiology departments from all 69 hospital organisations in the Netherlands were first contacted by telephone to ask them for cooperation for the study. Subsequently, an email was sent to the contacts of these departments explaining the purpose of the study and instructions regarding the retrieval of the requested information. This comprised the purchased numbers of bottles of isoflurane, desflurane and sevoflurane for their hospital organisation in the year 2019. These numbers had to be entered into an online counting form that was created with the online platform JotForm (<https://jotform.com>). If no response was received after four weeks, a reminder email was sent and if again no response was received after four weeks, the hospital pharmacist of the respective hospital was contacted directly asking for their cooperation and to provide the requested information. The online counting form was accessible for six months from July 2021 to January 2022. All data from the online counting forms were manually entered into a Microsoft Excel spreadsheet for calculating total volumes of all participating hospital organisations. From the supplied volumes, first the calculated amount of theoretically metabolised anaesthetic was subtracted. Then, using the specific gravity of the inhalation anaesthetic and its GWP₁₀₀, the amount of emitted CO₂ equivalents was calculated. Table 1 provides the details of the characteristics that were used for the calculation of the emissions of the VAs. No correction was made for the possible use of vapor capture technology (VCT) which allows inhaled anaesthetics to be captured after use as this technique was not yet available for the Dutch market in 2019.

Table 1. *Characteristics of inhalation anaesthetics.*

	sevoflurane	desflurane	isoflurane	nitrous oxide
Density (g/ml)	1.52	1.47	1.50	
Molar mass (g/mol)	200	168	184.5	
Metabolism (%)	5	0.02	0.2	0.005
Bottle volume (ml)	250	240	250	
GWP ₁₀₀ ^a	130	2,540	510	298
Mass per bottle (g)	380	353	375	
kg CO₂-eq/ bottle	49	896	191	

^a GWP₁₀₀: global warming potential calculated over 100 years.

The amount of N₂O that was sold in the Netherlands for healthcare purposes was collected from the Emission Registration (<https://www.emissieregistratie.nl/>) which is the central location for all Dutch emission data under the auspices of the RIVM. It provides the formal historical and most recent emissions data for the Netherlands and is an independent and reliable data source in which emissions of about 375 substances

and substance groups are registered. Ideally, the consumed amount of N_2O would have been obtained either directly from the supplier or through hospital purchasing figures. Both options were attempted in our study but did not provide reliable (incomplete) data. Unfortunately the Emission Registration data gave no information regarding the breakdown into pure N_2O and Entonox.



Results

Bottom-up purchase analysis of inhalation anaesthetics

Purchasing quantities of VAs were obtained from 61 of the 69 hospital organisations in the Netherlands (response rate 88.4%). The volumes of the in 2019 purchased inhalation VAs were 9,178 litres of sevoflurane (93.4%), 404 litres of desflurane (4.1%) and 245 litres of isoflurane (2.5%). Sevoflurane was used in all 61 hospitals (100%), desflurane in 16 (26%) and isoflurane in 3 (5%). Calculated emissions from these volumes were 1,722 tonne CO_2 -eq sevoflurane (50%), 1,502 tonne CO_2 -eq desflurane (41%) and 186 tonne CO_2 -eq isoflurane (5%). Linear extrapolation of these figures from 88.4 to 100% results in a total of 3,859 tonne CO_2 -eq due to the emission of VAs in the Netherlands in 2019. According to the National Emission Registration the emission of N_2O stemming from the Dutch healthcare system in 2019 was 31.4 tonne (8,321 t CO_2 -eq). Thus the total emission of inhalation anaesthetics in 2019 in the Netherlands came to 12.2 kilotonne CO_2 -eq, which account for 0.07% of the 17,575 kilotonne CO_2 -eq environmental impact of the complete Dutch healthcare sector as calculated for 2016.²⁴

Survey of Dutch anaesthesiologists

The survey was completed by 182 respondents, 150 consultants (82%) and 32 specialist trainees (18%). Mean years of experience of the consultants were 10.2 (SD +/- 8.0) years. The exact distribution of years of training and experience of the participants are shown in Table 2.

Of the respondents, 66 (36%) were employed at a university hospital, 69 (38%) at a large top clinical hospital, 41 (23%) at a small peripheral hospital and 6 (3%) at a private hospital. On the question 'In my daily practice, the drugs I use for general anaesthesia are as follows, in order of preference' most respondents selected propofol as their drug of choice (70%) followed by sevoflurane (25%), desflurane (1%) and isoflurane (1%). As the second choice sevoflurane was selected by 56% and propofol by 22% of the respondents (Figure 1).

Table 2. Distribution of years of training (specialist trainees) and experience (consultants) of the participants.

	Training/experience (years)	No. of participants	% of total
Trainee specialists	1	1	3%
	2	11	34%
	3	7	22%
	4	5	16%
	5	8	25%
	Total	32	100%
Consultants	0-5	61	41%
	6-10	27	18%
	11-15	24	16%
	16-20	17	11%
	>20	19	13%
	Total	148^a	100%

^aTwo consultants did not provide this information.

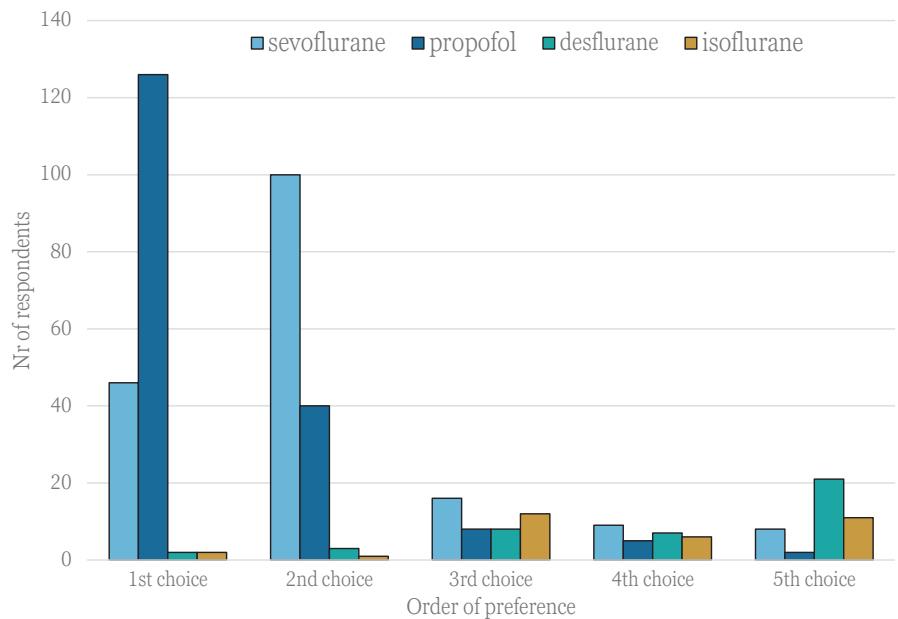


Figure 1. Ranking of preferences for anaesthetic agent use.

The reasons for choosing a particular anaesthetic (questions 3-7) are shown in Table 3. Propofol was most often chosen for low incidence of side-effects such as post-operative nausea and vomiting (PONV) by 94%, followed by environmental reasons (71%) and fast awakening and discharge times (64%). Sevoflurane was chosen for haemodynamic stability (48%), low chance of awareness (43%) and fast awakening and discharge times (36%).

Table 3. *Reasons for choosing a particular anaesthetic (questions 3-7).*

	sevoflurane		desflurane		isoflurane		propofol	
I do not use this agent	3	(2%)	151	(83%)	165	(91%)	0	(0%)
Low costs	23	(13%)	0	(0%)	7	(4%)	28	(15%)
Only available anaesthetic	21	(12%)	0	(0%)	1	(1%)	2	(1%)
Environmental reasons	7	(4%)	2	(1%)	2	(1%)	129	(71%)
Fast awakening/discharge	66	(36%)	21	(12%)	2	(1%)	116	(64%)
Low chance of awareness	78	(43%)	1	(1%)	6	(3%)	15	(8%)
Haemodynamic stability	88	(48%)	3	(2%)	6	(3%)	14	(8%)
Low incidence of side effects (PONV ^a)	5	(3%)	0	(0%)	0	(0%)	171	(94%)

Desflurane was not used by 83% of the respondents and isoflurane was not used by 91% of the respondents. Nitrous oxide was not used by 63% (115/182) of the respondents, 18/182 (10%) gave as reason for using N₂O the 'hemodynamic stability'. Almost 30% of respondents indicated under 'others' to use N₂O for the induction in children (as an adjuvant to sevoflurane) and also as an analgesic for painful moments during procedures. The estimated percentage of procedures where N₂O was used was indicated by 70 anaesthesiologists and was on average 4.6% (SD +/- 4.9).

Use of FGF <1 l/min was chosen by 138/182 (76%) and 1-2 l/min by 37/182 (20%), only 2 respondents indicated to use FGF > 2 l/min. Reasons for not using FGF <2 l/min were 'potentially unsafe' 4/182 (2%) and 'Against user's advice (the formation of compound A)' 5/182 (3%). On whether Et Control was used 132/182 (73%) answered 'true', 21/182 (12%) answered 'false' and 29/182 (16%) indicated that this technique was not available. When asked 'If patient safety is not compromised, I am willing to adapt my anaesthesia technique for the sake of the environment.' 90.7% agreed, 3.8% was neutral and 5.5% disagreed.



Discussion

Our study shows that healthcare emissions of VAs and N₂O in the Netherlands are responsible for 0.07% of the carbon footprint of the entire Dutch healthcare sector.²⁴ The total of 12.2 kilotonne of CO₂-eq emitted is comparable to the annual emissions of about 6,700 passenger cars (116 g CO₂/km, 15,000 km/yr). The primary explanation for these relatively low emissions compared to other countries is the limited use of N₂O and desflurane by Dutch anaesthesiologists and a strong preference for intravenously administered propofol as an anaesthetic.¹⁵ Desflurane, the VA with the highest GWP₁₀₀, was only available in 16% of Dutch hospitals and 83% of anaesthesiologists surveyed answered never to use desflurane. Nitrous oxide was not used by 63% of respondents, the remaining 37% reported using N₂O only in less than 5% of their cases. The intravenous anaesthetic propofol was chosen as the first drug of choice by 70% of survey respondents, with low incidence of side-effects such as postoperative nausea and vomiting (PONV), environmental reasons and fast awakening and discharge times as main reasons. Emission mitigation measures of inhalation anaesthetics such as FGF < 1 l/min and Et Control were already applied by 76% and 73% of respondents, respectively.

The purchased volume of desflurane in the Netherlands in 2019 was 41% of the total amount of VAs, but as a result of its high GWP₁₀₀, desflurane's calculated emissions accounted for 41% of total inhaled VAs emissions. Globally, desflurane's market share in 2019 was 5 times higher (20%) than in our study, accounting for 77% of the total CO₂-eq emitted due to VAs in that year.⁴ Atmospheric measurements also show that 80% of the emissions of VAs in the world stem from desflurane use.³ There is a wide variation in the use of desflurane in different countries. Reported emission rates of desflurane from Austria and Ireland (31% and 40%) match those of our study.²⁵⁻²⁷ However, in Germany and Australia, 77% and 88% of emissions are caused by desflurane, respectively.^{21,28} Although the popularity and use of desflurane has declined in the Netherlands since 2020 due to its environmental impact, this is not the only reason for its limited use reported in our study. Since the introduction of sevoflurane and desflurane in the 1990s, sevoflurane has enjoyed much greater preference among Dutch anaesthesiologists. This was partly because sevoflurane was marketed very aggressively during the introduction period and partly because it did not require the purchase of an expensive vapouriser like the one for desflurane. Furthermore sevoflurane is suitable for inhalation inductions of children, which is not the case for desflurane.

Comparing our data one-to-one with those of Australia and New Zealand, the first thing to note is the difference in the preference for desflurane use. Our survey showed that only 1% of Dutch anaesthesiologist had desflurane as their first choice while in the study by McGain et al 12% indicated this.²¹ Based on the consumption numbers

from that study, the effect of this is that 88% of emissions were caused by desflurane use in Australian situation in 2017. In addition, the volume of inhalation anaesthetics consumed in Australia was 53,250 litres versus 9,827 litres in the Netherlands. So a factor of five larger while the population of Australia is only 1.5 times as big. Assuming that the number of operations in both countries is proportionally equal, it can be inferred that intravenous anaesthesia with propofol is chosen much more often in the Netherlands, which was confirmed by the fact that 70% of the respondents in our study indicated anaesthesia with propofol as their first choice. So because of the preference of Dutch anaesthesiologists for intravenous anaesthesia with propofol and very limited use of desflurane, the calculated emission of volatile anaesthetics in 2019 in the Netherlands (3.9 kilotonne CO₂-eq) was 16% of that in Australia (63.7 kilotonne CO₂-eq) in 2017 which has about 1.5 times as many inhabitants.

With respect to our goal of investigating the potential for reducing healthcare GHG emissions from Dutch anaesthesia practices, 76% of respondents were found to be using FGF < 1 l/min and 73% were using Et Control. Similar numbers were also reported in the French and Australian/New Zealand surveys.^{21,29,30} In a recent worldwide survey among anaesthesiologists however only 49% of the respondents indicated to use FGF < 1 l/min.³¹ Managing FGF is a safe and effective way to reduce waste of inhalation anaesthetics and environmental pollution due to their GHG effect.²² With a minimum FGF of 0.5 l/min (minimal flow), the desired clinical effect can be achieved in patients. Using more than minimal flow results in wastage of inhalation anaesthetics. Since there is a linear relationship between the amount of fresh gas used and the amount of inhalation anaesthetics used reducing FGF is an effective mitigation strategy.^{17,32} Traditionally FGF was set manually, but nowadays ventilators can be equipped with an Et Control function with which the FGF is optimally adjusted according to the requested concentration of VA. In a comparative study of VA consumption with Et Control and manual control, the mean consumption of sevoflurane was 14 ml/h versus 30 ml/h (-53%) and of desflurane 27 ml/h versus 45 ml/h (-40%).²³ Our survey deliberately did not ask about the use of VCT as this technique to capture VAs from the anaesthesia machine outlet was not yet available on the Dutch market in 2019. The use of VCT can reduce the amount of VAs emitted into the atmosphere and VAs can potentially be recovered and reused, which can provide financial savings in addition to environmental gains.³³ This technique has recently become available to the market, but there are mixed results regarding its effectiveness in daily practice. In a clinical study performed on 13 patients 62% - 86% of the delivered desflurane was adsorbed with FGFs ranging from 0.5 - 3 l/min.³⁴ In a recent clinical trial in 80 patients, the median amount of desflurane recaptured was only 52%.³⁵ In 70 bariatric patients utilising minimal flow and Et Control 45% of the administered sevoflurane could be captured with VCT.³⁶ The presented hypothesis that



a significant residual amount of sevoflurane and desflurane was still present in the body after extubation and could thus not be captured seems less probable explanation since a computer simulation study showed that theoretically at least 73% of the administered amount of VA could be recovered and only very small amounts of VAs are exhaled in the first hour after surgery.³⁷ The exact effectiveness of VCT will require further study, but the capture and recycling of VAs offers prospects for reducing environmental pollution from their use. In fact, the modelled use of sevoflurane with low FGF and VCT has a similar carbon footprint to intravenous anaesthesia with propofol.¹⁷

The use of N_2O greatly affects total amount of GHGs emitted by anaesthesia practice worldwide due to its high GWP₁₀₀ and low potency.³⁸ Data from Ireland and Austria show that N_2O can be responsible for more than 80% of emissions from inhalation anaesthetics.^{26,27} Our calculation of 66% for the Dutch situation matches this order of magnitude. This large fraction is despite the fact that the use of N_2O in the Dutch healthcare system has fallen drastically in the past decades. In 2019, it was only 5% of the amount of N_2O emitted in 1990 (RIVM data). This recent decline in N_2O use for anaesthesiologic purposes has also been observed by others.³⁹⁻⁴¹ It is consistent with our survey results showing that anaesthesiologists indicate that N_2O is nowadays only rarely used. Nitrous oxide was initially widely used as an adjuvant to VAs to improve the clinical profile of these agents, but with the arrival of desflurane and sevoflurane in the 1990s, that need has been eliminated. Furthermore, the use of more efficient respirators and the introduction of the intravenous agent propofol during the same period reduced N_2O emissions by anaesthesiologists. Still the impact of N_2O on the total amount of emitted GHGs in our study is responsible for two thirds of total emissions and reducing their emissions should be a priority in mitigating climate impact of inhalation anaesthetics. Even though the clinical use of N_2O by Dutch anaesthesiologists has drastically fallen it is still readily applicable as an analgesic in obstetrics and emergency care. For this application there are not always equally effective alternative pain control methods available. In such cases, it is possible for 71-81% of the administered N_2O to be collected and to be catalytically destroyed at the bedside.⁴² Minimizing wastage of N_2O by routinely checking for leakages in N_2O pipeline systems or even decommissioning N_2O manifolds if possible should be encouraged given the reported significant leakages of N_2O into the atmosphere.⁶ The Royal College of Anaesthetists has issued a consensus statement on the removal of pipeline N_2O in the United Kingdom and Republic of Ireland recommending that given the fact that N_2O is no longer an essential drug in modern anaesthetic practice, N_2O manifolds should be decommissioned as soon as possible and if necessary replaced by point-of-care cylinders.⁴³ Furthermore legislation should ensure that gas residues in N_2O cylinders are destroyed rather than vented into the atmosphere before refilling.⁶

Our results show that Dutch anaesthesiologists prefer to perform their anaesthesia for the most part with intravenous propofol and can do so without the use of desflurane. In contrast, worldwide only 23% of anaesthesiologists indicate that they prefer intravenous anaesthesia and 64% prefer inhalation anaesthesia.³¹ As a result of efforts to make the healthcare sector more sustainable, several countries have reduced desflurane use in recent years. In Scotland, for example, the use of desflurane was completely phased out by 2023, and Australia and New Zealand have seen sharp reductions in its use. However, in Japan and Taiwan, desflurane is the most commonly used VA.⁴⁴ A risk-benefit analysis of desflurane versus sevoflurane regarding clinical, financial and environmental characteristics shows that there are no reasons to prefer desflurane as an anaesthetic agent.⁴⁵⁻⁴⁷ The European Union has issued a proposal with the intention to prohibit the use of desflurane as of January 2026. Given the importance of universally phasing down HFCs, this is a logical choice given the availability of the low-GWP₁₀₀ alternative sevoflurane. However, care must be taken to ensure that sevoflurane remains available to anaesthesiologists. Although intravenous propofol is a good alternative to sevoflurane for many indications, inducing anaesthesia in children with a facemask is a unique feature of sevoflurane. Also Dutch anaesthesiologists indicated choosing sevoflurane for its hemodynamic stability and low risk of awareness. Apart from the clinical differences between propofol and sevoflurane, the administration technique of VAs is completely different from that of intravenous agents. Anaesthesiologists have mastered this technique since the early days with ether, and it is important that the future generation of anaesthesiologists learn and maintain this technique. Furthermore, completely phasing out VAs in the interest of global warming would mean complete reliance on a single agent (propofol) to administer general anaesthesia. During the COVID-19 pandemic, the global shortage of propofol led to a flight to sevoflurane and isoflurane, even patients in the ICU were then kept under anaesthesia with these VAs.⁴⁸

Phasing out HFCs is of great importance given the relatively large impact these agents have as a result of their large GWP₁₀₀s. These agents are mainly used as refrigerants, propellants, foams etc. Given the exuberant global presence of these agents and their relatively short atmospheric lifetime, immediate phasedown can have a major impact on the ultimate global temperature rise.^{49,50} The phasing down of these HFCs is expected to avoid emissions of 8.8 gigatonne CO₂-eq per year by 2050 and potentially providing up to 6-10% of the needed mitigation to stay below 2°C average global temperature.⁵⁰ The share of global HFC emissions from VAs is estimated to be of 9.8 megatonne CO₂-eq in 2050 in a growth scenario (2% increase of emissions per year) of the aforementioned 8.8 gigatonne CO₂-eq which is 0.08%.³ This relatively low impact of VAs does not mean that anaesthesiologists need not worry about the



release of their agents, but can be seen as an argument for allowing the continued use of sevoflurane in particular. In order to minimize the environmental impact, the use of sevoflurane will have to be regulated by, for example, making Et Control and VCT mandatory if this agent is chosen for general anaesthesia.

Limitations of our study are that we were not able to obtain N₂O procurement data from Dutch hospitals as this was apparently too complicated to obtain. Instead, we used data from the national Emission Registration, which may have led to underreporting given that these data are based on voluntary declarations from the largest N₂O suppliers in healthcare. We would have liked to obtain purchase data of propofol, however, the problem is that propofol is used not only for general anaesthesia, but also for ICU sedation and procedural sedation, among others. The population of our survey might be skewed by the relatively large number of young respondents. It is possible that our results are influenced by this and that more propofol and N₂O is used by this group. However, our procurement data show a similar pattern.

Conclusion

Our study shows the modus operandi of Dutch anaesthesiologists have resulted in relatively limited greenhouse gas emissions from inhalation anaesthetics. A preference for intravenous propofol and very little desflurane and N₂O use results in a carbon footprint that is equal to the annual emissions of about 6,700 passenger cars. However, there is definitely room for improvement. Implementation of strategies to reduce clinical use and wastage of N₂O, complete elimination of desflurane for general anaesthesia and mandatory use of Et Control and VCT when using sevoflurane can make the insurmountable GHG emissions from anaesthesiologic care acceptable for future generations.

Appendix A.

Supplementary digital content

Survey questions: <https://links.lww.com/EJAIC/A104>

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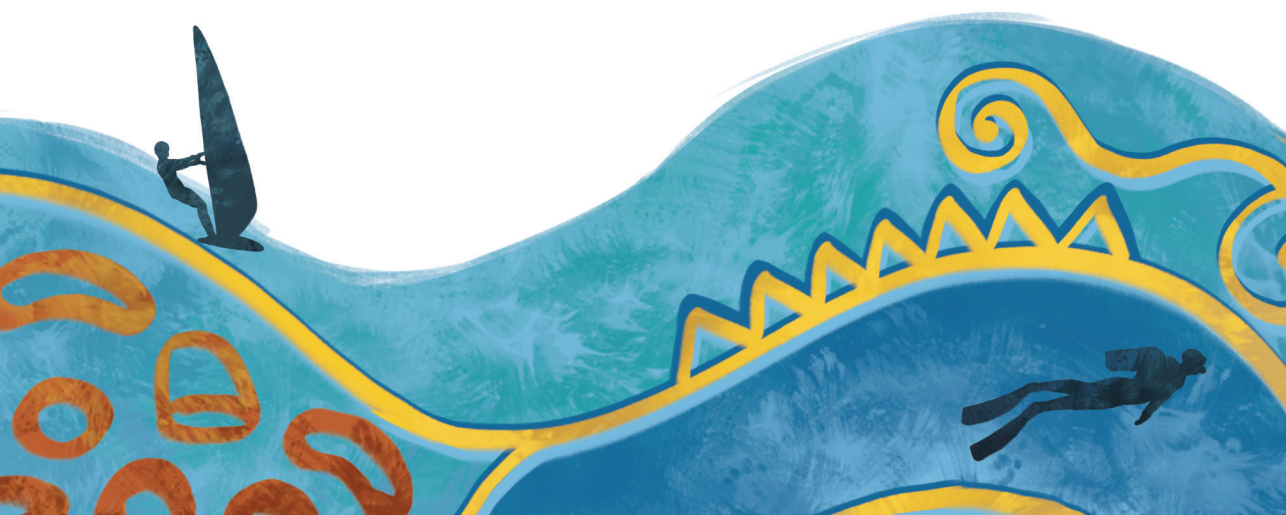
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CHAPTER 3

Effect of Unidirectional Airflow Ventilation on Surgical Site Infection in Cardiac Surgery: Environmental Impact as a Factor in the Choice of Turbulent Mixed Airflow

Authors:

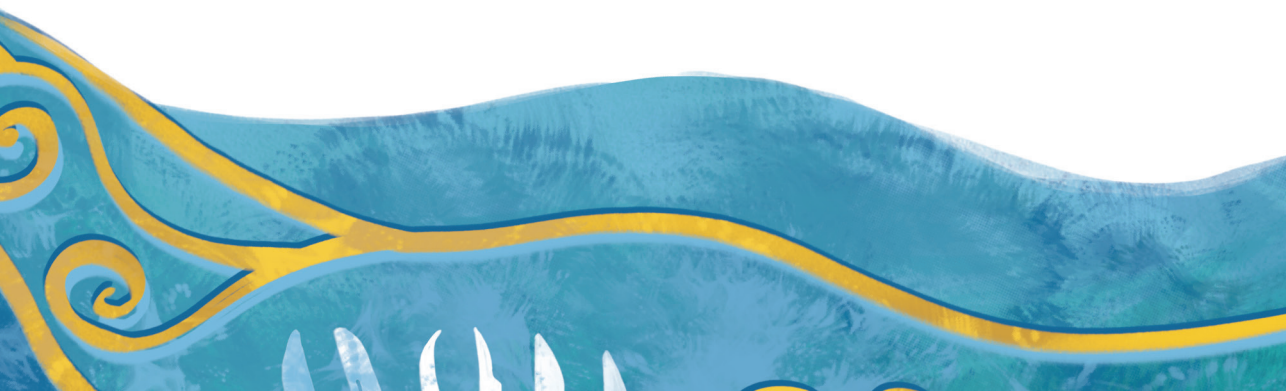
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Abstract

Background: Surgical site infection (SSI) in the form of postoperative deep sternal wound infection (DSWI) after cardiac surgery is a rare, but potentially fatal complication. In addressing this, the focus is on preventive measures as most risk factors for SSI are not controllable. Therefore, operating rooms (ORs) are equipped with heating, ventilation, and air conditioning (HVAC) systems to prevent airborne contamination of the wound either through turbulent mixed airflow (TMA) or unidirectional airflow (UDAF).

Aim: To investigate whether the risk of SSI after cardiac surgery decreased after changing from TMA to UDAF.

Methods: This observational retrospective single-centre cohort study collected data from 1288 patients who underwent open-heart surgery in two years. During the two study periods institutional SSI preventive measures were the same, with the exception of the type of HVAC system that was used.

Findings: Using multivariable logistic regression analysis taking into account confounding factors (diabetes, obesity, operation duration and re-operation) the hypothesis of TMA being an independent risk factor for SSI was rejected (odds ratio 0.9; 95% CI 0.4-1.8; $P > 0.05$). Therefore, we could not demonstrate the preventive effect of UDAF on the incidence of SSIs in open-heart surgery when compared to TMA.

Conclusion: Based on our results, the use of UDAF in open-heart surgery should be weighed against its low cost-effectiveness and negative environmental impact due to large electricity consumption. Reducing energy overuse by utilizing TMA for cardiac surgery can diminish the carbon footprint of ORs and thereby their contribution to climate-related health hazards.

Introduction

Surgical site infections (SSIs) are by definition infections that occur within a 30-day period after a surgical operation, affecting either superficial or deep tissues at the site of operation.¹ In cardiac surgery postoperative deep sternal wound infection (DSWI) is a rare but potentially fatal SSI.² The incidence of DSWI (mediastinitis) in cardiac surgery ranges from 0.6 to 8.7%, however DSWIs are associated with a significant morbidity, mortality and financial costs.³⁻⁵ Patient-related risk factors for DSWIs are multiple and include age, obesity, diabetes, and chronic obstructive pulmonary disease (COPD).⁶ Peri-operative risk factors for DSWIs include bilateral (particularly non-skeletonised) internal mammary artery use, re-exploration for bleeding and duration of surgery.^{3,4} Most of these risk factors are not controllable meaning that in avoiding SSIs it comes down to preventive measures. SSI guidelines and recommendations consist of preventive measures such as glucose control, timely antibiotic prophylaxis, hair removal with clippers, alcohol containing skin preparation, nasal *S aureus* decolonisation, perioperative normothermia and incisional negative pressure wound therapy.⁷⁻⁹

In addition to these preventive measures operating rooms (OR) are equipped with heating, ventilation, and air conditioning (HVAC) systems. These air treatment systems are intended to prevent airborne contamination of the wound. Frequent and high-quality air filtering with a high efficiency particulate air filter (HEPA) must ensure that the concentration of airborne pathogens from the skin and nasopharynx of those present in the OR is as low as possible. The traditional way to do this is with a displacement system called turbulent mixed airflow (TMA). With this type of system filtered air is blown into the OR which causes a dilution of the airborne bacterial load in the entire room. In the 1970s ultraclean air (UCA) OR ventilation systems were developed to reduce the microbe-carrying particles to a minimum ($\leq 10/\text{m}^3$ at the surgical wound).¹⁰ Over the years this type of air treatment system evolved into what is known today as a unidirectional airflow (UDAF) air treatment system. With this system airflows can be directed in such a way that the surgical field and the instrument table receive the filtered clean air at a high rate directly from the inlet in the ceiling of the OR (Figure 1). Within these classifications many different designs exist for both TMA and UDAF ventilation systems. For instance, there are TMA systems with higher airflows, and LAF systems with lower airflows.¹¹ The ISO 14644-1 classification is the international standard to describe the performance of the different ventilation systems with regard to air cleanliness. Measured by the amount of colony-forming units (CFU) UDAF systems show a better performance with regard to the bacteria concentration present in the OR.^{11,12} Yet, there is controversy in the literature as to whether UDAF actually reduces the incidence of SSIs.¹³ This lack of scientific evidence has led the World Health Organization (WHO) in



2018 to issue a conditional recommendation against the use of UDAF to reduce the risk of SSI for patients undergoing total joint arthroplasty (TJA) surgery.¹⁴ In a review of original studies, including studies executed before 1990, Whyte et al. do claim a favourable effect of UDAF on SSI in TJA.¹⁰ Most of the studies that have been carried out on the effect of UDAF in preventing SSI were aimed at TJA surgery because insertion of orthopaedic implants leads to an increased risk of SSI.¹⁵ Three studies carried out in non-orthopaedic surgery show conflicting results.¹⁶⁻¹⁸

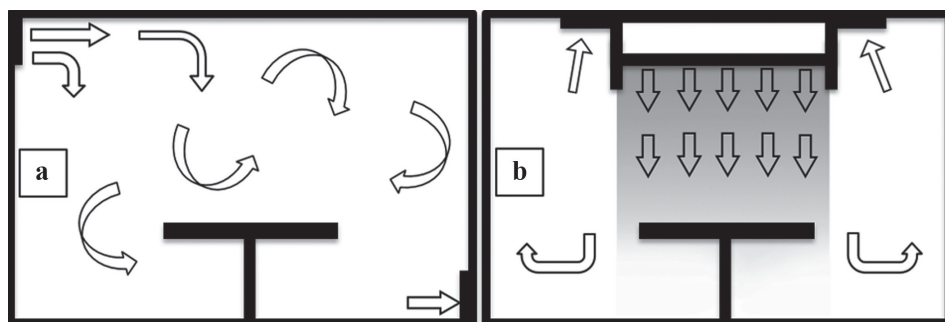


Figure 1. Turbulent Mixed Airflow (a) and Unidirectional Airflow (b).¹¹

In cardiac surgery it is particularly the dread of mediastinitis resulting in high costs and a high mortality rate that leads hospitals to implement UDAF systems for open-heart surgery. However, to date, to our knowledge, no studies have been conducted on the efficacy of UDAF compared to TMA in preventing SSI in cardiac surgery.

The aim of the present single-centre study is to assess whether, under the same perioperative institutional SSI prevention measures, there is a difference in the occurrence of SSIs in open-heart surgery when performed under UDAF compared to under TMA conditions. Our hypothesis was that TMA is an independent risk factor for SSI in open-heart surgery and that UDAF has a preventive effect with consequently a lower incidence of (deep) sternal wound infections.

Methods

Study design

This observational retrospective single-centre cohort study collected data from patients who underwent open-heart surgery at the Leiden University Medical Centre (LUMC) in the Netherlands in the years 2019 and 2021. The year 2020 was deliberately not included due to the potential effects of the COVID-19 pandemic on patient selection that year. For

the group of patients operated in 2019 the surgery was performed in ORs with a TMA air treatment system (ISO 14644-1 class 7). On 11 January 2021 the new ORs with UDAF systems (ISO 14644-1 class 5) for the cardiothoracic surgery department were put into service. The Medical Ethical Testing Commission of the LUMC gave approval for this study.

All patients who underwent open-heart surgery in the LUMC from 1 January through 31 December 2019 and 11 January 2021 through 11 January 2022 and were 18 years and older in the study period were included in this study. Patients who were under 18 years of age or underwent other procedures than open-heart surgery were excluded.

Data were extracted from electronic patient files using a computer query. Patient characteristics (age, gender, body mass index (BMI), diabetes), admission related variables (urgency for operation, type of operation, operation duration, re-operation, admission duration) and SSI variables (location, depth, wound culture, treatment) were collected. All missing data were supplemented after manual search in patient records.

Screening for wound infections was done by searching the medical record course with a computer query consisting of the keywords 'wound infection', 'pus', 'VAC' and 'wound outpatient clinic'. These key words were based on known patients with SSI in the study period from the private database of co-author AdW. SSIs were categorised on the basis of location (sternal incision, site of venectomy) and depth according to Centers for Disease Control (CDC) criteria: superficial, deep, organ/space.¹⁹ There was a 90-day follow-up period after the operation date, as recommended for cardiac surgery by the CDC.¹⁹ Individual records of patients with potential SSI were manually reviewed and the diagnosis and classification of SSI was established by an experienced cardiac surgeon (AdW).

During the two study periods all institutional SSI preventive measures (Table 1) were the same; there were no changes in the applied bundle of preventive measures with the exception of *S. aureus* screening which was not performed in 2021 due to COVID-19 measures.

The characteristics of the two types of ventilation systems that were used in 2019 and 2021 respectively (TMA, UDAF) are specified in Table 2. In the new ORs with UDAF the size of the UDAF ceiling air inlet is 3 × 3 metres, ensuring all surgical tables can be placed within the UDAF field. In these ORs the surgical lamps are integrated in the ceiling, so no obstacles are present between the ceiling and surgical field and a 'skirt' is placed around the plenum to stimulate more downflow and to prevent early entry of particles into the protected area.²⁰



Table 1. *Institutional SSI preventive measures. ^a2019 only*

Period	Measure	Description
Preoperative	Preoperative bathing	Evening before operation showering with Chlorhexidine gluconate
	Smoking cessation	No specific measures
	S. aureus screening	Decolonisation of nasal S. aureus carriage ^a (5 days preop mupirocin)
Peroperative	Glucose control	Target blood glucose below 10 mmol/l
	Hair removal	Before skin preparation with electric razor
	Skin preparation	Chlorhexidine
	Surgical hand scrub	Water and soap, subsequently alcohol
	Surgical attire	Disposable skull cap, surgical mask, no jewellery head & neck, short sleeve scrub suit
	Antibiotic prophylaxis	Cefazolin, 2 grams 15-60 min pre-incision, redose every 4 hours, 24 hours continuation postoperative
	Intraoperative normothermia	Normothermia after cardiopulmonary bypass cessation
	Wound protectors	Impervious plastic wound protector chest wound
	Wound closure	Sternum with interrupted steel wire. Skin in layers with absorbable sutures
	Wound care	Dry absorbent dressing, bandage taken off 18 hours postoperative

Table 2. *Ventilation system characteristics. UDF, unidirectional flow; HEPA, high efficiency particulate air.*

	Turbulent Mixed Airflow (2019)	Unidirectional Airflow (2021)
Airflow (m ³ /h)	3,200	9,500
OR content (m ³)	131	119
Recirculation of air (%)	0	74
Plenum size (m ³)	73	9
UDF	no	yes
HEPA-filter	H14	H13
Electricity use (kWh)	3.3	6.6

Statistical analysis

All statistical analyses were performed with IBM SPSS software, version 25. Descriptive statistics (frequencies and means with standard deviation) were presented for the characteristics of the study population and the surgical procedures, comparing both groups. Characteristics of the population included the factors age, gender, diabetes, BMI,

Euroscore-II and number of days of admission. Characteristics of the surgical procedures included the urgency of the procedure, type of operation, operation duration in minutes and re-operation.

The SSI rate was presented as the percentage of the total patients per group and for their comparison the Pearson chi-square test was used. Using a univariate logistic regression the frequencies and odds ratios with the corresponding 95% confidence interval (CI) and p-values for potential risk factors for SSI (TMA air treatment, diabetes, obesity (BMI > 30), operation duration > 320 min and re-operation) were presented in a table. An operation duration greater than the 75th percentile was considered as a risk factor for SSI.²¹ The association of SSI risk factors was compared using a multivariate logistic regression analysis which corrected for the TMA air handling system, diabetes, obesity, duration of surgery > 320 min and re-operation. The results were presented in a table, showing the occurring odds ratios, 95% CI and p-values.

Results

In total 1,288 patients underwent open-heart surgery in the two-year study period. Of these, 599 patients were operated in 2019 using the TMA air treatment system and 689 in 2021 were operated under UDAF conditions. The characteristics of the included patients and the characteristics of the surgical procedures they underwent are presented in Table 3. Patient characteristics (age, sex, diabetes, BMI, Euroscore-II and admission duration) were evenly distributed in both groups. In 2021, there were almost 11% more isolated coronary surgeries and almost 7% fewer isolated valve surgeries. This may possibly be explained by the postponement of elective surgeries in 2020 due to the COVID-19 pandemic.

Overall 29 patients developed an SSI of the sternal wound. The overall incidence of SSI in the TMA group (2.0%) was not statistically different from the incidence in the UDAF group (2.5%, $P=0.58$). The frequencies of the depth of infection according to CDC criteria in both groups are presented in Figure 2. In the TMA and UDAF group respectively 1.0% and 1.3% of patients who underwent open-heart surgery were diagnosed with mediastinitis (CDC grade 'organ space'). A SSI of the venectomy wound was diagnosed in 0.8% of patients in the TMA group and in 0.6% of patients in the UDAF group. In-hospital mortality in the group of patients with SSI of the sternum was 17% (5 cases).



Table 3. *Characteristics of the study population (N=1,288).*

Characteristic	Type of operating room ventilation	
	Turbulent Mixed Airflow (2019) (n = 599)	Laminar Airflow (2021) (n = 689)
Age, mean (SD), years	63.6 (11.8)	63.8 (12.2)
Sex		
Male	68.8%	74.3%
Female	31.2%	25.7%
Diabetes	21.4%	21.5%
BMI, mean (SD), kg/m ²	26.6 (4.4)	27.2 (4.3)
Euroscore-II, mean (SD), %	3.75 (5.4)	3.24 (5.8)
Admission duration, mean (SD), days	12.7 (12.9)	10.5 (10.9)
Urgency of operation		
Elective/urgent	93.7%	93.6%
Emergency	5.5%	5.5%
Salvage	0.8%	0.9%
Surgical procedure		
Isolated coronary surgery	39.7%	50.5%
Isolated valve surgery	36.6%	30.0%
Combined surgery	12.2%	11.6%
Aorta surgery	6.2%	4.6%
Other	5.3%	2.9%
Operation duration		
Mean (SD), minutes	278 (94)	281 (100)
> 75 th percentile (320 min)	23.0%	26.3%
Re-operation rate	9.0%	8.9%

BMI, body mass index; SD, standard deviation

Microbial aetiology could be identified in wound cultures of 55% of patients with sternal SSI, of the other 45% of the patients with sternal SSI no cultures were taken since this is not standard practice in our institute. *Staphylococcus aureus* was the most common isolated pathogen (seven cases), followed by *Staphylococcus epidermidis* (three cases), *Enterococcus faecalis* and *Pseudomonas aeruginosa* (both two cases), *Klebsiella pneumonia* and *Serratia marcescens* (one case each).

Univariate analysis and multivariate analysis results are summarised in Table 4. In the univariate analysis SSI of the sternal wound is significantly associated with obesity, operation duration >320 minutes and re-operation. Air treatment with TMA was not

found to be a significant risk factor for sternal wound SSI. Multivariate analysis found that only BMI greater than 30 kg/m² and re-operation were significantly associated with sternal wound SSI, diabetes, operation duration >320 minutes and air treatment with TMA were not (OR 0.9, 95% CI 0.4-1.8).

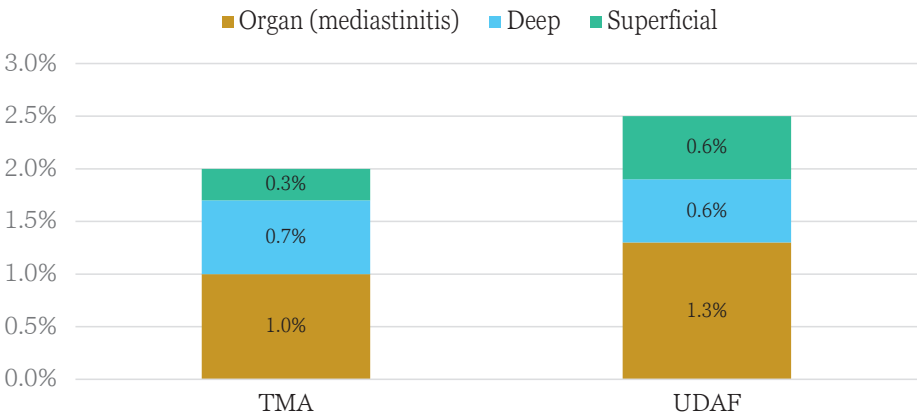


Figure 2. Frequency of SSI distributed by depth Centers for Disease Control (CDC) classification. TMA, turbulent mixed airflow; UDAF, unidirectional airflow.

Table 4. Association between risk factors and sternal wound surgical site infection (SSI).

Parameter	Univariate analysis				Multivariate analysis	
	SSI (N=29)	No SSI (N=1,259)	OR (95% CI)	P-value	OR (95% CI)	P-value
Diabetes	9 (3.3%)	267	1.6 (0.8-3.7)	0.2	1.6 (0.7-3.6)	0.29
Obesity (BMI > 30 kg/m ²)	12 (4.4%)	263	2.7 (1.3-5.7)	0.01	2.4 (1.1-5.2)	0.03
Operation duration (> 320 min)	13 (4.1%)	306	2.5 (1.2-5.3)	0.01	2.0 (0.9-4.4)	0.08
Re-operation	10 (8.7%)	105	5.8 (2.6-12.8)	0.00	4.9 (2.1-11.1)	0.00
Air treatment with TMA	12 (2.0%)	587	0.8 (0.4-1.7)	0.58	0.9 (0.4-1.8)	0.68

BMI, body mass index; TMA, turbulent mixed airflow; OR, odds ratio; CI, confidence interval.

Discussion

The hypothesis for this research was that TMA is an independent risk factor for SSI in open-heart surgery. This could not be confirmed, neither in univariate analysis (OR 0.8, 95% CI 0.4-1.7) nor in multivariate analysis (OR 0.9, 95% CI 0.4-1.8). So under the same institutional SSI preventive measures and with a state-of-the-art (ISO 14644-1 class 5)

UDAF system we could not demonstrate a protective effect of UDAF on the incidence of SSIs in open-heart surgery. There was no difference in the incidence of SSI in the TMA group (2.0%) and the UDAF group (2.5%, $P=0.58$). Mediastinitis (CDC grade 'organ space') occurred in respectively 1.0% (TMA) and 1.3% (UDAF) of patients who underwent open-heart surgery with a 17% overall in-hospital mortality due to mediastinitis.

The incidence of mediastinitis and its mortality rate in this study are consistent with the numbers reported in the literature.⁵ The feared risk of mediastinitis in open-heart surgery has led to the practice that these operations are preferably performed under UCA conditions. There seems to be no dispute that UDAF results in a reduced bacterial and particle load, which would suggest it to be an important preventive measure for SSI.²² However, whether this UCA leads to fewer SSIs is unclear in the literature. In light of this scientific uncertainty it seems justified to consider the effectiveness of UDAF systems in reducing SSI in specific types of operations such as cardiac surgery, also given the fact of the environmental impact and high acquisition and operating costs of UDAF systems.¹⁵ UCA conditions are often, but not always, realised by utilizing UDAF ventilation systems.²³ Romano et al. in their research on performance of OR ventilation systems found that the contamination performance in operational conditions of UDAF ISO class 5 systems such as ours had average values of 5.5 CFU/m³ and were always better than those of TMA systems (72.8 CFU/m³).²⁴ In our study we may therefore assume that the air cleanliness was significantly better under UDAF conditions.

It seems plausible that if there are fewer airborne bacteria due to cleaner air during surgery that there should be less risk of wound infections. The studies performed over the years on TJA, however, do not give unequivocal results. This may be partly due to the methodology of these studies.^{10,25} Numerous factors are involved in the occurrence of SSI, and each of these factors can be a potential confounder in studies comparing different types of air handling systems. It is well established that the incidence of SSI depends on patient-related factors, surgery-related factors and preventive measures.⁹ As for the latter, air cleanliness depends on many factors such as the type of air handling system, door openings, the position of surgical lamps, plenum size and type of clothing.^{15,23} This multifactorial aspect of SSI risk and the lack of control over these variables may explain the conflicting results in literature since no recent RCTs have been conducted. In the 1970s RCTs were conducted as part of the MRC study.¹⁰ These studies remain very valuable, but much has changed in 50 years in terms of technology and SSI prevention. This means that probably not all results are applicable to the current state of affairs and justifies in our opinion the need to do new RCTs.

In a recent single institution retrospective cohort study with the only variable being the OR ventilation system Wang et al. have demonstrated no reduction on the risk of periprosthetic joint infection in TJA due to UDAF.²⁶ These results are in accordance with our findings in open-heart surgery.

Operating rooms are a very resource-intensive segment of hospitals with consequently a considerable environmental burden. MacNeill et al. measured an average carbon emission per OR of 188 tonne of CO₂-eq annually.²⁷ This is roughly equivalent to annual emissions of 95 petrol cars per OR. The carbon footprint of ORs is mainly determined by the direct emissions of greenhouse gases (GHG) such as inhalation anaesthetics, indirect emissions from HVAC energy consumption and indirect emissions due to the surgical supply chain and waste disposal.²⁷ The HVAC is responsible for 90-99% of energy consumption in ORs.²⁷ This energy consumption depends, among other things, on the type of air treatment system used.^{11,12} Alsved et al. evaluated the air cleanliness and energy consumption of UDAF and TMA ventilation systems during orthopaedic operations. The energy consumption of the TMA system was 65% less than that of the UDAF system. This was due to high airflow rates of 12,000 m³/h that are a characteristic of UDAF. However, the air cleanliness in the OR of the UDAF was significantly better than that of TMA.¹¹ In a Norwegian hospital, using mock surgery simulations, UDAF and TMA were compared looking at energy consumption and factors affecting it such as outdoor temperature, the amount of fresh air supply, heat recovery and setback strategy when the OR is empty. After outdoor temperature correction the median electricity consumption of TMA was 45% less than that of UDAF.¹² Both these studies show that the energy requirements of UDAF are significantly higher than those of TMA. Greenhouse gas emissions due to electricity consumption depend on the percentage of renewable energy used. In 2019, the share of renewable energy worldwide was estimated to be around 27%. So overall, a significant portion of the energy used globally for operating room HVACs results in emissions of CO₂. Furthermore, it will also be important in the future to reduce energy wastage since there is an imbalance between the amount of renewable energy that can be generated and the ever-increasing worldwide demand for electricity.

These data should be taken into consideration if UDAF cannot be shown to have a positive effect on the incidence of SSI. Healthcare's climate footprint is equivalent to 4.4% of global net CO₂ emissions and herewith contributes to climate-related health hazards.²⁸ The global disease burden from the GHG emissions of the United States healthcare sector alone is estimated to be 209,000 disability adjusted life-years (DALYs), indicating that healthcare in itself is detrimental to human health.²⁹ 'If it does not help, it will not hurt' is therefore not a good strategy when UDAF is chosen as an infection



prevention measure in cardiac surgery if, as has been demonstrated in this study, there is no protective effect on the incidence of SSI. Deploying scientifically non-evidence-based infection prevention measures such as these can be classified as overuse, which is in part responsible for the carbon footprint of healthcare. Reducing overuse of healthcare in general is expected to yield the most significant results in terms of carbon reduction in healthcare.³⁰ As the HVAC has a large impact on the carbon footprint of the OR, it seems effective, based on our results, to use TMA for open-heart surgery and thus reduce carbon emissions due to overuse of electricity. To prevent DSWI, the focus should be on infection prevention measures that have been proven effective by RCTs.²

Our study has some limitations. The observational nature of our study means that a clinically relevant effect of UDAF cannot be completely ruled out based on our results and a well-designed RCT could possibly do so. The study was retrospective in its design, therefore the collecting and recording of the data has not been controlled which may reduce its reliability in comparison to a RCT. However, since the data were extracted from electronic patient files using a computer query and all missing data were supplemented after manual search in patient records we are confident that the reliability of the data is thereby ensured. There was a small difference between the cohorts in the number of coronary artery bypass grafting (CABG) operations (Table 3). A slightly higher SSI incidence in CABG operations compared to valve surgery has been reported in the literature.^{4,31} Statistical analysis of our data on the type of surgery and SSI-risk by means of a univariate logistic regression showed no association of CABG operation with SSI-risk (OR 1.046 (0.5-2.162)). So we are confident that difference between the cohorts in the number CABG operations had no significant influence on our results. We did not characterize the performance of the ventilation systems with respect to air cleanliness during the operations expressed as colony-forming units per cubic meter of air (cfu/m³). However, in a recent study on OR ventilation system performance UDAF system in ISO 5 class showed to be an effective and stable solution for guarantying a low airborne bio-burden contamination.²⁴ The institutional SSI preventive measures (Table 1) were strictly protocolised and patient characteristics were evenly distributed in both groups (Table 3). Although the two cohorts differed only in the type of air treatment used during the procedure, the retrospective study design meant that there was no complete control for other relevant factors such as staff work practice, door openings and clothing systems. However, in the two study periods there was no significant change staff work practice in terms of number of people present during surgery or staff movements, door openings were always unrestricted and the clothing system was unchanged. In the context of SSI prevention in the TMA group (2019) a preoperative nares screen on *S. Aureus* was executed, and if positive a subsequent 5-day mupirocin eradication was performed. This was not done in the 2021 UDAF group due to COVID-19 measures. In a

recent systematic review of eight studies on targeted mupirocin-based decolonisation in patients undergoing cardiothoracic surgery Wang et al. concluded that the results were inconclusive due to contrasting evidence from RCTs and retrospective studies.³² In view of this conclusion we are confident that this difference in treatment between our two cohorts has no relevant impact on our results. Another limitation is that this is a relatively small study population with a very low incidence of the outcome measure, it would benefit the reliability of the study to have a larger study population in order to reduce the chance of a statistical error.

Future research should ideally consist of RCTs to demonstrate the effect of UDAF on SSI in multiple types of surgery. Given the low incidence of SSIs, a RCT will presumably need to be a multicentre study to include large numbers of patients. It would need a precise description of the air handling system under investigation, air quality should be measured during operations and possible confounders should be controlled beforehand. The latter, given the multifactorial aspect of SSI, may make the implementation of such RCTs unfeasible in practice. However, given the devastating consequences for each patient with DSWI we would encourage such research. Furthermore, it would be useful to establish a rating of infection prevention methods based on their cost-effectiveness and environmental impact. More environmentally friendly options can be available, implementation of which could be enabled by considering the environmental impact as an additional dimension of quality of care, next to patient safety and clinical effectiveness.³³

Conclusion

Based on our results, there seems to be no indication for UDAF to prevent sternal wound infections and mediastinitis in cardiac surgery. With the same effectiveness in preventing SSIs as TMA, the choice for UDAF systems should be weighed against their environmental impact due to a significantly higher energy consumption. In the current climate crisis, the environmental impact of infection prevention measures like the air treatment system of an OR should be considered and seen as a dimension of quality of care.³³ HVAC systems have a lifespan of up to 30 years and when a UDAF system is already implemented, it pays to use renewable energy and reduce its energy consumption. Demonstrated ways to save substantial amounts of energy on HVAC systems include optimisation during off-use periods, heat recovery from expelled air, reducing the amount of fresh air added and reducing the number of air changes.^{12,22,34,35} Doing so can improve the carbon footprint of UDAF systems without even compromising the air cleanliness in the OR.



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CHAPTER 4

Reducing the Environmental Impact of Sterilisation Packaging for Surgical Instruments in the Operating Room: A Comparative Life Cycle Assessment of Disposable Versus Reusable Systems

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Abstract

Background: The widespread use of single-use polypropylene packaging for sterilisation of surgical instruments (blue wrap) results in enormous environmental pollution and plastic waste, estimated at 115 million kilograms on a yearly basis in the United States alone. Rigid sterilisation containers (RSCs) are a well-known alternative in terms of quality and price.

Aim: This paper deals with two research questions investigating the following aspects: (A) the environmental advantage of RSC for high volumes (5,000 use cycles) in big hospitals, and (B) the environmental break-even point of use-cycles for small hospitals.

Methods: An in-depth life cycle assessment was used to benchmark the two systems. As such a benchmark is influenced by the indicator system, three indicator systems were applied: (a) carbon footprint, (b) ReCiPe, and (c) eco-costs.

Findings: The results are as follows: (1) the analysed RSC has 85% less environmental impact in carbon footprint, 52% in ReCiPe, and 84.5% in eco-costs; and (2) an ecological advantage already occurs after 98, 228, and 67 out of 5,000 use cycles, respectively.

Conclusion: Given these two alternative packaging systems with comparable costs and quality, our results show that there are potentially large environmental gains to be made when RSC is preferred to blue wrap as a packaging system for sterile surgical instruments on a global scale.

Introduction

The healthcare sector is known to be a large contributor to environmental pollution. On average, 5.5% of the total national carbon footprint of countries is from the healthcare sector, with developed countries such as the Netherlands, the United States, Belgium, and Japan in the lead with 7.6 to 8.1%.¹ In 2013, the global disease burden due to the environmental impact of the U.S. healthcare sector was calculated to be 614,000 disability-adjusted life-years (DALYs) annually.² This paradox of healthcare having indirect adverse effects on public health calls for action to improve the environmental performance of the healthcare sector by energy savings as well as pollution and waste reduction.³

Being a very resource-intensive part of the hospital, the operating room (OR) is an area where CO₂ emission saving measures potentially have a large impact. The carbon footprint of the OR is primarily determined by the use of inhalation anaesthetics; energy use by the heating, ventilation, and air conditioning (HVAC); supply chain; and waste production.⁴ OR waste production is constantly growing, being partially explained by the increased use of disposable products in the last two decades. Disposables have replaced reusables and are nowadays the standard in healthcare. The rationale for this transition being infection prevention, cost reduction, and convenience. Many items that were once reusable in the OR have been replaced by disposable alternatives. Some examples are surgical gowns and drapes, laparoscopic instruments, and anaesthetic equipment such as facemasks and breathing circuits. Discarding these disposables after use results in a considerable waste production that has become characteristic for the OR. In the meantime, a single operation generates an average of 12 kg of waste, causing the OR to be a major source of total hospital waste production.⁴

Although recycling is frequently considered as the primary solution to reduce OR waste, it is often difficult in an OR setting because of a lack of knowledge of recyclable materials and the fact that it often involves the handling of infectious materials.⁵⁻⁷ Apart from these practical barriers to recycling, it is important to realise that the majority of packaging materials and disposable products used during operations are made of plastics and that recycling is actually downcycling of these products. In practice, recycled materials are rarely used as raw materials for similar products in the OR. Therefore, from an environmental perspective, it is better to reduce waste by first applying the other cornerstones for waste reduction 'reduce', 'reuse', and only then consider 'recycle'.⁸ Recycling is an important way to ensure that valuable raw materials are not wasted in a circular economy. However, first and foremost, prevention of waste being generated is the best way to improve the OR's environmental impact.^{9,10} Surgery has in this a distinct opportunity to aid the transition to more environmentally friendly OR strategies.¹¹



The use of blue wrap as disposable packaging material for sterile surgical instruments is a major contributor to OR waste.⁷ Estimates are that 115 million kilograms of blue wrap is discarded on a yearly basis in the United States alone.⁸ Blue wrap is a multilayer non-woven packaging material made from polypropylene (PP) supplied as sheets. Surgical instrument nets are wrapped in the sheets, in a similar way as packages being wrapped. Through the manufacturing process of spun bonding and melt blowing, a unique PP trilaminate is produced that is characterised by robustness and bacterial resistance and that withstands high temperatures necessary for the sterilisation process.¹²

After unpacking sterile surgical instruments, blue wrap packaging is discarded, making up 11.5% of total OR waste.⁶ Reducing OR waste is possible by considering reusable alternatives for perioperative disposables. An alternative to blue wrap is a reusable rigid sterilisation container (RSC).¹³ However, no compelling evidence exists for whether the quality of either of these packaging systems would be better than the other. RSCs are used by the majority (60%) of sterilisation departments in Europe, but much less in North America, China, and India, where blue wrap is preferred.¹⁴ The overall total costs of purchase and use of both packaging systems are comparable.¹⁵ However, relatively large capital investments are required to purchase the containers, more storage space is needed, and the containers are ergonomically inferior because of their weight. These drawbacks of RSCs are a possible explanation for the worldwide popularity of blue wrap.

For a number of perioperative textiles, surgical instruments, and anaesthetic devices, a life cycle assessment (LCA) has been done and has shown reusables to be environmentally favourable to disposables.¹⁶⁻²³ However, this effect may depend on the local situation, as was evident in a LCA study of single-use anaesthetic equipment where the results depended considerably on the power mix in the region of research.²⁴ To this day, no LCA studies have been conducted to research the ecological burden of blue wrap or RSC.

For the present study, our hypothesis was that, in the European situation, the use of the reusable RSC has less environmental impact than single-use blue wrap, even when closed loop upcycling is applied. This hypothesis was tested by two research questions investigating the following aspects: (A) the environmental advantage of RSC for high volumes (5,000 use cycles) in big hospitals, and (B) the environmental break-even point of use-cycles for small hospitals.

An in-depth life cycle assessment was used to benchmark the two systems, cradle-to-grave, as well as for cradle-to-cradle ('closed loop') solutions. The influence of the power mix will be examined to assess the effect of local renewable electricity (i.e., electricity with a 'bundled' renewable energy certificate) or electricity of other regions of the world.

Methods

Life Cycle Assessment

The system and the functional unit

This study used the three-layered spunbond-meltblown-spunbond (SMS) one-step non-woven H300 model Quick Check Sterilisation wrap 101 cm × 101 cm as a representation of blue wrap (Figure 1). As RSC, the standard container of B. Braun Medical BV. with bottom model JK441 (59.2 × 27.4 × 12.0 cm) and lid model JP489 was chosen (Figure 2). Both the type of blue wrap and the brand of RSC were chosen on the basis of availability in our hospital (the Leiden University Medical Centre (LUMC) in the Netherlands). The sizes of both blue wrap and RSC were chosen to fit a standard format instrument tray (European Standard DIN: 480 × 250 × 60 mm).



Figure 1. *The Halyard blue wrap.*

The scope of this research is a comparative cradle-to-grave LCA benchmarking study, which includes four phases during the product life: the production phase (includes the extraction of material, transport to the production site, and manufacturing), the transport phase (from production site to the hospital), the use phase (washing and sterilisation process), and the

end-of-life phase (incineration, landfill, and recycling). The processes included for the four systems under study are presented in the flow charts in Figure 3. Key data for the LCA of the Halyard sterilisation wrap and the B. Braun RSC are shown Appendix A. The production of capital goods, such as washing machines and autoclaves, is excluded from the LCA.

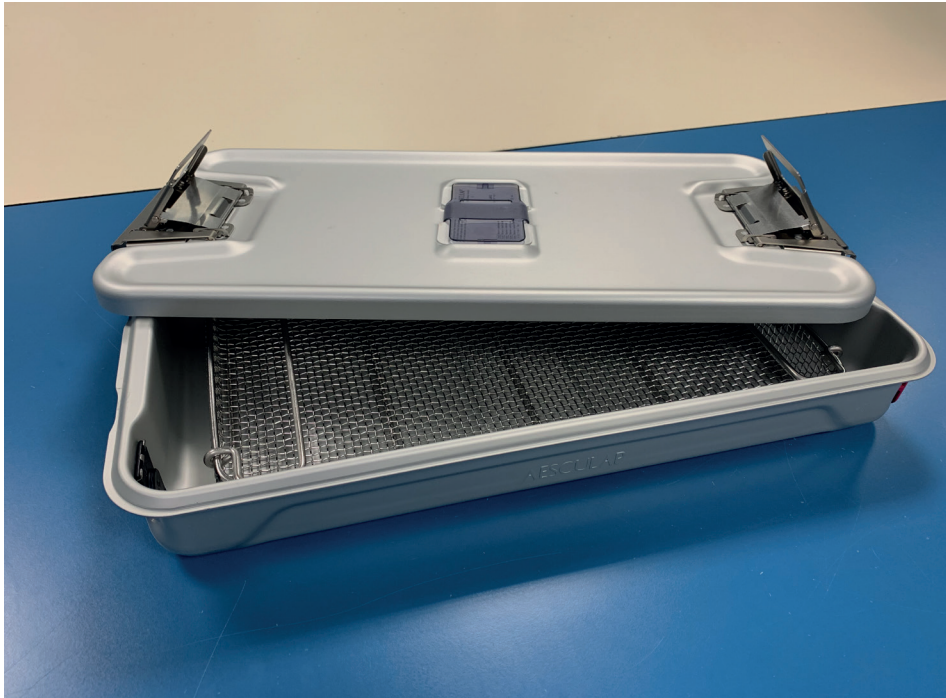


Figure 2. *The B. Braun RSC.*

The functional unit is defined as follows: sterile packaging of a standard format instrument tray for 5,000 sterilisation cycles. The RSC is validated for 5,000 cleaning and sterilisation cycles, using ten reusable filters (five times two filters, each usable for 1,000 cleaning and sterilisation cycles). This implies that 5,000 Halyard H300 Quick Check Sterilisation wraps are comparable to one RSC used 5,000 times.

The material composition of both the blue wrap and RSC was determined using manufacturer information. For accuracy, each individual material of the RSC was weighed using a microgram scale. Data on electricity, water, and detergent usage of the washing machine were gathered from the manufacturer. Data on transportation were specific to our hospital in Leiden, the Netherlands. Alternative scenarios for recycling, power source use, and the RSC's lifespan were considered to make the results applicable in a wider range of practical situations.

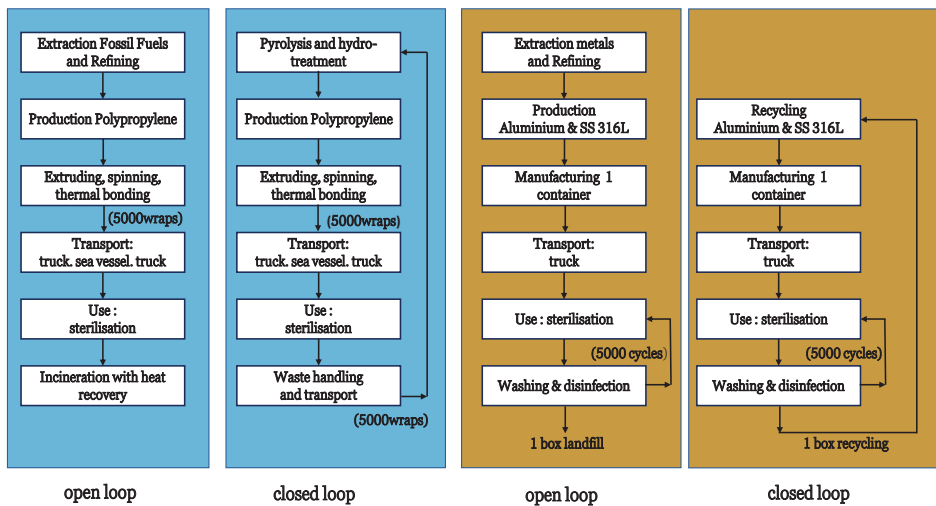


Figure 3. Summary flow charts of the processes included in the four systems under study: Blue wrap open and closed loop and RSC open and closed loop.

Choice of single indicators

LCA is used here to determine whether ‘system A is better than system B’, so-called ‘single score methods’ are applied, as has been recommended by the Society of Environmental Toxicology and Chemistry and the Joint Research Centre of the EU.^{25,26} As the LCA scores depend on the choice of indicator system, the calculations were performed for three indicator types: (i) carbon footprint, as a ‘single issue method’; (ii) ReCiPe, as a ‘damage-based method’; and (iii) eco-costs, as a ‘monetised prevention-based method’. In their sectors, these three indicators are the most applied methods in science.

The carbon footprint is well known, but has the disadvantage that toxic emissions and materials’ depletion are not counted in the system. We apply the IPCC 2013 midpoint table (‘with climate-carbon feedback’). The ReCiPe system, version 2016, has the advantage that toxicities and materials’ depletion are incorporated.²⁷ The disadvantages are that it is complex, not very transparent, and not easy to communicate the results to non-experts. We apply the ReCiPe 2016 Endpoint (H), World (2010) H/A.

The eco-costs is a system of marginal prevention costs that is in compliance with ISO 14008:2019.²⁸ Although monetisation in LCA is not very common, the advantage of eco-costs is that they are related to ‘external costs’ (i.e., costs for our society that are not yet incorporated in the price of a product), so they have a direct meaning to decision-makers, and are easy to communicate. Recently, there have been increasing

applications of eco-costs in design and engineering, especially for innovations in the Circular Economy. Eco-costs are also applied in full cost accounting, which is also called true cost accounting (TCA). The basic philosophy behind TCA is that the external costs of a product should be added to the economic costs to enable a fair comparison in product benchmarking between a cheap but polluting product and a 'clean' product.

The eco-costs of a product are the sum of all eco-costs of emissions and use of materials during the life cycle from 'cradle to cradle', in fact a mass and energy balance, conforming to ISO 14040 and ISO 14044 for LCAs ²⁹; see Figure 4.

The Delft University of Technology has calculated the LCA results in eco-costs for all 6,600 useful LCI data lines of Ecoinvent V3.6 and, in addition to that, 1,200 LCIs from scientific peer-reviewed papers and databases from other universities (on materials, processes, electricity, and heat), resulting in two data sets (EI_V3-6 and Idemat, respectively) with five Excel lookup tables.³⁰ This way of calculating with the use of a spreadsheet and open access background process databases is called Fast Track LCA. It makes it possible to compare the environmental burden of products in a limited time, with no need for company software or licenses, and without any compromise in terms of accuracy. The Idemat data as well as the eco-costs system are also available in Open LCA and can be downloaded for Simapro. The calculations of this paper were done in Simapro version 9.2.

For the hot-spot analysis in Appendix B, and the alternative scenarios for electricity in Section 3.3, we apply the eco-costs, as the eco-costs method is the preferred system in the discussions on the main system improvements in our hospital.

Modelling parameters

For the composition of an RSC, the current trade mix aluminium is used (12.5% recycled). The fabric of blue wrap is known as SMS polypropylene. The production process involves extrusion, spinning, and melt blowing. Travel distances from the production site to the LUMC, The Netherlands, were estimated with Google Maps. All factors regarding the sterilisation process were assumed to be equal as the dimensions of the instrument tray wrapped in blue wrap or placed in a RSC are similar, and thus the same number of trays can be loaded into a sterilisation machine. A study of steam sterilisation's energy and water footprint shows that the load mass of a steam steriliser is low, but not negligible in regard to its energy consumption.³¹ Therefore, the amount of energy needed to heat the packaging material from 20 °C to 134 °C was taken into account in the use-phase of the LCA. The washing process for the RSC was taken into account as well in the use-phase, based on the PG8930 Miele washing machines.

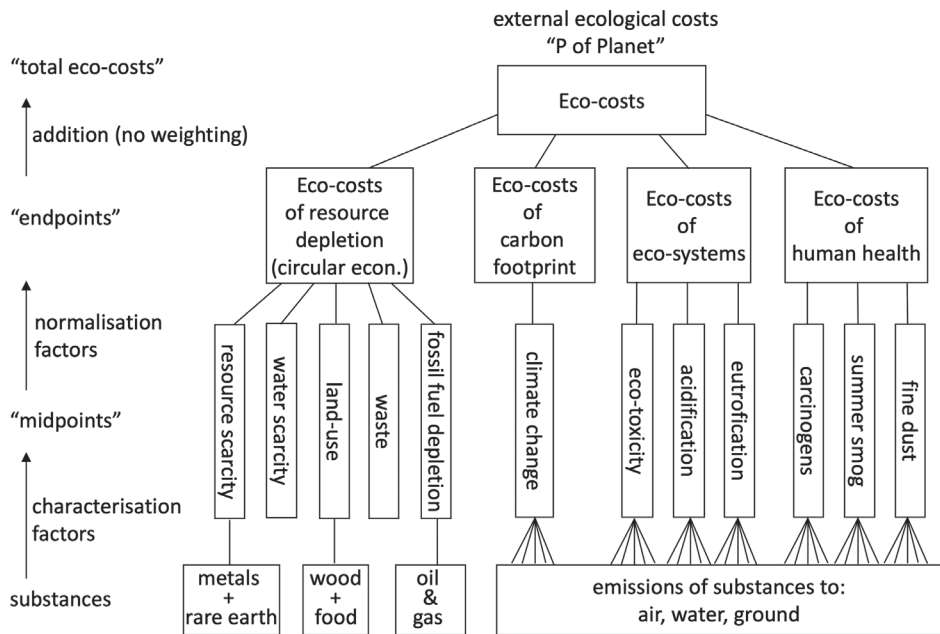


Figure 4. The eco-costs system calculation structure.²⁹

For blue wrap, two end-of-life scenarios were calculated: (1) 'open loop' waste incineration with heat recovery and (2) a future scenario of 'closed loop' recycling.³² For the RSC, the two end-of-life scenarios were calculated as follows: (1) landfill and (2) recycling of the metals.

Three scenarios for electricity

Electricity is an important determinant for the environmental impact in the use phase of sterilisation and washing. Three scenarios for the electrical power supply were tested: (1) the current electricity mix in the European Union, i.e., the base case; (2) 100% photovoltaic (PV) cells for the European climate condition; and (3) 100% coal-fired power plants (the average in the United States, China, and Europe).

Results

The Environmental Gain for 5,000 Cycles (Research Question A)

The results from the three indicator systems (carbon footprint, ReCiPe, and eco-costs) for 5,000 use cycles of both packaging systems (blue wrap and RSC) are shown in Figure 5a–c.

In Figure 5a, the carbon footprint scores of blue wrap and the RSC are given for two scenarios: the current open loop situation and the future closed loop recycling. The current open loop situation gives by far the highest carbon footprint: 1,869 kg CO₂-eq/5,000 cycles. That carbon footprint can significantly be reduced by a closed loop system with mechanical recycling of the PP (shredding and melting): 883 kg CO₂-eq/5,000 cycles. As mechanical recycling is downcycling (the quality of the PP deteriorates at each recycling loop), 10% virgin PP is added at the manufacturing plant. The RSC has the lowest carbon footprint of 285 kg CO₂-eq/5,000 cycles for landfill and 270 kg CO₂-eq/5,000 cycles for recycling. Closed loop scores hardly lower than the current open loop recycling in Western Europe. The reason for the small difference is that the RSC 5,000 cycle case is dominated by the use-phase (i.e., washing and sterilisation). See Table A5 in Appendix B.

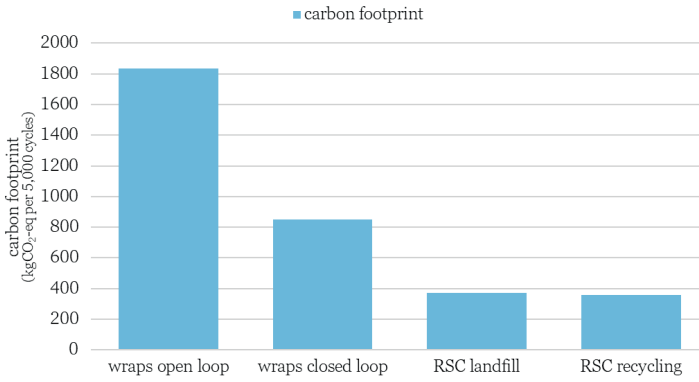
The results in terms of ReCiPe points are given in Figure 5b. ReCiPe is about damage in terms of human health, ecosystems, and resource depletion, and has no separate score for global warming. However, the toxicity of the carbon footprint (kg CO₂-eq) is rather dominant in human health. The reasoning is that global warming, i.e., higher temperatures, results in more diseases, and thus more DALYs.

For blue wrap (open loop), the CO₂-eq component in human health in our calculations is 79%. That is the main reason that the ReCiPe results look similar to the results of the carbon footprint. It should be mentioned here that the uncertainty in these damage-based calculations on CO₂ is rather high, because of the many calculation steps in the required calculations, and the many assumptions. This is in contrast to the prevention-based eco-costs of CO₂.

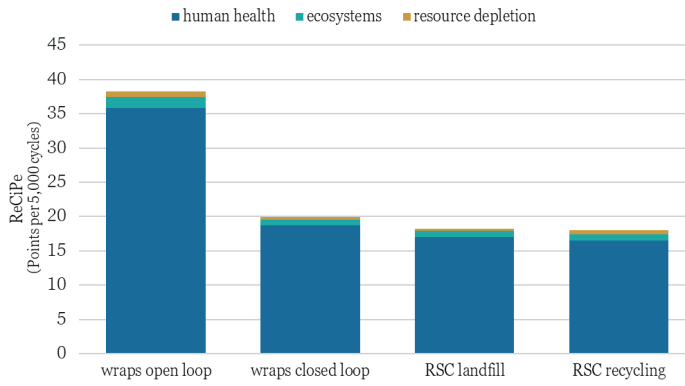
For RSC (recycling), the CO₂-eq component in human health is only 34%. The other main components are 31% for fine dust, 30% for the human health effect of water scarcity (caused by the rather high water consumption of the washing machine in the use phase), and 5% for human toxicity.

Another issue in ReCiPe is that resource depletion (e.g., the fossil fuels embedded in plastics) hardly counts in the system. Thus, the plastic waste mentioned in the Introduction is barely counted in ReCiPe.

(a)



(b)



(c)

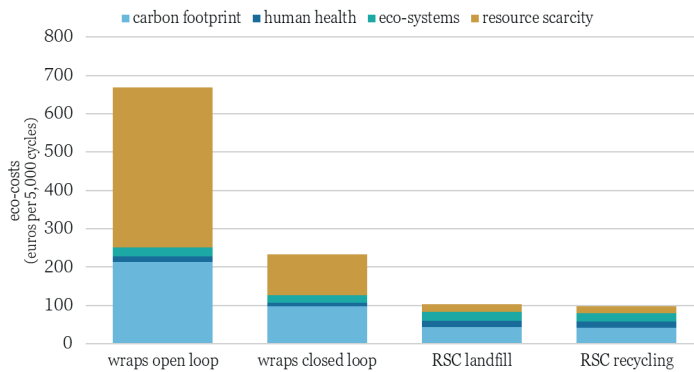


Figure 5. (a) The carbon footprint of blue wrap and the RSC for 5,000 cycles. (b) The ReCiPe points of blue wrap and the RSC for 5,000 cycles. (c) The eco-costs of the wraps and the RSC for 5,000 cycles.

It appeared in our research project that the eco-costs system provided the best basis for the analysis and communication. The calculation results are given in Figure 5c. Characteristic for the eco-costs system is that materials' scarcity has a relative high share of the total eco-costs of plastics (as well as metals), which makes eco-costs suitable for C2C calculations in the circular economy. Detailed data tables (per process step) for hot spot analyses are given in Appendix B.

From Figure 5a–c, it may be concluded that (a) the RSC system has much lower environmental pollution than the blue wrap system and (b) the pollution of the blue wrap system can be reduced to 50% or less when a closed loop recycling system is introduced.

It is obvious that these conclusions depend on the number of cycles as defined by the functional unit (the RSC becomes less attractive at less cycles). Thus, it makes sense to calculate the break-even point for both systems (blue wrap and RSC), which is relevant for small hospitals.

The break-even points of both packaging systems (research question B)

The potential environmental gain by the switch from a blue wrap system to a RSC system, which has been calculated in the previous section, is interesting to big hospitals. Small hospitals might have a far lower functional unit than 5,000 cycles. For these small hospitals, the break-even point of number of cycles is interesting (the question is, at how many cycles does the RSC have the same environmental burden as the blue wrap system?). The answer to this question (our research question B) is depicted at Figure 6a–c for carbon footprint, ReCiPe points, and eco-costs, respectively. The data were calculated for specific scenarios for end-of-life: the wraps are incinerated with heat recovery and the RSCs are landfilled.

For waste incineration with heat recovery ('open loop') and landfill of the RSCs (Figure 6a–c), the break-even points are as follows: 98 cycles for the carbon footprint, 228 cycles for ReCiPe, and 67 cycles for eco-costs.

It is obvious that the break-even points are higher for the case of recycling of the wraps (closed loop mechanical recycling), as the eco-burden of the mechanical recycled wraps is much lower than the eco-burden of wraps from virgin PP. The results of the calculations are as follows: 150 cycles for the carbon footprint, 1293 cycles for ReCiPe, and 88 cycles for eco-costs.

Note that, in ReCiPe, the eco-burden of the closed loop blue wrap system (5,000 cycles) is not much higher than the eco-burden of the RSC system; see Figure 5b. Hence the high break-even point in ReCiPe.

Alternative scenarios for electricity of the use-phase (sterilisation and washing)

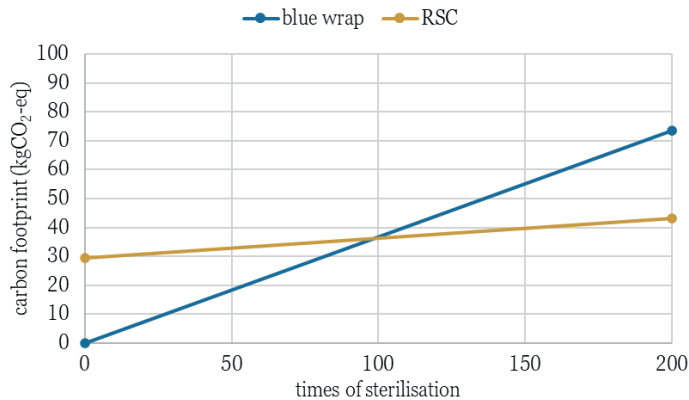
The major component of the RSC system is the power consumption in the use-phase at the hospital: 1,996 MJ per 5,000 cycles; see Tables A5 and A6 in Appendix B. This triggers the discussion on the potential positive environmental effect of PV cells on the roof of the hospital. The positive effect in terms of eco-costs is given in Figure 7. This figure also gives information for electricity in countries outside the EU.

Compared with the electricity mix in EU-27 (the base case), there is a potential reduction in the eco-cost of the RSC system of 28 euros per 5,000 cycles (-74%) when electricity from local photovoltaic (PV) cells is used.

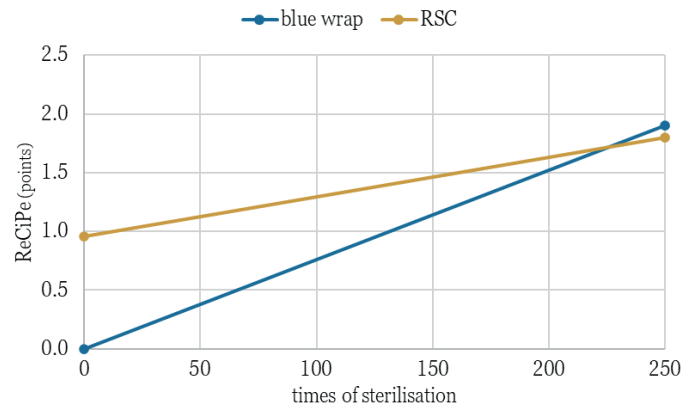
Note that the electricity in the use-phase for blue wrap is rather negligible: 103 MJ per 5,000 cycles; see Table A3 in Appendix B.



(a)



(b)



(c)

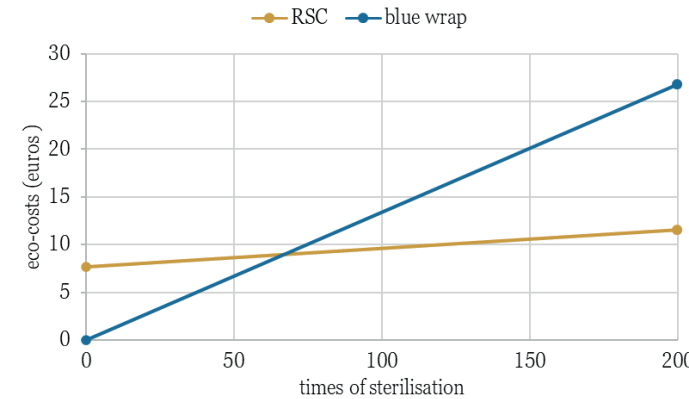


Figure 6. (a) Break-even analysis of blue wrap (open loop recycling) and RSC (landfill) for the carbon footprint. (b) Break-even analysis of blue wrap (open loop recycling) and RSC (landfill) for ReCiPe. (c) Break-even analysis of blue wrap (open loop recycling) and RSC (landfill) for eco-costs.

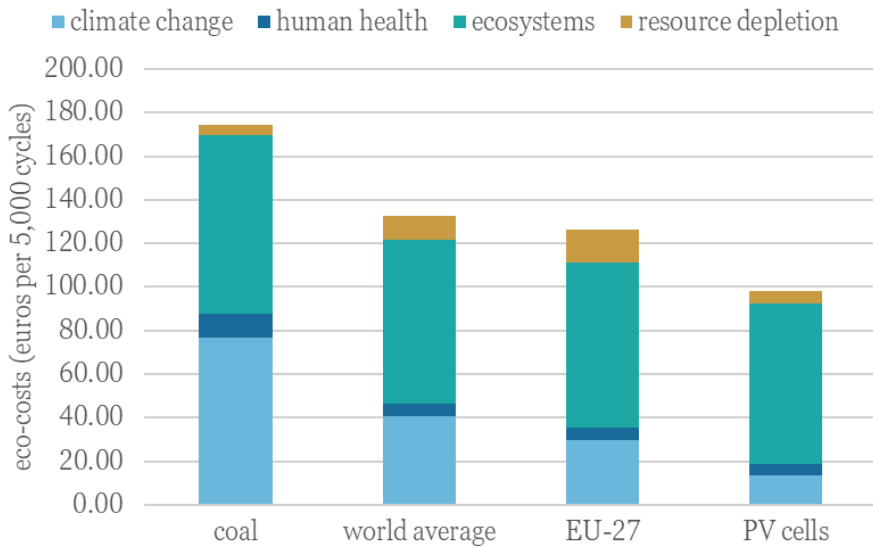


Figure 7. Alternative power source scenarios for the use-phase of the RSC system (i.e., power for the sterilisation and the washing machine). PV, photovoltaic.

Discussion

Disposable blue wrap is a very popular surgical instrument sterilisation packaging system that is used by many sterilisation departments in Europe, North America, China, and India. However, its use causes a great deal of healthcare waste and does not match the goal of a circular economy. In this context, it was hypothesised that choosing a reusable packaging system would be environmentally preferable.

This is the first peer-reviewed research into the environmental impact of RSCs and blue wrap. An LCA benchmarking study of these two packaging systems was executed. The main result of our study is that, in the European situation, an aluminium RSC, as a packaging system for surgical instrument sterilisation, has 84% less eco-costs compared with the current three-layered, one-step, non-woven polypropylene blue wrap for a functional unit of 5,000 cycles (which is the answer to our research question A). The advantage in eco-costs for the RSC already occurs after 68 out of 5,000 use cycles (which is the answer to our research question B). The production phase of blue wrap is the main contributor to its eco-costs (88%), primarily owing to the PP pellets. For the RSC, the use phase (washing and sterilisation) causes 93% of its eco-costs, primarily owing to the detergents and electricity usage.

In the context of regional differences in the energy mix of washing and sterilisation, we modelled the effects on our results of switching to electricity generated exclusively by renewable energy sources or by bituminous coal power plants. This had hardly any influence on the results of blue wrap and only a moderate influence on those of the RSC (see Figure 7 and Table A6 in Appendix B).

As an alternative to switching to the RSC system, we studied the impact of closed loop mechanical recycling instead of incineration of blue wrap as an end-of-life scenario. Modelling closed-loop polypropylene recycling reduced blue wrap eco-costs to 35%. However, in this scenario, the RSC still outperformed blue wrap ecologically by more than a factor of two.

The choice of a packaging system for sterile instruments may depend on many factors. Financial arguments may be important in this regard. For example, the RSC system requires upfront investment in washing and sterilisation machines in addition to the purchase of the containers. The purchase of blue wrap is relatively inexpensive in this regard. However, Krohn et al. have shown that the total costs of ownership of these two systems are quite similar over time.¹⁵ They conclude that a choice for a particular system may then depend on the availability of financial resources for the necessary investments or that time savings in container handling may be a motive if there are personnel shortages. From a patient safety perspective, according to the guidelines, both systems are suitable as packaging for sterile instruments.³³ However, a concern is the fragility of blue wrap, which, if damaged, may violate the sterile barrier.^{34,35} This is the reason that containers are preferred in some cases such as when heavy orthopaedic instruments are concerned.

Thus, switching from blue wrap to RSC may have financial and practical consequences. If this is not desirable or the time is not yet ripe, a choice can be made to recycle blue wrap. However, recycling medical plastics is challenging as separation in the workplace is difficult and there is the danger of potential infection hazards.⁷ In the case of blue wrap, it is technically possible to reuse the recycled polypropylene as a raw material. Moreover, the risk of infection is low because blue wrap can be collected cleanly before the surgery.¹² However, contamination of the product in the sense of tape and the presence of chemical indicators must be taken into account.

Limitations due to modelling uncertainty and constraints are inherent to every LCA. The functional unit, impact indicator, and databases may each have an effect on the impact assessment. All data used from the Idemat (EcoInvent) databases are modelled and present limitations. The measures of impact found in different databases are

generally comparable, though differences of 30% are possible. The eco-cost indicator is advantageous because it allows relatively easy and transparent calculations, there is no need for panel weighting of each impact category, and the results can be explained in terms of costs and measures to be taken.

We did not measure water and energy consumption, but calculated these from the manufacturer's information. Moreover, estimates were made about the modes of transportation and, for certain production processes, alternatives were chosen because they were not available in the database registers. None of these are expected to have a significant influence on the final results. With regard to the water and energy consumption, even a doubling of the eco-costs of the use phase of the RSC would not alter the conclusions drawn. The transport phase of both RSC and blue wrap is a relatively small part of the eco-costs (0.2 and 5%, respectively), which makes it unlikely that alternate assumptions would suddenly dominate the results.

Only three-layered, one-step, non-woven polypropylene wrap and RSCs made of aluminium were included in our study, as these are the two most widely used systems in the world. However, there are other packaging materials available for surgical instrument sterilisation that may show different results; for example, other multilayer non-wovens, paper, cotton, and mould bush drums. The latter two are mainly still used in developing countries, as they do not meet the ISO standard (11607) for sterilisation packaging materials.

Future research should be directed at executing more LCAs of disposable items found in the OR, as they are known to be a significant contributor to its carbon footprint.⁴ Much research that has been done on the carbon footprint of the OR has focused on the effects of inhalation anaesthetics, HVAC, and waste production. A small number of LCA studies have already been done, but for many disposable items in the OR, the answer to the question regarding the environmental impact has not yet been given.¹⁶⁻²³

Conclusion

This study shows that the use of a rigid sterilisation container has 84% less eco-costs than when blue wrap is used to package surgical instruments for sterilisation. This difference is of such an order of magnitude that the container is more environmentally friendly after only 68 of the 5,000 use-cycles.



When the choice of blue wrap as a packaging system is made, recycling blue wrap is an option. In the closed loop recycling scenario, with all three single indicators, there was a halving of the pollution from the blue wrap system compared with the cradle-to-grave system.

The widespread use of disposable blue wrap packaging in developed countries is an example of healthcare pollution that could be reduced by opting for reusable sterilisation containers. With a healthcare system that is co-responsible for the impact of pollution on public health, it is the role of doctors and healthcare managers to point out the need for a transition to circular management in their industry.³⁶ Our results show ecological benefits that must be included in the decision-making process of procurement.

Doctors should be conscious of how encultured disposables like blue wrap have become in healthcare. Often, unrealistic expectations regarding infection prevention, perceived price benefit, and ease of use underlie the choice for disposables.³⁷ We need to be more informed of the destructive effects of our disposables on the environment and demonstrate which alternatives exist on the basis of LCA-driven scientific research. Our reliance on healthcare disposables has resulted in excessive wastage and pollution and has exposed us to supply chain vulnerability, as the current COVID-19 crisis has made painfully clear.

Appendix A.

Supplemental digital content: Key Data for LCA

<https://www.mdpi.com/2071-1050/14/1/430>

Appendix B.

Supplemental digital content:
Tables for Hot-Spot Analyses in Eco-Costs

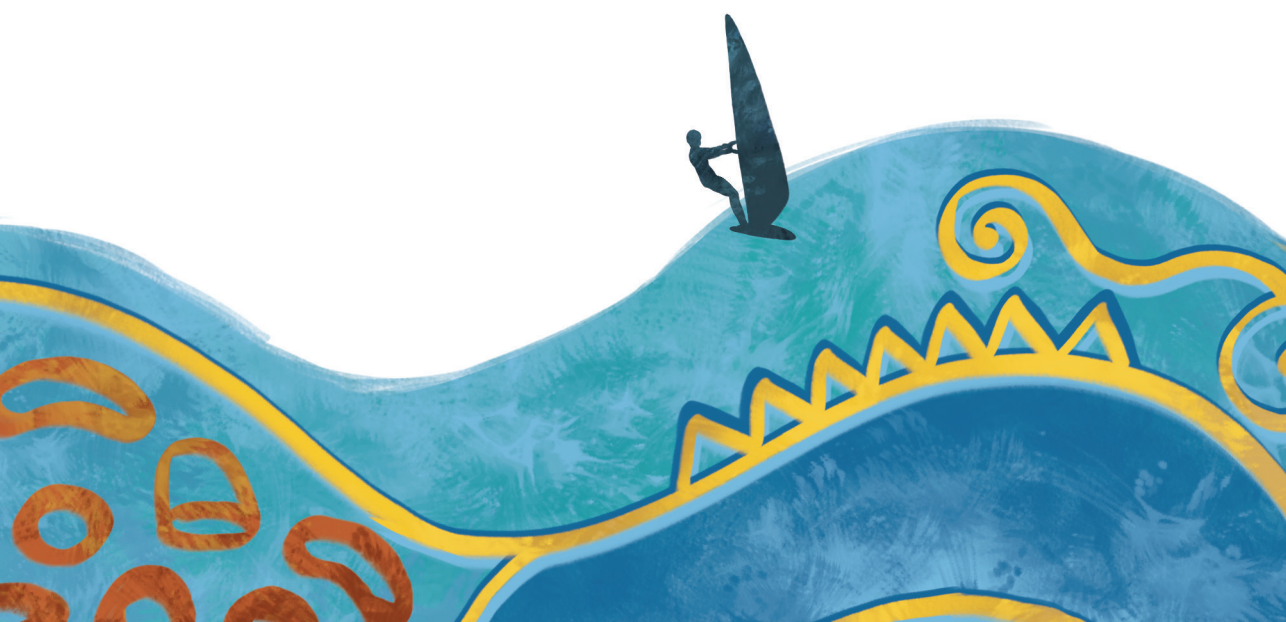
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CHAPTER 5

A Comparative Environmental Life Cycle Assessment Between Transfemoral Transcatheter Aortic Valve Implantation and Isolated Surgical Aortic Valve Replacement

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Abstract

Background: Comparisons between transfemoral transcatheter aortic valve implantation (TF-TAVI) and surgical aortic valve replacement (SAVR) in severe aortic stenosis have demonstrated a consistent mortality benefit, lower one-year costs and greater quality adjusted life years in favour of TF-TAVI. However, the differences in the environmental impact of these two interventions have not yet been sufficiently investigated. The aim of the present study was to compare the intra-procedural environmental impact of these two procedures and to identify emission hotspots in order to mitigate their environmental impact.

Methods: In this prospective, observational, single-centre study, usage data was collected from 15 TF-TAVI and 15 SAVR procedures. All products, energy and water consumed during the procedures were identified and were used in a comprehensive comparative environmental life-cycle assessment (LCA) to quantify the intra-procedural environmental impact of these two interventions.

Results: The material use in SAVR amounted to 17.7 kg compared to 8.7 kg in TF-TAVI, consisting of 84% and 69% plastics, respectively. Electricity use in TF-TAVI was 52% less than in SAVR, in both interventions energy use was dominated by the use of electronic devices. In SAVR the water consumption was 30 times higher than in TF-TAVI (5,800 versus 194 litres), mainly due to the heating cooling system of the cardiopulmonary bypass in SAVR. In all ten calculated environmental impact categories, SAVR had a greater life cycle impact. Its carbon footprint was 181.2 kg CO₂-eq, compared to 68.6 kg CO₂-eq per TF-TAVI.

Conclusion: TF-TAVI outperformed SAVR in all categories of environmental impact and had a carbon footprint of 38% that of SAVR. In TF-TAVI 51% less material, 52% less energy, and 97% less water was used. Despite these impressive results, there is still room for improvement in the environmental impact of TF-TAVI by using fewer disposable items, powering down idle imaging systems, and introducing reusable/remanufactured valve delivery systems.

Introduction

The environmental impact of healthcare systems has gained increasing attention in recent years, especially given the paradox that healthcare, which aims to improve human health, can simultaneously contribute to adverse health outcomes due to its own environmental footprint. Global healthcare is responsible for nearly 4.9% of global greenhouse gas (GHG) emissions, with hospitals accounting for almost 30% of this impact.^{1,2} As a resource-intensive sector within hospitals, studies have shown that the average operating room (OR) can emit between 30 and 50 tonne of CO₂-eq GHGs annually.³ This environmental burden of the healthcare sector contributes to a loss of disability adjusted life years (DALYs) on a population level, as the resulting environmental degradation -such as air pollution and climate change- leads to increased morbidity and mortality across different populations.⁴

A life cycle assessment (LCA) is a standardised method for evaluating the environmental impacts associated with a product, process, or service throughout its entire life cycle. Conducted in accordance with ISO 14040 and ISO 14044 standards, an LCA typically consists of four phases: goal and scope definition, life cycle inventory analysis, impact assessment, and interpretation. The method quantifies resource use, emissions, and waste generation from raw material extraction through production, use, and end-of-life treatment. By adopting a cradle-to-grave perspective, LCA enables a comprehensive comparison of environmental performance and helps identify the main contributors to environmental impact. The carbon footprint is a specific category of environmental impact that is widely used both in scientific research and in other contexts, and specifically refers to the impact on climate change.

In order to determine opportunities to improve the environmental impact of ORs, calculation of the carbon footprint of many surgical procedures has been performed in the last decade. In a systematic review by de'Angelis et al. including 36 studies, a wide range of kg CO₂-eq emissions per surgical case was reported. The lowest reported value (6 kg CO₂-eq) was for cataract surgery in India and the highest (814 kg CO₂-eq) was reported for robotic hysterectomy in the United States, primarily due to energy consumption, disposable medical supplies, and anaesthesia gases.⁵

Regarding the environmental impact of cardiovascular healthcare, cardiac imaging, pharmaceutical prescribing and in-hospital care contribute significantly to climate related impacts to health.⁶ To assess the environmental impact of cardiac surgery van Bree et al. performed a state of the art life cycle assessment (LCA) of a coronary artery bypass grafting (CABG) trajectory including the OR, intensive care unit (ICU) and patient travel. Of the total 414 kg CO₂-q emitted, 314 kg CO₂-eq were emitted intraoperatively, 77 kg CO₂-eq during the ICU stay and 23 kg CO₂-eq were as a result of patient travel.⁷



In the context of cardiovascular interventions such as transfemoral transcatheter aortic valve implantation (TF-TAVI) and surgical aortic valve replacement (SAVR), the clinical outcomes are well-documented, with both procedures reducing DALYs in patients with severe aortic stenosis. A recent meta-analysis showed a consistent mortality benefit of TF-TAVI versus SAVR and economic evaluation demonstrated lower one-year costs and greater quality adjusted life years (QALY) gains for the TF-TAVI approach compared with SAVR.^{8,9} However, the environmental costs of these interventions, and the associated DALYs lost as a result of their environmental impact, remain insufficiently studied. With an ever-growing and ageing global population and the associated increase in demand for healthcare, healthcare providers must take sustainability into account when treating patients. They therefore need to be able to balance the clinical and financial benefits against the environmental costs of these procedures. The aim of the present study was to compare the intra-procedural environmental impacts of SAVR and TF-TAVI, and to identify emission hotspots in order to mitigate these environmental impacts.

Methods

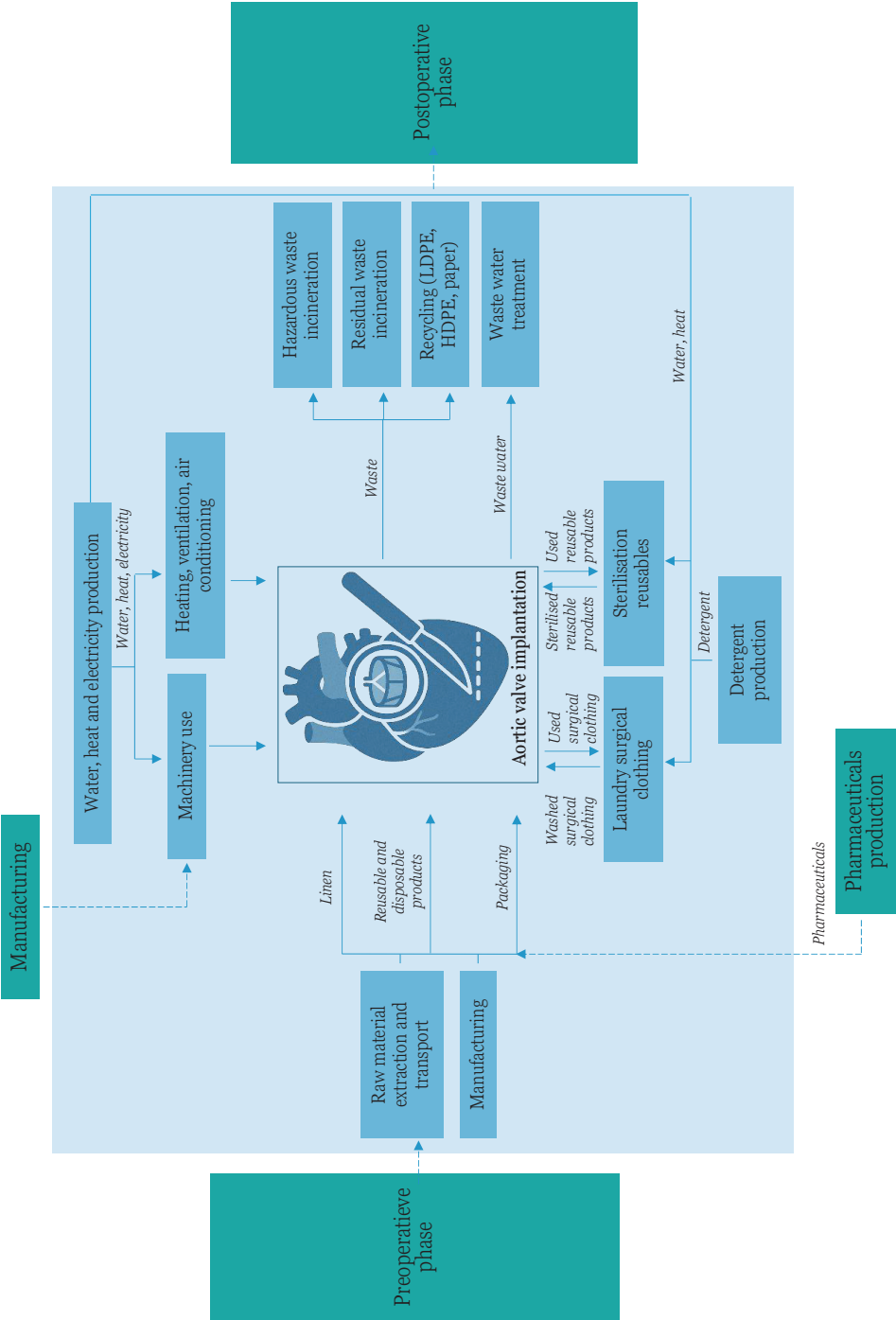
Study design

This prospective, observational, single-centre study was conducted in the cardiovascular intervention centre (CVIC) at the Leiden University Medical Centre (LUMC, Leiden, the Netherlands). The CVIC consists of four ORs, two hybrid catheterisation rooms and three heart catheterisation rooms. Annually 200 TF-TAVI and 50 isolated SAVR procedures are performed in the CVIC. The study acquired approval of the research board of the anaesthesiology department of the LUMC. Since no patient data was retrieved except type of surgery, the medical ethical commission of the hospital declared that this research did not fall under the scope of the WMO (Medical Research Involving Human Subjects Act) and no further approval was necessary (N22.003). Data was collected from 15 randomly selected TF-TAVI and 15 SAVR procedures during a 6-month period. Only procedures that were not combined with other procedures were included and all were electively performed. These numbers were chosen to take intersurgical variability into account. TF-TAVI was performed under local anaesthesia in awake patients, SAVR was performed under general anaesthesia with propofol; no inhalation anaesthetics were used for anaesthesia maintenance. The energy mix of the LUMC in the study period was for 60% from fossil fuels and 40% from renewable energy sources, which was used to calculate the environmental impact of the electricity during the investigated procedures.

Life cycle assessment

The environmental impact assessment of this research is based on the life cycle assessment (LCA) framework as formulated by the methodological standards ISO 14040 and ISO 14044.¹⁰ This framework consists of four steps: 1) Goal and scope definition, 2) Inventory analysis, 3) Impact assessment and 4) Interpretation. The inventory results were modelled in CMLCA software, making use of the Ecoinvent v3.4 database.^{11,12} The goal of this research was a comparison of the environmental impact of TF-TAVI and SAVR. The scope was limited to the intraoperative processes, from the moment the OR was being prepared for the surgery up until the moment the patient left the OR. The functional unit was defined as providing one patient with an aortic valve implant. In order to perform a comprehensive life cycle impact analysis of these medical procedures all apparatus, disposables, reusables and other products required for the procedures were identified. The boundaries of the determined environmental impact are illustrated in Figure 1. This LCA includes processes across the entire life cycle from the mining of raw materials to the treatment of waste (cradle-to-grave). Manufacturing of capital goods (e.g. electronic medical devices) was not included in the assessment which is common practice. The information is hard to obtain and the related environmental impact for single procedures (either TF-TAVI or SAVR) is assumed to be negligible since capital goods are used for many different procedures and for multiple years. Dye material for fabrics was left out of the assessment since limited data are available regarding its environmental impact. The sterilisation process for disposables using gamma irradiation has not been included in our analyses, as this information was not available. A study into the sterilisation of both disposable and reusable surgical instrument sets showed that the carbon footprint of sterilising disposable surgical instrument sets using gamma radiation was negligible.¹³ Pharmaceuticals used during both TF-TAVI and SAVR were excluded from the LCA since only a few pharmaceuticals have a known carbon footprint, and for these, the information is limited to active pharmaceutical ingredients (API's) production and packaging (cradle-to-gate).¹⁴ Research by Davies et al. on the environmental impact of perioperative paracetamol use shows that the API accounts for only a small proportion of the carbon footprint of intravenously administered paracetamol and that it is primarily driven by the manufacture of packaging and supplies.¹⁵ Similar conclusions were drawn by McAlister et al. who found that almost 90% of the carbon footprint of morphine manufacture occurred in the final stages, namely packaging, mixing, filling and sterilisation.¹⁶ Furthermore, by far the greatest environmental impact of intraoperative drugs comes from inhalation anaesthetics, which were not used for anaesthesia maintenance in SAVR.⁵ Transfusions of blood products have not been included in our analysis. Although data on red blood cell transfusions are available (7.56 kg CO₂-eq per unit), there are significant differences between hospitals and between countries.¹⁷ Furthermore, no data are available regarding plasma and platelet transfusions.





◀ **Figure 1.** *System boundaries.*

For this study processes in the light blue area were included in the LCA, processes in the grey boxes were not included. LDPE, low-density polyethylene; HDPE, high-density polyethylene.

Data collection and assumptions

A methodological approach was set up to gather comprehensive life cycle inventory data. All materials used during surgery and their packaging were identified through field research during the procedures. After identification a qualitative material composition was determined (e.g. PET, stainless steel) and quantitative material composition and weight (e.g. 45% weight PET, 55% weight stainless steel) was established. The composition of the materials was determined either by information from the manufacturer or if this was not possible by a hierarchical approach of assumptions: based on the composition of a similar product, based on similar material characteristics of other products or based on general material characteristics (e.g. plastic packaging foil is often LDPE). For disposable items the assigned disposal process was determined (Regulated Medical Waste or non-hazardous waste). For reusable items the lifespan was estimated to enable calculating the part of the production process for one surgery. For the sterilisation process of surgical instruments data regarding water, electricity and detergent use were obtained from a different Dutch University Medical Centre, since no local data were available. Water consumption and detergent use was calculated per kilogram sterilised instruments. Energy use was determined for medical equipment, heating, ventilation, and air conditioning (HVAC), sterilisation of surgical instruments and washing of surgical clothing and linen. The electricity use of medical equipment was calculated by multiplying the electric power consumption by the usage time. The energy demand of the HVAC was provided by the energy coordinator of the LUMC for the year 2021. Energy use of the sterilisation process was based on a study by McGain.¹⁸ Water and electricity use for cleaning of surgical clothing was provided by the laundry company. The following modelling choices were made for the CMCLA software tool into which the inventory data are imported. Cradle-to-gate production of material flows was set to global to calculate the average input data for mining processes. For the transforming of collected materials into specific products standard transforming processes from Ecoinvent were applied. Specific product assembly was not included due to lack of data. For the renewable energy mix in the Netherlands 50% solar energy and 50% wind energy was modelled. A detailed overview of energy flows and material flows is included in Supplementary Materials S1-4.



Results

Between August 2021 and February 2022, data was collected during the investigated procedures. A total of 128 disposable items, 12 reusable items and 31 electromechanical medical devices were identified for SAVR procedures. For TF-TAVI procedures, 56 disposable items, 4 reusable items and 10 electromechanical medical devices were identified. A detailed overview is included in Supplementary Materials S1-4.

Materials, energy and water

For all procedures the material composition and weight of the consumed products was determined. The mean amount of materials used in a SAVR was 17.7 (SD 0.5) kg compared to 8.7 (SD 1.6) kg in TF-TAVI (Table 1a). In both SAVR and TF-TAVI the main composition of materials used were plastics, 84% and 69% respectively. Polypropylene (PP), whose weight primarily originated from surgical drapes and gowns and blue wrap, contributed to the largest proportion of materials, 5.7 kg (32%) in SAVR and 2.4 kg (28%) in TF-TAVI. The transparent and resistant material polyvinyl chloride (PVC) used in disposables such as drains and infusion sets, accounted for 3.8 kg (22%) of materials in SAVR and 0.8 kg (9%) in TF-TAVI. Packaging materials, predominantly consisting of low-density polyethylene (LDPE) and high-density polyethylene (HDPE) accounted for 2.7 kg (15%) in SAVR and 2.4 kg (27%) in TF-TAVI. Needles, blades and other metal products were responsible for 8% of the SAVR materials (1.5 kg) and 5% of the TF-TAVI materials (0.4 kg). Paper and cardboard packaging materials were 0.6 kg (3%) in SAVR and 1.8 kg (21%) in TF-TAVI.

Water consumption in SAVR was 29.9 times higher than in TF-TAVI, with volumes of 5,800.4 (SD 868.5) L and 194.0 (SD 72.6) L respectively (Table 1b). Per SAVR procedure, the cardiopulmonary bypass (CPB) machine used 78% (4,535 L) of the total water consumption. The water usage of the CPB is mostly due to thermal regulation of the blood for which 15 L heated tap water flows through the oxygenator per minute. Water used for sterilisation of surgical instruments was the second most important source of water utilisation in SAVR, 1,096 L (19%). For cleaning of linen and scrub suits 132 L and 70 L were respectively used in SAVR and TF-TAVI. HVAC was responsible for the smallest share of water consumption, representing 38 L (0.6%) in SAVR and 9 L (4.4%) in TF-TAVI.

The electricity use in SAVR was 2.1 times higher (116.1 (SD 17.3) kWh) than in TF-TAVI (55.9 (SD 11.1) kWh) (Table 1c). In SAVR electromechanical medical devices were responsible for 49% of electricity use, sterilisation of surgical instruments 21% and the HVAC 29%. In TF-TAVI 70% of electricity use was explained by the use of large

electricity consuming imaging equipment providing fluoroscopy-guiding. HVAC electricity consumption was directly related to the duration of the procedures, which was 69.3 (SD 9.7) minutes for TF-TAVI and 304.1 (SD 57.6) minutes for SAVR.

Table 1 (a,b,c). *Material, water & electricity use per person with an aortic valve implant.*

	SAVR			TF-TAVI		
1a. Material (kg)	Mean	SD	%	Mean	SD	%
PP	5.7	0.2	32	2.4	0.4	28
PVC	3.8	0.2	22	0.8	0.1	9
HDPE	1.6	0.1	9	1.6	0.9	18
LDPE	1.1	0.0	6	0.8	0.2	9
Other plastics	2.7	0.1	15	0.4	0.0	5
Metals	1.5	0.0	8	0.4	0.1	4
Paper cardboard	0.6	0.1	3	1.8	0.2	21
Others	0.7	0.1	4	0.5	0.1	5
Total	17.7	0.5		8.7	1.6	
1b. Water (L)	Mean	SD	%	Mean	SD	%
Machinery	4535.0	867.5	78	0.0	0.0	0
Cleaning	131.6	14.9	2	70.1	10.1	36
Sterilisation	1,096.2	108.5	19	115.3	71.6	59
HVAC	37.5	7.1	1	8.5	1.2	4
Total	5,800.4	868.5		194.0	72.6	
1c. Electricity (kWh)	Mean	SD	%	Mean	SD	%
Machinery	56.4	11.0	49	43.6	8.2	78
Cleaning	2.3	0.3	2	1.2	0.2	2
Sterilisation	24.2	2.4	21	3.5	1.7	6
HVAC	33.3	6.3	29	7.6	1.0	14
Total	116.1	17.3		55.9	11.1	

Average and standard deviation (SD) of material use (kg), water use (L) and electricity use (kWh) in surgical aortic valve replacement (SAVR) and transfemoral transcatheter aortic valve implantation (TF-TAVI). PP, polypropylene; PVC, polyvinyl chloride; HDPE, high-density polyethylene; LDPE, low-density polyethylene; HVAC, heating, ventilation, and conditioning.

Life cycle impacts

TF-TAVI had a lower environmental impact in all ten impact categories compared to SAVR (Figure 2). The carbon footprint of TF-TAVI was 68.6 (SD 6.6) kg CO₂-eq compared to 181.2 (SD 10.6) kg CO₂-eq for SAVR. In TF-TAVI and SAVR mining, transport and transforming of materials were responsible for respectively 33% and 39% of their



carbon footprint, incineration of disposable products was responsible for respectively 29% and 20% (Table 2). In SAVR electricity use for HVAC and electrical medical devices was 23% and sterilisation of surgical instruments 14% of the total carbon footprint.

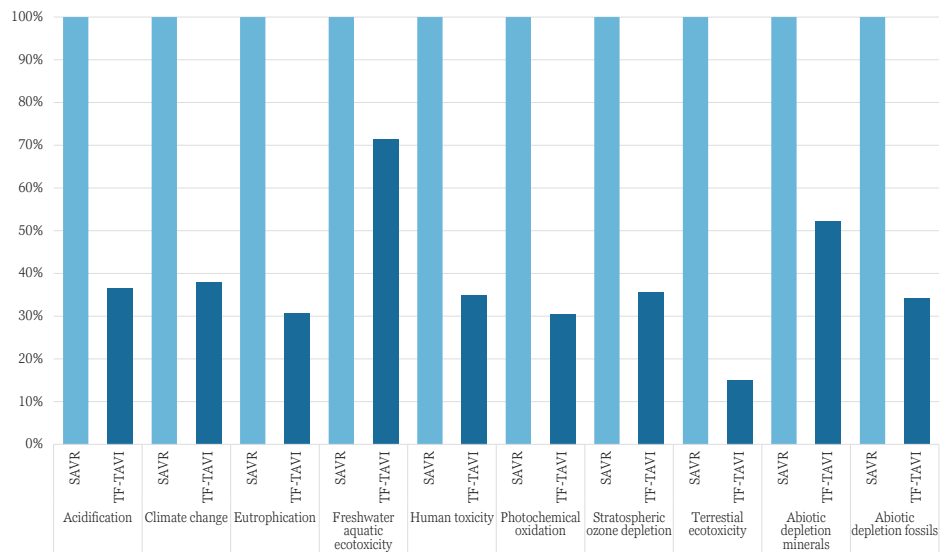


Figure 2. Comparative characterisation results impact categories. Results are normalised to 1 for the largest characterisation result per category.

Table 2. Carbon footprint per person with an aortic valve implant.

Climate change (kg CO ₂ -eq)	SAVR			TF-TAVI		
	Mean	(SD)	%	Mean	(SD)	%
Mining & transport	55.6	1.2	31	18.6	3.4	27
Transforming processes products	14.7	0.4	8	3.9	1.2	4
Incineration disposables	37.0	1.0	20	20.2	3.6	29
HVAC	19.0	3.6	10	4.3	0.6	6
Electronic devices	23.7	4.6	13	17.0	3.2	25
Sterilisation reusables	25.2	2.5	14	2.6	1.6	4
Washing linen and scrubs	2.9	0.3	2	1.5	0.2	2
Waste water treatment	2.9	0.4	2	0.1	0.0	0
Others	0.3	0.0	0	0.4	0.0	1
Total	181.2	10.3	100	68.6	6.6	100

Average and standard deviation of climate change (carbon footprint) in surgical aortic valve replacement (SAVR) and transfemoral transcatheter aortic valve implantation (TF-TAVI). HVAC, heating ventilation, and air conditioning; SD, standard deviation

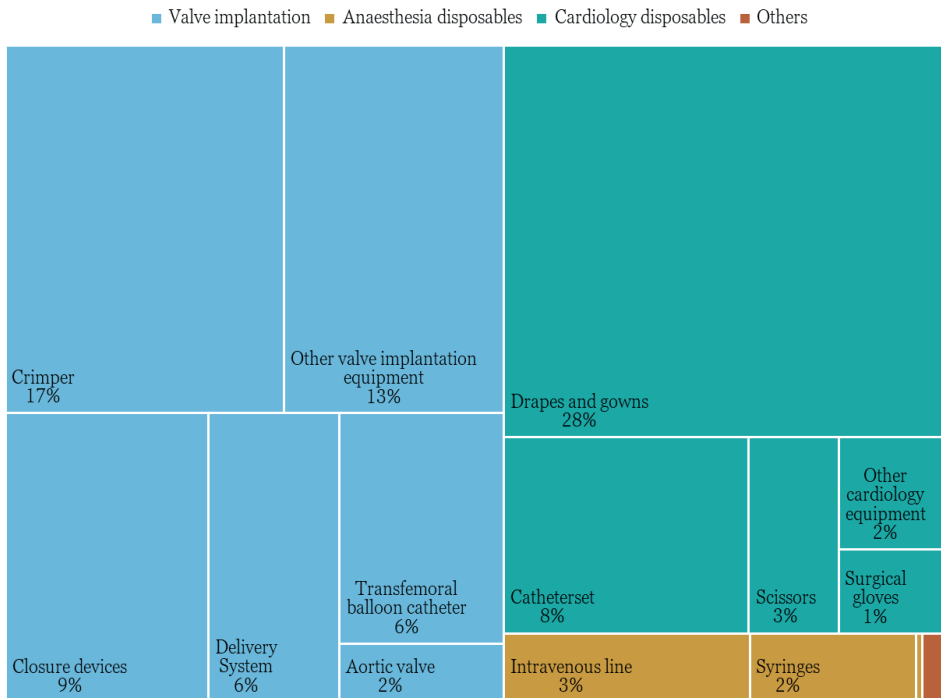


Figure 3. Carbon footprint of disposables used in TF-TAVI. Percentage of 35.5 kg CO₂-eq total.

At product level disposable materials were responsible for 35.5 kg CO₂-eq (52%) of the carbon footprint in TF-TAVI and 103.9 kg CO₂-eq (57%) in SAVR. Carbon hotspots in TF-TAVI were drapes and gowns (28%) and the valve implantation equipment (36%) (Figure 3). In SAVR the carbon hotspots were CPB heart-lung pack (27%), the hazardous waste bin (16%) and surgical drapes and gowns (12%) (Figure 4).

Sensitivity analysis

The effect on the impact categories of both TF-TAVI and SAVR of the following modelling choices was calculated: electricity consumption of the imaging equipment (+50%), electricity consumption of the HVAC system (-15%), energy demand manufacturing disposable materials (+15%), energy demand sterilisation process (+15%) and the effect of the percentage of renewable energy use (0-100%). None of the aforementioned interventions led to a meaningful change in the outcome that TF-TAVI outperformed SAVR in both carbon footprint and all other nine impact categories. A detailed overview is included in Supplementary Materials S5.

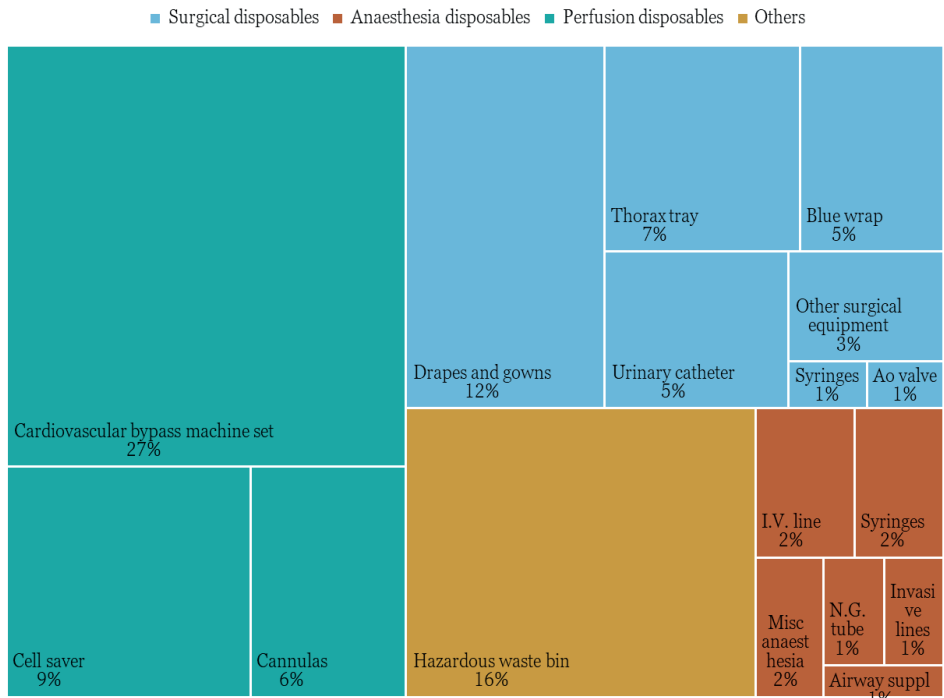


Figure 4. Carbon footprint of disposables used in SAVR. Percentage of 104.0 kg CO₂-eq total.

Discussion

In this study, we quantified the environmental impact of two different procedures for aortic valve replacement (TF-TAVI and SAVR). In aortic valve replacement by TF-TAVI 51% less materials were used, 52% less energy and 97% less water was consumed compared to SAVR. This can be explained by the fact that fewer staff (e.g. personal protective clothing) are required for a TF-TAVI procedure, the procedures take less time (energy consumption HVAC), and no heart-lung machine is needed. TF-TAVI performed better in all ten environmental impact categories. The total carbon footprint (climate change) of TF-TAVI was 68.6 (SD 6.6) kg CO₂-eq compared to 181.2 (SD 10.3) kg CO₂-eq for SAVR.

Comparison to other studies

Blitzer et al. performed a carbon emission analysis of transcatheter and surgical aortic valve replacement including pre- and postoperative data.¹⁹ They also found that TF-TAVI had a smaller carbon footprint than SAVR. However, their absolute intraoperative carbon emissions were higher compared to ours (103 kg CO₂-eq for

TF-TAVI and 421 kg CO₂-eq for SAVR). This might be explained by the fact that their methodology differs fundamentally from ours, using 18 emission factors derived from other studies instead of calculating a cradle-to-grave LCA to determine carbon emissions of their own data. By using emission factors from various studies the heterogeneity and the different underlying methods and assumptions of these studies are expected to influence the results obtained by Blitzter et al. We are confident that a robust LCA, such as ours, in which a cradle-to-grave analysis of all used materials, energy and water consumption is performed, will yield more reliable scientific results.

A study on the environmental impact of CABG by van Bree et al. was done using a state-of-the-art LCA method.⁷ Using a similar methodology, comprising cardiac surgery and also having been conducted in the Netherlands makes this study suitable for a comparison of their results with ours. That study demonstrated that a CABG procedure had an intraoperative carbon footprint of 314 kg CO₂-eq, compared to 181 kg CO₂-eq in the SAVR from our study, which is 133 kg CO₂-eq (73%) more. Given that CABG is a more extensive procedure this difference can be explained by the fact that in the CABG 9 kg (61%) more material was used, the operations lasted 92 minutes (30%) longer, two more reusable instrument trays were used and inhalation instead of intravenous anaesthetics were used.

Future perspectives

Indirect CO₂ emissions due to procurement of goods and waste generation, are estimated to account for over 71% of the emissions of the entire healthcare sector.¹ These are the concealed emissions contained in the products and services as a result of upstream and downstream activities and are therefore difficult to measure and influence by the healthcare sector.²⁰ The main sources of this kind of emissions in the OR are disposables, equipment and pharmaceuticals. The majority of items used in ORs today are single-use. In this research, we demonstrate that in both types of aortic valve replacement, 99% of the materials used are disposable and account for more than 50% of the carbon footprint of the procedure. It is crucial to focus on reducing these emissions in healthcare to ensure that the healthcare sector is resilient to serve this, and future generations. The most important way to achieve this goal is through the transition from a linear to a circular healthcare economy. A circular economy aims to preserve the value of products, materials and resources for as long as possible. To this end the 10R Framework (a refinement of the 3R concept: Reduce, Reuse, Recycle) can be used, a model for transitioning from a linear to a circular economy based on hierarchical measures.²¹ The 10R Framework has three main objectives: avoiding waste, extending product life and recycling waste. This not only results in less raw material consumption, but also lower CO₂ emissions because fewer materials and products need to be manufactured, which means less energy consumption for production.



Limitations of the study

Limitations of our research included having to omit the environmental impact of for example pharmaceuticals, transfusions of blood products, and complex medical products such as the heart valves. Manufacturers of medical products should provide transparency about the environmental impact of their products so that users can make environmentally conscious decisions based on this information. Potentially not including these products could influence the outcome of our study. Pharmaceuticals are known to have important environmental impact, but since these are mainly used for general anaesthesia in SAVR this is not expected to influence the favourable environmental outcome of TF-TAVI. With regard to heart valves, it can be stated that similar valves are implanted in both procedures, which again is unlikely to influence the final outcome.

Our research was limited to a single centre in the Netherlands, which could mean that the results are not applicable to other hospitals where TF-TAVIs are performed. However, we believe that the use of a robust LCA method and the detailed description of the results provide a clear insight into where the two procedures differ in terms of environmental impact.

Lastly, our study was limited to the intraoperative period and did not include the preoperative and postoperative periods. Preoperative examination for both groups consisted of an angiogram and a trans-thoracic echocardiogram. Preoperative SAVR patients also underwent a chest X-ray, and TF-TAVI patients underwent a CT scan with contrast. Postoperatively, SAVR patients stayed in the ICU for one night and in the ward for 7-8 days. TF-TAVI patients were admitted on the same day and discharged after 24 hours. All the aforementioned with exception of the CT-scan, are to the detriment of SAVR in relation to our comparative study. Therefore, this is not likely to lead to different conclusions.

Conclusion

The ever-growing and ageing global population is accompanied by an increase in demand for aortic valve replacement. Our research has demonstrated that with regard to aortic valve replacement TF-TAVI is the environmentally more sustainable procedure. In addition, our contribution analysis has led to several recommendations on improving both procedures such as replacing disposable items by reusables, energy saving measures regarding the interventional imaging system and sterilisation of surgical instruments and avoiding wastage of fresh drinking water by the CPB. With these results, healthcare professionals will be able to meet the needs of the current generation without compromising the ability of future generations to meet their own needs.

Appendix A.

Recommendations for mitigation based on hotspots.

Materials

Single use valve implantation equipment

Both TF-TAVI and SAVR were characterised by the abundant use of disposables most of which were made of plastics. The single-use valve implantation equipment in TF-TAVI in particular had a large carbon footprint. There are currently no reusable alternatives for this on the market, but parts of the system such as the valve crimper could be suitable for reuse. For other parts, such as the delivery system, refurbishing, as is already done with other high risk single-use medical devices such as electrophysiology (EP) catheters, could be a solution. Schulte et al. demonstrated with a LCA that remanufacturing EP catheters reduced the carbon footprint by 50.4% and the abiotic resource use by 28.8%.²² Although reuse after reprocessing is permitted under European legislation, it is still prohibited in many European countries.²³ While reprocessing of these devices is considered safe, this cannot be concluded based on the currently available evidence.²⁴ Another option in the context of circularity includes partial recycling, whereby precious metals such as gold and platinum are recycled from EP catheters.²⁵ Alternatively, reusing single-use EP catheters through re-sterilisation leads to cost reduction but at the expense of a twentyfold increase in environmental impact, mainly due to the detoxification process.²⁶

Reusable surgical gowns

Switching to reusable surgical gowns would bring about a simple and effective reduction in GHG emissions. Using reusable surgical gowns instead of disposable resulted in 64% less energy use, 66% less GHG emissions, 83% less water consumption and 84% less solid waste generation.²⁷

Rigid sterilisation containers

Replacing single-use blue wrap as sterilisation packaging for surgical instruments by reusable rigid sterilisation containers (RSC) reduces GHG emissions by 85%. The carbon footprint break-even point for RSC to outperform blue wrap was determined at 98 cycles.²⁸

Hazardous waste bins

For hazardous waste bins, given the special requirements that apply to the disposal of this type of waste, no reusable alternative is available. However, hazardous waste bins are now available that meet the special safety requirements and are made from



recycled plastic instead of virgin plastic, halving their carbon footprint. In addition, it is essential to ensure that no other waste streams end up in these bins through proper waste separation in order to keep the number of bins as low as possible.

Energy

Interventional imaging system

The interventional imaging system used in TF-TAVI was primarily responsible for the electricity consumption in this procedure. Vosschenrich et al. have demonstrated that the annual energy consumption of these imaging systems is comparable to that of MRI and CT scanners and equals the energy consumptions of five four-person households.²⁹ Their research showed that the imaging systems in the catheterisation laboratory had an inactive energy consumption of 52.6%. Energy consumption was reduced by 80% when switching from idle to off. Considering that the start-up time of these systems from the off position is only 2-3 minutes, the manufacturer has recommended switching off the system when idle for more than an hour. By switching from idle to off status for 12 hours at night, energy savings of 59% were achieved, and when this was combined with switching off for 48 hours at the weekend, savings of 75% were achieved.

Sterilisation of reusable surgical instruments

The sterilisation of surgical instruments involves a significant amount of water and energy consumption and accounted for 14% of the carbon footprint in SAVR. Considerable environmental gains can be achieved by optimising the trays for use. Removing unnecessary instruments from the trays to prevent them from being returned unused after surgery to be washed and sterilised again can result in a 40-60% reduction in carbon footprint.³⁰ Research in which the tray composition was reduced using a computer model based on the actual use of instruments and the necessity of their presence by surgeons showed that a 36.7% reduction in the number of instruments was possible with no instruments missing during surgery and no necessary alterations after a one year follow-up.³¹

Water

Wall water system of the CPB

The water consumption (15 L/min) of the wall water system of the CPB implies that in 20 SAVR procedures the equivalent of one person's annual water consumption (90,000 L) is used. Given the impending global drinking water shortage in the near future, heater-cooler systems would be a more sustainable solution to control blood temperature.

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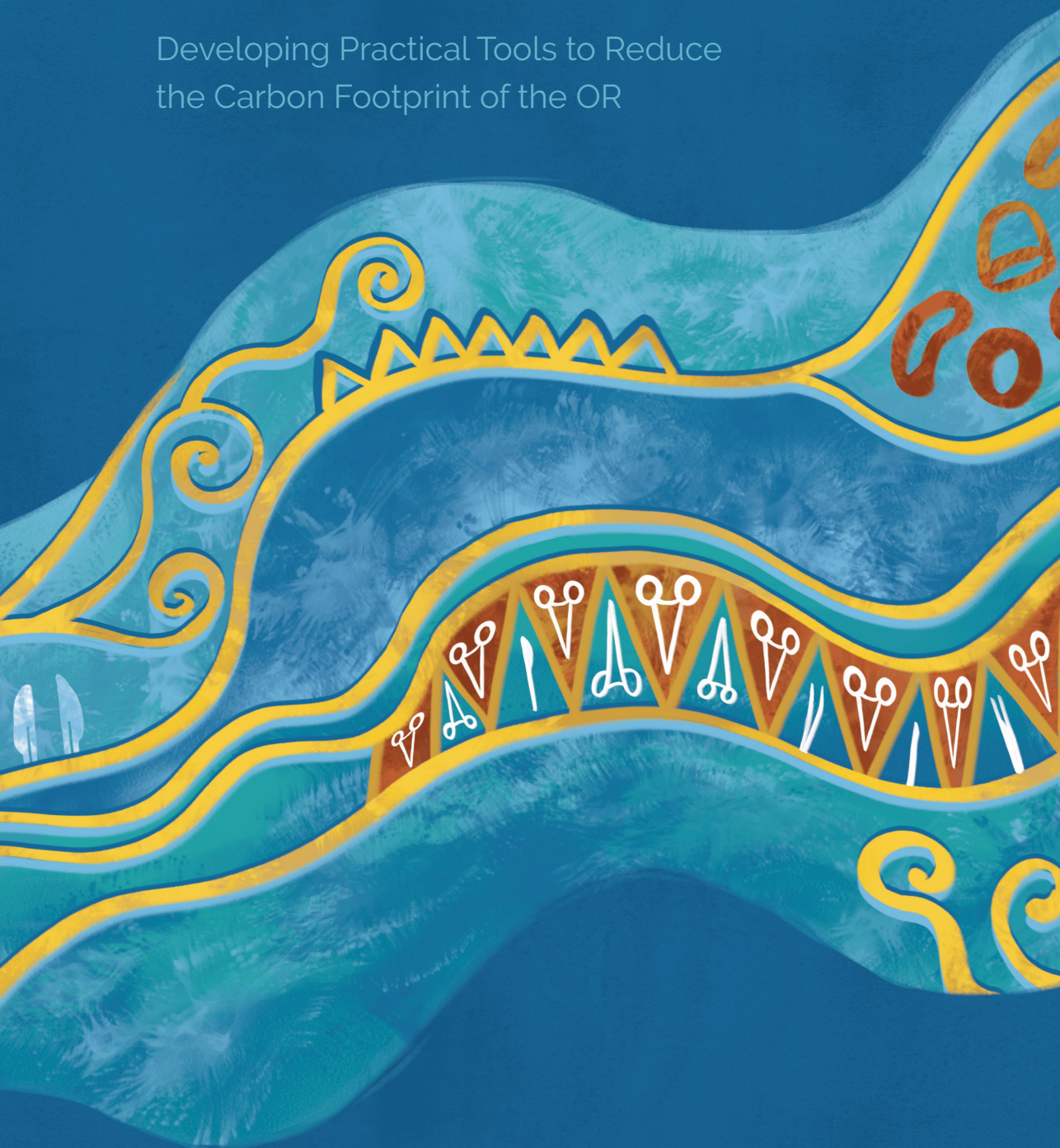


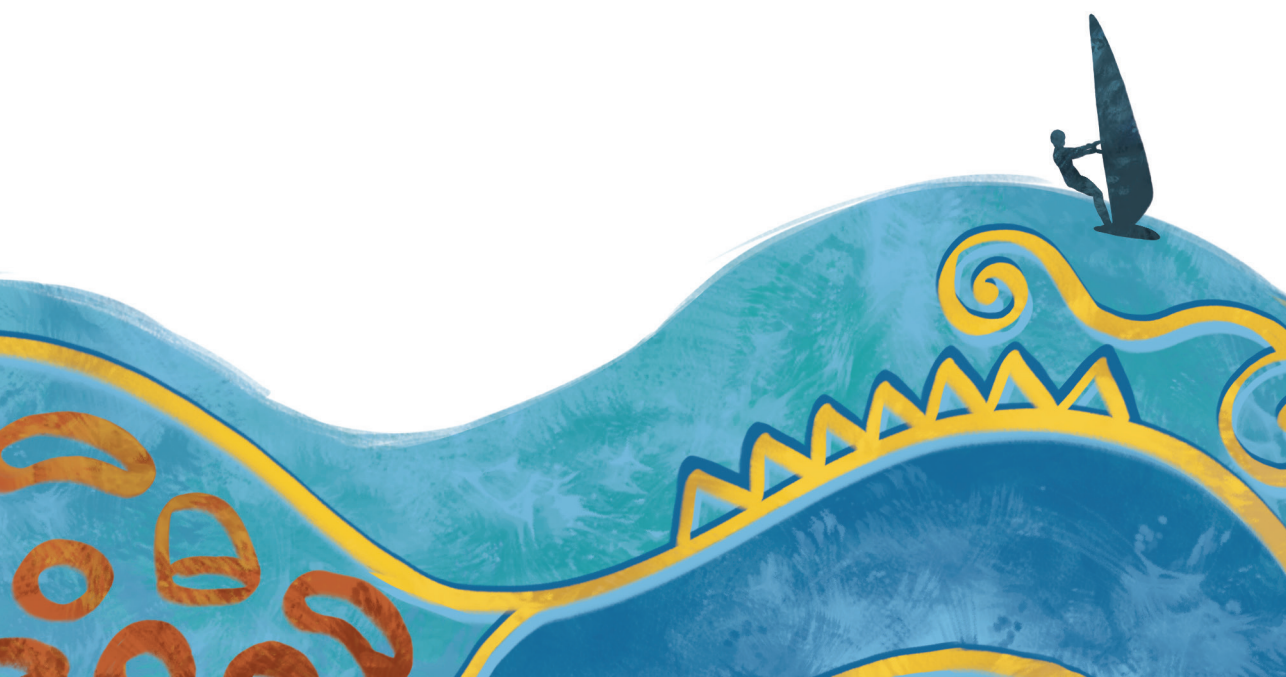
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PART II

Developing Practical Tools to Reduce
the Carbon Footprint of the OR





CHAPTER 6

A New Method to Improve the Environmental Sustainability of the Operating Room: Healthcare Sustainability Mode and Effect Analysis (HSMEA)

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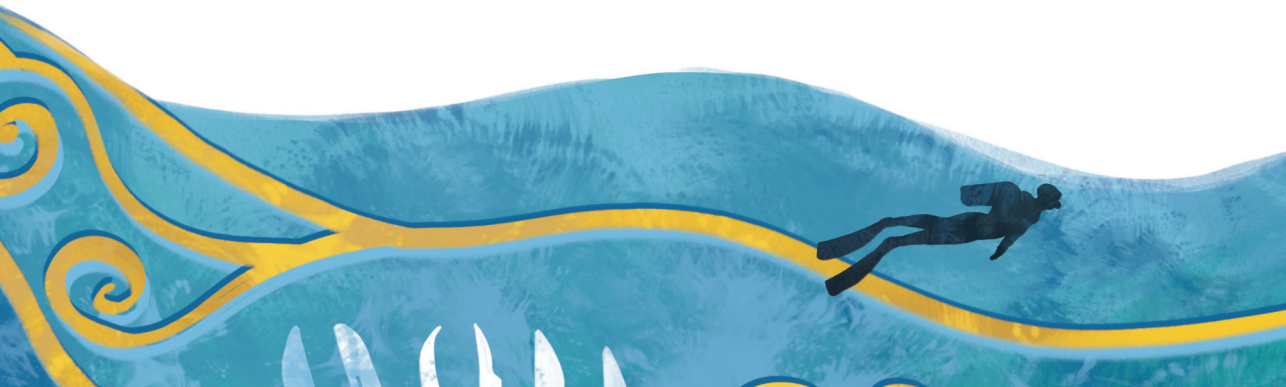
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Abstract

Background: A proven successful prospective risk analysis tool to improve the safety of complex healthcare processes (Healthcare Failure Mode and Effect Analysis) was adapted to reduce the environmental impact of surgical waste.

Aim: The purpose of this study was to describe a new method to effectively improve the environmental impact of operating rooms through a systematic approach.

Methods: For this novel method, named the Healthcare Sustainability Mode and Effect Analysis (HSMEA), a multidisciplinary team, using a structured step-by-step approach, systematically inventories surgical waste, quantifies its environmental impacts, identifies hotspots, and provides solutions for improvement.

Findings: The five steps of the HSMEA are described (definition of the topic, team assembly, flowchart creation, hazard analysis, actions and outcome measures) and the surgical procedure of a caesarean section was used as a case study to assess the applicability of this method to improve its environmental impact. Applying the HSMEA to caesarean sections resulted in a 22% volume reduction and a 22% carbon footprint reduction in surgical waste. This was achieved by revising the disposable custom pack in order to reduce the overage that was present, and by intensifying waste stream segregation for plastic and paper recycling.

Conclusion: The HSMEA is a practical work floor tool to aid in the reduction of the environmental impact of surgical waste that is applicable to all types of operations. It is reproducible, and because it identifies carbon hotspots, it enables an efficient approach to the issue of operating room pollution.

Introduction

The healthcare sector is known to be a large contributor to environmental pollution. On average, 5.5% of the total national carbon footprint of countries originates from the healthcare sector.¹ The healthcare sectors of developed countries such as the United States (US), Belgium, and Japan are in the lead, being accountable for 7.6 to 8.1% of carbon output.¹ In 2013, the global disease burden due to the environmental impact of the US healthcare sector was calculated to be 614,000 disability-adjusted life years (DALYs) annually.² This paradox, where healthcare has indirect adverse effects on public health, calls for action to improve environmental performance of the healthcare sector through energy savings and a reduction in environmental pollution and waste generation.^{3,4}

Healthcare waste (HCW) and its disposal cause pollution and consequently pose health risks that may result in disease and premature death.^{5,6} Being one of the largest industries in the world, healthcare generates a vast amount of waste, which is expected to increase in the coming decades due to a growing number of healthcare interventions, as a result of global population growth and increased life expectancy.⁶ Producing 8.4 kg/bed/day, resulting in three billion kilograms of waste annually, the US currently ranks first in the world with regard to HCW generation.⁷

The World Health Organization (WHO) estimates that 85% of HCW is non-hazardous waste, while the remaining is either infectious, toxic, or radioactive.⁵ The most common methods of disposal of HCW are incineration and landfill, both of which can lead to the production of hazardous chemicals and pollutants.⁶ Not only because of its environmental impact but also given the financial consequences and health hazards, it is of the utmost importance to reduce the generation of HCW.

Hospitals are known large polluters; in developed countries, they generate 1% of a nation's solid waste.⁸ Being resource intensive, it is estimated that up to 33% of all hospital waste is generated in operating rooms (ORs).⁸ In their study on the carbon footprint of three Western academic hospitals, MacNeill et al. found that a single operation yields up to an average of 16 kg of solid waste.⁹

Addressing waste generation in an OR setting can be very challenging for a number of reasons. Firstly, in recent decades there has been an emphasis on the employment of single-use items, which by definition generate a lot of waste. Secondly, a portion of OR waste consists of hazardous waste. Proper segregation of this waste stream from the non-hazardous waste is desirable because the non-hazardous waste contains a fraction of important recyclable material.¹⁰ In practice, this waste segregation has proven to be



complicated mainly due to a lack of knowledge on the work floor, and because OR waste contains contaminated materials.^{11,12} As with waste reduction in general, the cornerstones for waste reduction in the OR are ‘reduce’, ‘reuse’, and ‘recycle’.¹³

A reduction in surgical waste can be achieved by preventing wastage. During surgical procedures, there is often overage in the form of disposable sterile materials and instruments that are opened but not used.^{14–17} Additionally, disposable custom packs (sets of disposable products pre-packaged for specific procedures) frequently contain unnecessary materials.¹⁸ Hygiene regulations dictate that these unused instruments and materials may not be used for another patient and must therefore be discarded. Preventing these forms of wastage not only benefits the environment, but also increases cost efficiency.

Reusing instruments, gowns, and drapes instead of using disposable alternatives can provide significant waste reduction in the OR.¹² Using reusable sterile gowns instead of disposable gowns resulted in 84% less waste.¹⁹ Blue wrap, a single-use polypropylene wrap for sterile surgical instruments, is a major source of surgical waste.²⁰ Estimates suggest that 115 million kilograms of blue wrap is discarded on a yearly basis in the US alone.²¹ Reusable rigid aluminium containers are a good alternative to blue wrap, as instead of utilising a single-use wrapper, surgical instruments are sterilised in a reusable aluminium case. A comparative life cycle assessment (LCA) of these two packaging systems showed that the carbon footprint of the aluminium containers is 85% less than that of blue wrap.²²

Recycling is an important way to ensure that raw materials are not wasted in a circular economy. In part due to the fact that many discarded materials are contaminated, only 20–25% of OR waste is eligible for recycling.¹⁰ This potentially recyclable fraction mainly concerns paper and plastic packaging, because catheters, syringes, etc., are not suitable for recycling. Recycling is frequently considered to be the primary solution to reducing OR waste.^{20,23,24} However, from an environmental point of view, it is often preferable to address waste output in the OR by considering ‘reduce’ and ‘reuse’ first, since in recycling, energy has to be added to produce new products, and in many cases the quality of the raw material decreases (downcycling).

All of these different approaches to addressing OR waste can ensure that the environmental sustainability of the OR is improved. However, not every strategy is equally eco-effective, and frequently it is not obvious which waste results in the largest environmental burden. For example, reducing the number of redundant cotton gauzes from a custom pack has a much greater environmental impact than recycling

polypropylene items from the same kit.¹⁸ A classical LCA can reveal where environmental hotspots are in OR waste. However, it takes a lot of time and effort to perform a full LCA for every single disposable item in the OR. An alternative is to look at the environmental impact of waste itself. By using Department for Environment, Food and Rural Affairs (DEFRA) greenhouse gas (GHG) life cycle conversion factors, MacNeill et al. calculated the carbon footprints of surgical waste based on the material composition of waste streams in the OR.⁹ DEFRA conversion factors take into account GHG emissions that are generated both upstream (in the supply chain) and downstream (during disposal).²⁵

Many studies on reducing OR waste focus on a particular source of OR waste, or on a single solution such as reducing overage or recycling.^{10,14,15,20,23,26-28} However, with this practice, it is not clear that the approach chosen is most effective in addressing environmental impact from OR waste as a whole. A well-structured, multidisciplinary approach to waste inventory and the implementation of solutions is expected to yield better results.

In the context of increasing patient safety, DeRosier et al. described a prospective risk analysis tool with which healthcare processes can be analysed to identify and address patient hazards.²⁹ This healthcare failure mode and effect analysis (HFMEA) is a structured method in which a multidisciplinary team goes through a step-by-step process that is characterised by the use of a flow diagram, a hazard analysis, and a decision tree with which critical and relevant parts of the process are identified for improvement.²⁹ Evaluation of the HFMEA has shown that although it is a time- and resource-intensive method, it is useful for assessing and improving the safety of healthcare processes.³⁰⁻³² The HFMEA has proven successful for improving patient safety in processes such as blood transfusions, drug administration, and in the introduction of new surgical techniques.³³⁻³⁵

The primary research question for this study was whether it is possible to transform the HFMEA into a tool for identifying and addressing the environmental impact of OR waste. As far as we know, to date, no comparable structured, multidisciplinary approach has been described in the literature to address the OR waste problem in such a comprehensive way. As a secondary research question, we investigated whether the application of this novel method, the Healthcare Sustainability Mode and Effect Analysis (HSMEA), could identify carbon hotspots in surgical waste and provide solutions for improvement.



Methods

Healthcare Sustainability Mode and Effect Analysis (HSMEA)

The failure mode and effects analysis (FMEA) is a risk assessment tool that is frequently used in the manufacturing industry. Its purpose is to prospectively identify the ways in which a process may fail (failure mode) and examine their consequences (effect analysis). In order to apply this method to healthcare processes for improving patient safety, the healthcare FMEA (HFMEA) was created.²⁹ The HFMEA is a structured step-by-step method characterised by the key elements listed in Table 1.

Table 1. *Key elements HFMEA.*

Element	Description
Multidisciplinary team	Subject matter experts
	Advisor (to keep the team on target)
	Team leader (skills in group processes)
Flowchart	Insight into the process
	Keep the team on track
	Allow for timely completion
Hazard analysis	List all possible failure modes for each subprocess
	Determine their severity and probability and calculate a hazard score
Decision tree	Determine if further action is needed (critical?, control measure available?, detectable hazard?)
	Triage function: focus on critical and relevant parts of the process

A multidisciplinary team of 6–8 people carries out the five analytical steps (Table 2) of this method in a series of 4–6 meetings. The five steps that comprise the HFMEA were taken as a template for the Healthcare Sustainability Mode and Effect Analysis tool.²⁹

Table 2. *The five analytical steps of a HFMEA.*

Step	Title
1	Topic definition
2	Team assembly
3	Process flowchart
4	Hazard analysis
5	Actions and outcome measures

Step 1: topic definition

In order to perform a focused analysis of the subject, a very precise topic needs to be chosen. This will provide guidance to the team performing the HSMEA analysis. In the context of patient safety, the HFMEA recommends topics that are in a high-risk or high-vulnerability area. By analogy, healthcare processes that have a large environmental impact (e.g., GHG emissions, surface water pollution) can be a topic for review using the HSMEA. This research focuses on waste production from the OR, but other topics in the areas of energy consumption, water consumption, use of pharmaceuticals, etc., are eligible, as long as they are topics that can potentially increase the sustainability of healthcare, that are readily quantifiable, and for which opportunities for improvement exist.

Step 2: team assembly

For this step, a multidisciplinary team is assembled, and meetings are scheduled in which the various process steps will be completed. Since the processes under investigation are often complex in nature, where no one person has all the knowledge about all aspects, it is important to assemble a team that is multidisciplinary. Team members should include subject matter experts, outsiders, and a leader. Subject matter experts have specific knowledge of (parts of) the process being studied. Outsiders, on the other hand, are healthcare professionals from other fields who are unfamiliar with the process being studied, potentially favouring an unbiased outcome. The role of the team leader is crucial for the successful completion of a HFMEA.³¹ The team leader must be someone with leadership skills who preferably has experience with previous FMEAs. The team leader's role is to maintain an overview, monitor the process, guide the team, and ultimately ensure a final result. The optimal size of a multidisciplinary FMEA team is 6–10 members. The team must be large enough to have sufficient expertise regarding all facets of the process, and small enough to ensure that meetings can be attended by a sufficient number of individuals.³⁰ The number of meetings advised is 4–6, each lasting 2–3 h, thus being long and often enough to allow for progress, but with attention to feasibility, and the focus and enthusiasm of the team.³⁰

Step 3: process flowchart

A graphical representation of the entire process provides not only an overview, but also insight into the various sub-processes. The purpose of the flowchart is to be complete, to prevent parts of the process from being overlooked, and further, to guide the team so that they are not overwhelmed by the complexity of the process.²⁹ In order to obtain a detailed understanding of the process of waste generation, the team investigates what kind of products and materials are disposed of. Every group of items that is disposed of is called a sub-step (for example, the disposal of 10 identical cotton gauzes counts as 1 item). They then investigate which waste streams they are disposed of through, and how this waste stream is handled. This is described graphically by means of a flowchart.



Step 4: hazard analysis

In the original HFMEA, this step identifies all the possible failure modes of the sub-steps, and a hazard score (a measure of the impact on patients if the error occurs) is calculated. This hazard score is displayed in a matrix to provide an overview of the severity and probability of the potential error.

In our HSMEA, the environmental hazard of all sub-steps (items that are disposed of) identified in Step 3 are quantified in Step 4 by means of the amount of waste (in kg) produced, and the carbon footprint of the waste stream it is disposed of through (kg CO₂ equivalents). In order to calculate the carbon footprint, DEFRA greenhouse gas life cycle conversion factors for waste disposal are used (Table 3).

Table 3. Waste stream CO₂ equivalent emission factors (kg CO₂-eq/tonne).²⁵

Material	Recycling	Production	Waste disposal	Total Waste stream
Plastic foils	Y	2,591	-447	2,144
Average plastics	Y	3,179	-282	2,897
Paper and cardboard	Y	1,107	-219	888
Paper and cardboard	N	1,107	-519	588
Municipal Solid Waste	N	3,179	1197	4,376
Regulated Medical Waste	N	3,179	1833	5,012

These conversion factors take into account GHG emissions generated both upstream (production, transport) and downstream (transport, disposal). MacNeill et al. used this method to quantify the carbon footprint of surgical waste in their study on carbon footprinting operating theatres in three health systems.⁹

Furthermore, in Step 4, a decision tree is applied to each sub-step. The decision tree serves as a triaging function. It ensures that if a solution to a similar problem has been encountered in a previous HSMEA, this process does not have to be gone through again. The decision tree then determines whether the HSMEA process should continue for the sub-step ('proceed') or should be terminated ('stop') (Figure 1).

Step 5: Actions and outcome measures

For every sub-step (items that are disposed of), as identified in Step 3, that passes through the decision tree, the team members now have to identify a sustainable solution. Here, the cornerstones for waste reduction in the OR ('reduce', 'reuse', and 'recycle') are applied.¹³ These classic three Rs of waste minimisation strategies have

been supplemented with 'rethink', 'refuse' and 'refrain' from action. 'Rethink' to consider alternatives for the item instead of waste disposal, 'refuse' if the item turns out to be redundant and can be omitted, and 'refrain' if some sub-steps cannot be made more sustainable at the moment.

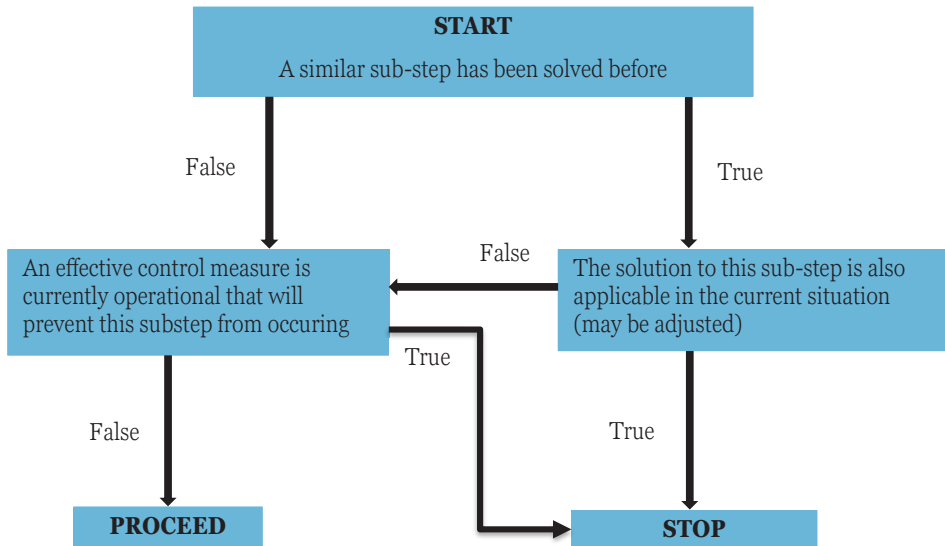


Figure 1. Decision tree used for every sub-step in Step 4.

After selecting one of these six Rs as a solution for each item, the tool automatically recalculates the new environmental hazard (carbon footprint) using the revised weight and emission factor. The environmental hazard of an item may decrease as a result of it being less present (fewer kilograms) in the waste after the chosen solution (refuse, reduce, reuse, rethink), or because it is disposed of in a different waste stream with a lower carbon footprint, such as when plastic is separated for recycling ($2.1 \text{ kg CO}_2\text{-eq/kg}$) instead of entering the municipal solid waste (MSW) stream ($4.4 \text{ kg CO}_2\text{-eq/kg}$). It is also checked for every sub-step whether it would have an impact on stakeholder safety. Now, the hotspots for sustainable intervention can be determined by comparing the baseline situation from Step 4 to the new situation from Step 5. By categorising the proposed solutions, it becomes apparent which solution category has the largest impact on the carbon footprint. These categories are called hotspots and are prioritised to implement in daily practice.

Spreadsheet

All of the calculations for Steps 4 and 5 are conducted in a spreadsheet. For Step 4, the number, weight, and waste stream of the items that are discarded must be entered. The spreadsheet then calculates the carbon footprint of each sub-step, and colour-coding is used to indicate whether it represents a carbon hotspot. For Step 5, one of the 6 sustainable solutions must be selected, for which the spreadsheet calculates the new carbon footprint.

Validation study

After the HSMEA was designed, it was validated with a group of potential users at the Leiden University Medical Centre (LUMC) to ensure it was suitable in a clinical setting. Three sessions of 1.5 h were organised over an eight-week period, in which the HSMEA was finalised for a case study. For the validation sessions, five potential users with different backgrounds were invited. Two medical specialists, one being the leader of the Green Team and the other a specialist regarding the investigated procedures, attended the meetings. Also in attendance was one OR nurse, who was also a member of the Green Team; the head of the sterilisation department of the LUMC, as she had extensive experience and knowledge about HFMEA; and lastly, the primary investigator of the study, who was the team leader.

During the first validation session, the HSMEA tool was explained step-by-step to the members of the group on the basis of a fictitious case study by means of a PowerPoint presentation. The topic for the validation session (Step 1) was determined beforehand by the team leader and concerned the reduction of waste generated in the preparation room for a fictional but realistic procedure. In this first session, the team created the flowchart of Step 3 by writing the individual steps on Post-It sticky notes and creating a graphical representation of the entire process on an A3 sheet of paper. At the second validation session, Step 4 and Step 5 of the tool were completed by the team. All the weights and the waste streams of all the pieces that are discarded during the procedure were determined. During the completion of Step 5, several suggestions were made by the team on how this step could be improved. For example, categorising the solutions as long- or short-term implementation could help the team to have a better overview of the solutions. Furthermore, they suggested that waste handling costs should be implemented as well to provide a more complete overview of the implications of the solutions proposed in Step 5.

During the third validation session, the fulfilment of the method's requirements (easy to use, systematic, resulting in improvement of environmental impact) was tested by means of a concise questionnaire. The questions from the survey can be found in Figure 2. All questions required an answer on a scale from 1–5, with 1 being 'Do not agree at all' and 5 being 'Agree

completely'. For every item, an average score of 3.5 was considered as positive fulfilment of the requirement. When a participant gave an item a score of 3 or lower, this was discussed with this participant to find out why this score was awarded and how this could be improved.

1. I think this tool to improve sustainability is easy to use
2. I think this tool is useful to improve sustainability
3. The tool is intuitive
4. The tool is systematic
5. The tool can be used independently (after two validation sessions)

Figure 2. Survey questions.

Following these validation sessions, a case study was conducted of surgical waste produced in three caesarean section procedures in a two-week study period to assess the applicability of the HSMEA in a clinical setting.

Results

Step 1: Topic definition

For the case study, the topic was defined as: lowering the carbon footprint from the surgical waste generated in the preparation room and OR during a caesarean section (C-section). We chose the C-section for the validation since it is a very common procedure. In LUMC, all members of the OR team were familiar with the procedure and it is highly standardised, which means that there is virtually no variation in the amount of disposable and reusable products used during surgery. This made this operation ideal for investigating whether the HSMEA could improve its environmental sustainability.

Step 2: Team assembly

The team performing the HSMEA consisted of six people: two medical specialists (one being an expert regarding the studied procedure, the other the leader of the OR Green Team), one OR nurse (expert regarding the waste generation process), one manager of the Department of ORs of the LUMC (expert regarding HFMEA), one coordinator of the waste handling department of the LUMC (expert regarding waste management and recycling), and the project leader.

Step 3: Process flowchart

The flowchart, as presented in Figure 3, was created during the first meeting. Here the waste stream of the identified products was determined. The number of sub-steps (items) that contributed to the generation of each waste stream is indicated in parentheses.

The first block represents the items that are brought into the preparation room. The instrument tray contains the reusable surgical instruments that are used during the procedure. This tray originates from the Central Sterile Supply Department within the hospital and is packed in polypropylene blue wrap. Apart from the instrument tray, a custom pack is used for every C-section. This is a pre-packed tray with sterile disposable items assembled especially for a specific kind of surgery. Furthermore, individually wrapped disposable and reusable products can be collected separately when requested by the surgeon.

The second two blocks represent the preparation room and the OR. In these two areas, waste is allocated to different waste streams. In the preparation room, the packaging of the four categories from block 1 is disposed of. Other waste, such as protection caps or superfluous products, is disposed of here as well. The products that are needed for the surgery are brought into the OR, and they are disposed of inside the OR after use.

Disposal in the preparation room occurs in three separate waste streams (MSW, paper waste, and plastic foils). Twenty-two items were identified that are disposed of in this area. Eight items are disposed of as MSW, which is incinerated. Eleven items are disposed of as paper waste. These items are collected separately but are all treated as MSW by the waste handling company and incinerated. Three items are disposed of as plastic foils and will be recycled. In the OR, most items (19 out of 20) are disposed of as MSW and incinerated. The remaining item is disposed of as regulated medical waste (RMW) and incinerated as well, but at a different waste incineration plant.

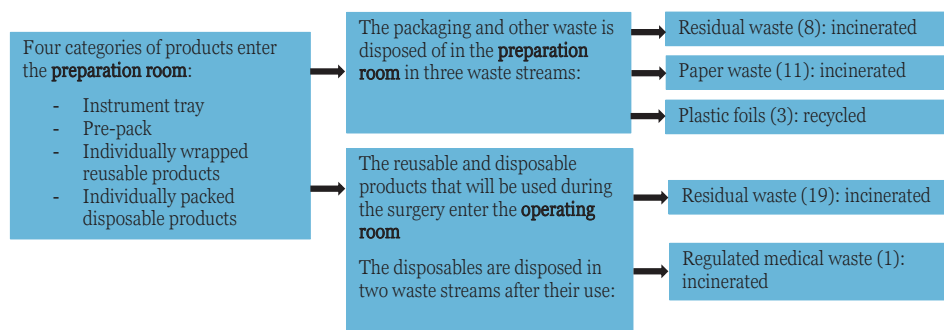


Figure 3. Process flowchart of waste generation in the preparation room and the OR, with number of items disposed of in parentheses.

Step 4: Hazard analysis

The baseline carbon footprint was calculated for each item by multiplying its weight by the appropriate conversion factor from Table 3. The amount of waste and emissions created in both the preparation room and the OR for the baseline situation can be found in Table 4. From these baseline data, hotspots of environmental burden could be identified. In the preparation room, the item with the highest carbon footprint (0.45 kg CO₂-eq) was the polypropylene blue wrap used to package the reusable instrument trays. Its carbon footprint accounts for 48% of all items disposed of in the preparation room. Inside the OR, the disposal of sterile gauzes (2.0 kg CO₂-eq) and the four sterile surgical gowns (2.0 kg CO₂-eq) are responsible for the highest proportion of the carbon footprint of all items disposed of, each representing 19%.

Table 4. *Baseline data hazard analysis.*

	Preparation Room	Operating Room	Total
Waste (kg)	0.34	2.45	2.79
Emission (kg CO₂-eq)	0.94	10.7	11.64



Step 5: Actions and outcome measures

All sub-steps (items) passed through the decision tree (Figure 1) and were assigned a sustainable solution using the 6 Rs. In the preparation room, 14 items were recycled, and for 8 items there was no sustainable solution possible ('refuse'/'refrain from action'). In the OR, two items could be 'reduced' by leaving them out of the custom pack, and for 18 items no sustainable solution was possible at this time. All solutions were discussed among the team to determine whether they compromise stakeholder safety. This was not the case for any assigned solution. An overview of the sustainable solutions assigned to each sub-step in the preparation room and OR can be found in Figure 4.

For the polypropylene blue wrap, the sub-step with the highest carbon footprint in the preparation room, the solution 'refrain from action' was chosen. The use of this wrapping is necessary in order to maintain the sterility of the instrument tray. The blue wrap is currently not accepted for recycling by the waste handler. The alternative of a reusable rigid container has too many implications for business operations to be a realistic option in the short term.

To the sub-steps with the highest carbon footprint in the OR, the following solutions were assigned. For the disposal of four surgical gowns, the solution 'reduce' was chosen. One of these four gowns was disposed of unused. This gown is included in the custom pack in case a fourth assistant (intern) joins the operation. However, this is the fact in only a minority of cases. Therefore, this gown should be removed from the custom pack and

wrapped individually for use when an intern is present. Two packages of sterile gauzes were present in the custom pack. For the package of small gauzes, 'refuse' was chosen since the 10 large gauzes proved to be sufficient for the entire operation.

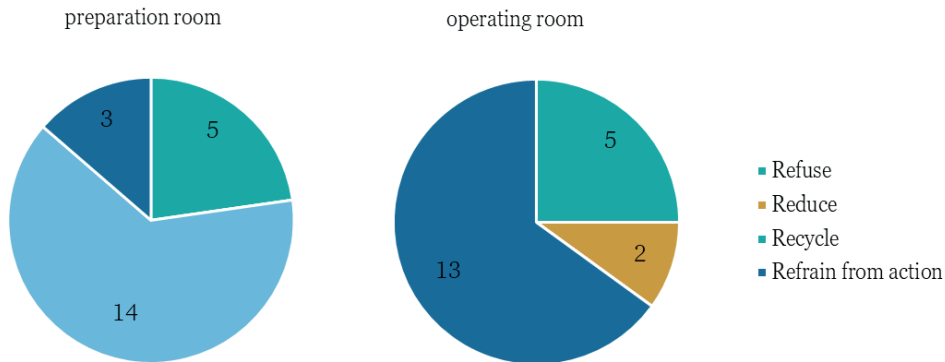


Figure 4. Sustainable solutions assigned to each item. OR, operating room.

The overall result of the implementation of sustainable solutions in the preparation room and the OR for the C-section was a waste reduction of 600 g (–22%) and a carbon footprint reduction of 2.5 kg CO₂-eq (–22%).

Practical implications

After the HSMEA was completed, the team started with implementing the proposed recycling solutions into daily practice in the OR department. Now, the paper waste stream is recycled, as is all plastic waste. The different waste bags are consistently colour-coded throughout the OR complex. For each trash bag, written instructions are present which aid the personnel with choosing the correct trash bag. In order to improve the workflow, it was decided to collect all types of plastic in one trash bag, instead of collecting every type of plastic separately (e.g., plastic foils, hard plastics). This was deemed the most appropriate solution in this situation after consultation with operating nurses and the waste handling department. Now, a waste collection station with three trash bags is present in the preparation room, collecting paper, plastic, and MSW.

Revising the custom pack was identified as having a major environmental impact for both the preparation room and the OR. Of the total carbon footprint reduction, 98% was attributable to the revision of the custom pack, while only 2% resulted from paper and plastic recycling. The custom pack revision included the removal of 11 items that turned out to be superfluous. Two items that were always used during the operation but were delivered separately were added to the package, which meant less packaging material was needed.

HSMEA user feedback

For survey questions 1 (I think this tool to improve sustainability is easy to use), 2 (I think this tool is useful to improve sustainability), and 4 (The tool is systematic), the participants scored an average of more than 3.5 out of 5, which was interpreted as a sign of a positive fulfilment of the tool's requirement. On the question of whether this tool was intuitive, respondents answered with an average score of 3.3 (range 3–4). To improve this, the spreadsheet was modified in a number of respects in consultation with the users. When asked whether the tool could be used independently in a subsequent HSMEA, the average score was 2.5 (grades 1–4). The most important factor here was that the team leader should be familiar with the HSMEA tool. A possible solution was to educate someone from the LUMC to be a process leader for HSMEAs.

Discussion

Healthcare waste and its disposal cause pollution and consequently pose health risks that may result in disease and premature death.^{5,6} The fact that ORs are responsible for up to 33% of all hospital solid waste makes this an important issue to address.⁸ Addressing this problem of healthcare waste requires quantifying its impact on the environment and finding solutions to reduce it.

To address the primary research question of this study, it was found that it was possible to successfully transform a method of identifying hazards in healthcare processes (HFMEA) into the novel HSMEA to quantify and systematically reduce the carbon hotspots of healthcare waste. In the first three steps, the topic is specified, a multidisciplinary team is assembled, and the generated waste is accurately mapped. In the fourth step, the original hazard analysis of the HFMEA is replaced by an environmental hazard calculation based on the carbon footprint of waste streams. Identifying carbon footprint hotspots makes it possible to focus on projects that will yield the most potent effect in reduction initiatives. In the last step, sustainable solutions are applied by preventing the generation of waste (refuse, reduce, reuse, rethink) or by depositing the waste in a waste stream with a lower carbon footprint (recycle).

To assess the applicability of the HSMEA, and in doing so answer the secondary research question, a caesarean section was used as a template to reduce the carbon footprint of surgical waste generated during this procedure. Several carbon footprint hotspots were identified during the sub-step analysis of the surgical C-section waste. The most environmentally harmful item in the preparation room was the blue wrap that is used to pack surgical instruments. The use of blue wrap as packaging material for sterile



surgical instruments is known to be a major contributor to OR waste. Estimates are that 115 million kilograms of blue wrap is discarded on a yearly basis in the US alone.²¹ It is a multilayer non-woven packaging material made from polypropylene that is used in many sterilisation departments in the world. After unpacking sterile surgical instruments blue wrap packaging is discarded, making up 11.5% of total OR waste.¹⁰ We were not able to find a sustainable solution in our hospital for blue wrap, which was a carbon footprint hotspot in the preparation room waste. Possible solutions are recycling blue wrap, or the use of a reusable rigid container that can be considered as a packaging system for sterile instruments.²²

In the OR itself, cotton gauzes and disposable surgical gowns that were in the custom pack caused the most environmental burden. Polypropylene is the most common material of disposables used in custom packs for operations. However, when the life cycle of the items in disposables custom packs for a traditional vaginal childbirth were studied, cotton gauzes were found to have the biggest environmental impact.¹⁸ Adjusting the composition of the custom pack yielded by far the greatest environmental gain in our HSMEA of the C-section (98%), which involved removing unnecessary items such as small cotton gauzes and a spare disposable surgical gown.

During the process of solution creation, it became clear that recycling had only a very limited impact on the reduction of the carbon footprint of surgical waste generation. Inside the OR, recycling was not a solution due to the risk of contamination with infectious materials. In the preparation room, even though recycling was 14 out of 21 times the chosen solution, it was only responsible for 2 percent of the overall reduction in carbon footprint. Recycling is an important way to ensure that raw materials are not wasted in a circular economy. However, recycling is difficult to achieve in an OR setting with potential infectious waste. Also, it is much better to ensure that waste is not created in the first place by refusing, reducing, reusing, and rethinking materials.

In their systematic evaluation of user feedback from 13 HFMEA analyses, Habraken et al. showed that its multidisciplinary, systematic, and stepwise approach, which are also tenets underlying the HSMEA, are the strengths of this method.³¹ As a result, this method provides insight into the entire process from different perspectives and is very detailed and comprehensive. User feedback showed that the HSMEA is perceived as a systematic approach that is easy to use and promotes sustainability. However, when asked if a subsequent project could be conducted independently, the HSMEA scored less than desired. The importance of having a skilled and effective team leader has also been mentioned previously in evaluations of the HFMEA. A facilitator with knowledge and overview of the process is critical to the success of HFMEA.^{31,32}

The weakness of the HSMEA, like its predecessor (HFMEA), lies in the fact that it is a resource-intensive and time-consuming method. The case study of the C-section involved six healthcare professionals who completed three one-and-a-half-hour sessions with each other. These drawbacks are also known issues with the HFMEA and must be weighed against the aforementioned benefits.³¹

Limitations

In order to make the HSMEA method broad and easy to apply, a number of shortcomings of the carbon footprint tool have been accepted. Firstly, only the global warming potential (carbon footprint) is calculated and all other environmental effects like acidification, eutrophication etc., as well as materials depletion, are not taken into account. The advantage of expressing environmental damage in the form of a carbon footprint is that it is a concept that has become understandable to the general public. Secondly, the carbon footprint was calculated from waste streams instead of doing Life Cycle Assessments of all materials present. The latter is an extremely long and labour-intensive process compared to the identification and weighing of waste. Using DEFRA greenhouse gas life cycle conversion factors for waste disposal is permitted, as the majority of OR waste is composed of a mixture of different plastics.⁹ The HSMEA analysis could be supplemented by other methods that do take the aforementioned factors into account by performing a Life Cycle Assessment with, for example, ReCiPe 2016.³⁶ However, this will be at the expense of user-friendliness, while the present results appear to be in line with previous studies.¹⁸ In the validation study, we did not include all waste generated during the C-section, as anaesthetic waste was not taken into account. Waste from anaesthetic practice contributes substantially to OR waste. McGain et al. showed that 25% of total OR waste came from anaesthesia.³⁷ In the future application of the HSMEA, however, this can certainly be included in the research given the similarities in the materials found in both surgical and anaesthetic waste.

Another possible limitation is that the validation was limited to the C-section. This procedure was selected because it is always performed in the same way at the LUMC and therefore there is little or no variation in waste production. When different surgeries are studied, more waste audits will be needed to ensure a good understanding of the waste produced. However, this should not be an obstacle to applying this newly introduced method.

Future research

One strength of the HSMEA lies in the structured analysis and quantification of the environmental impact of a process by a multidisciplinary team, after which sustainable solutions are sought for carbon hotspots. Future research should focus, in addition to OR waste, on the application of HSMEA to other resource-intensive areas of healthcare, such as the Intensive Care, Cath labs, and Dialysis units.



Apart from application to waste from other hospital departments, this method could also be used in areas such as water and electricity savings. Specific topics such as, for example, water consumption for handwashing can be the subject of a HSMEA. The process can be mapped and the various sustainable solutions to save water (water-saving taps, critical appraisal of the handwashing protocol, etc.) investigated, implemented, and its environmental benefits quantified. Similarly, energy consumption in the OR department, or any other section of the hospital, can be chosen as a topic with energy-saving measures or the use of renewable energy as sustainable solutions.

Conclusions

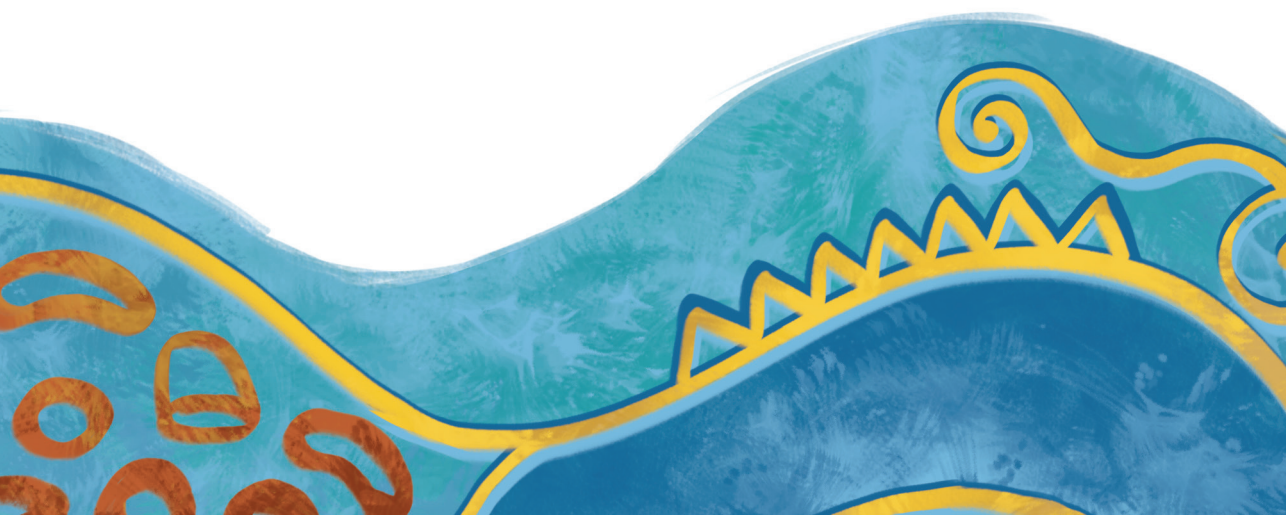
The HSMEA has proven to be a structured and practical tool that can help reduce the environmental impact of surgical solid waste. The meticulous analysis of the waste produced allows the researchers to efficiently address its environmental impact. It is expected that the HSMEA method will be applicable not only to the C-section, but also to all other surgical operations. It may even be relevant to waste produced by other medical procedures in healthcare, since the current practice throughout the healthcare system is based on the use of disposables, and the wasting of unused items is ubiquitous. This is particularly true for developing countries. In future research, the HSMEA may also prove applicable to water and energy savings in healthcare settings.

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CHAPTER 7

Surgical Carbon Footprint Auditing Tool for Less Emissions (SCALE): An Evidence-Based Nationwide Cross- Sectional Assessment to Reduce the Environmental Impact of the Operating Room

Authors:

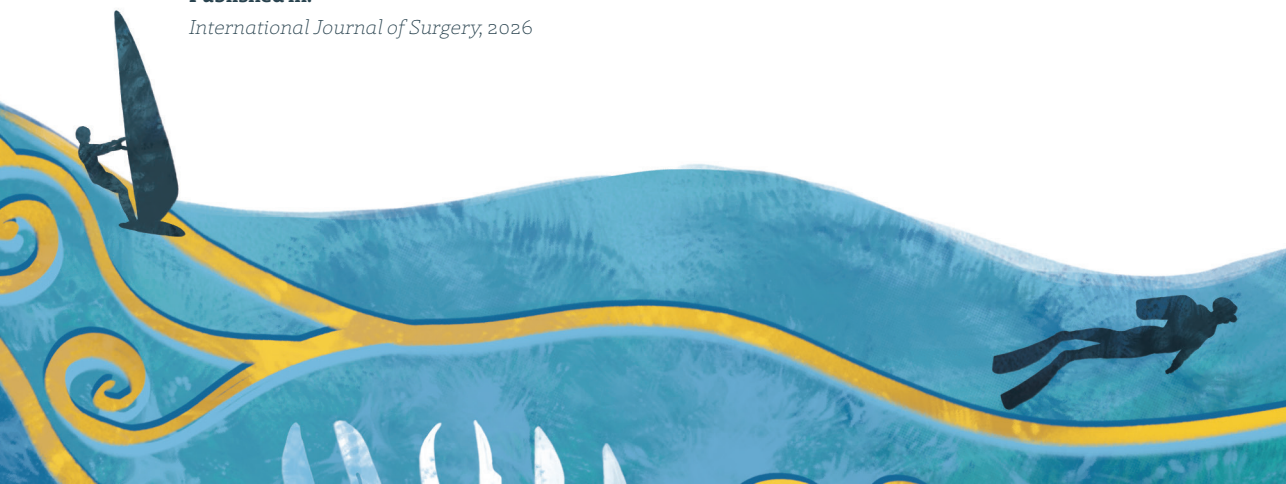
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Abstract

Background: The healthcare sector significantly contributes to global carbon emissions, and operating rooms (ORs) are particularly resource-intensive environments. ORs are therefore potentially impactful targets for emission reduction. Growing knowledge of carbon footprint hotspots in surgery should be integrated into a systematic approach to mitigate the environmental impact of ORs.

Materials and methods: We developed the *Surgical Carbon footprint Auditing tool for Less Emissions* (SCALE), an evidence-based model combining published life cycle assessments (LCAs) with real-world surgical practice to quantify OR-related carbon emissions and high-impact mitigation strategies. A questionnaire assessing qualitative and quantitative aspects of surgical practice was distributed to 60 Dutch hospitals. Collected data were incorporated into the model to calculate the carbon footprint and mitigation potential of individual ORs. Ten priority interventions were provided to each surgical centre. All data were combined to establish a national baseline.

Results: Forty surgical centres (594 ORs) completed the questionnaires. The model consisted of defined variables on surgical practice in five categories, including less-emitting alternatives for carbon footprint calculations: (1) organisation and reporting, (2) energy, (3) anaesthetics, (4) medical products, and (5) decontamination. Implementation of sustainable practices could reduce emissions by 76.3%, saving a mean 729.9 kg CO₂-eq/week per OR. The six most impactful interventions, accounting for over 95% of the achievable reduction, were the transition to renewable energy, phase-out of nitrous oxide and desflurane, use of vapour capture technology and end-tidal control, adoption of heat recovery technology, and use of reusable sterile gowns.

Conclusion: SCALE provides a framework to reduce the carbon footprint of surgical practice by identifying effective measures at the hospital and national levels in the Netherlands. By prioritising these high-impact strategies, SCALE facilitates progress towards sustainable healthcare. Given the urgency of the climate crisis, yielding a rapid and substantial environmental gain with these interventions is crucial.

Introduction

Human health is threatened by the unfolding climate crisis. Rising temperatures and environmental pollution contribute to morbidity, and mortality through multiple direct and indirect pathways, ranging from cardiovascular disease caused by poor air quality, undernutrition as a result of decreased food supply, and vector-related disease due to changes in ecosystems.¹ The healthcare sector is responsible for 4.4% of the global carbon footprint and faces a paradoxical role as both an affected party and contributor.^{2,3}

Hospitals are responsible for substantial proportions of the healthcare-related carbon footprint.⁴ The operating room (OR) is the most resource-intensive environment within hospitals and, therefore, a potentially high-impact target to reduce greenhouse gas (GHG) emissions, which depend on multiple aspects. Energy consumption per m² in ORs is three to six times higher than the hospital average.⁵ In addition, as potent GHGs, anaesthetic gases emitted an estimated 200 kilotonne of CO₂-eq annually in England, 325 kilotonne in Australia, and 12.2 kilotonne in the Netherlands.⁶⁻⁸ Furthermore, single-use items account for 69-87% of the surgical carbon footprint^{9,10} and disposal of contaminated waste contributes substantially to the environmental impact of healthcare institutions.⁹⁻¹¹ Previous research has determined environmental hotspots of ORs and specific types of surgical procedures.^{5,6,10,12-17} Energy and resource consumption vary substantially across sub-specialties depending on procedural duration and medical products.¹⁸ This heterogeneity highlights the necessity for a framework translating environmental hotspots into sustainable measures at individual OR level, while reflecting diverse surgical settings.

This study aims to provide an evidence-based tool to identify and prioritise interventions to reduce the OR's carbon footprint and quantify their potential impact. By integrating literature on environmental impacts of OR-related processes and products, we developed the Surgical Carbon footprint Auditing tool for Less Emissions (SCALE). SCALE enables benchmarking of individual ORs, quantifies carbon footprint reduction potential, and identifies practical interventions to achieve this reduction. By providing a baseline assessment and framework, SCALE facilitates informed decision-making toward sustainable surgical practice at individual and national levels.

STROCCS

This cross-sectional study has been reported in line with the STROCCS guidelines.¹⁹



Methods

Search strategy

The primary outcome of this study was the carbon footprint reduction potential of an individual OR (kg CO₂-eq/week); the secondary outcomes were the interventions to achieve this reduction. To identify the carbon footprint of every OR-related process and product, a systematic literature search was performed in PubMed. Inclusion criteria consisted of English and Dutch articles determining the carbon footprint of products and processes with lower-emission alternatives in surgical practice, without time restriction. Studies on items without alternatives (e.g. medication) were excluded. MeSH terms and free-text words such as 'Carbon Footprint,' 'Operating Rooms,' 'Surgical Procedures,' 'Anaesthetics,' 'Climate Change,' 'Greenhouse Effect,' and 'Medical Waste' were combined with terms related to life cycle assessment (LCA), such as 'life cycle assessment' and 'lifecycle inventory'.

Selection process

In December 2022, two authors (JD, ML) independently screened eligible articles and extracted information on the carbon footprint of energy consumption, anaesthetic agents, single-use and reusable products, and decontamination services. Where multiple LCAs were available for similar processes and products, the study most representative for the Dutch healthcare context was selected. The inclusion and selection criteria are described in Appendix A, Inclusion criteria literature search. As LCAs differ in scope, such as functional unit, and system boundaries, individual results are not directly comparable. However, heterogeneity was accepted as the tool aimed to prioritise high-impact interventions, for which the order of magnitude was more relevant than precise emission values.

Categorisation model

Based on the selected literature, surgical practice was categorised into five domains: (1) organisation and reporting, (2) energy, (3) anaesthetics and medication, (4) medical products and waste, (5) decontamination (cleaning, disinfection and sterilisation). The first category consisted of qualitative indicators of organisational practices that facilitate or hinder transition. It was used to qualitatively assess boundary conditions necessary for implementation.

Standard OR definition

A focus group of clinicians (surgeons, anaesthesiologists, and gynaecologists) with experience in surgical clinics, academic, top-clinical, and regional hospitals in various regions, biomedical engineers, and an OR manager – all with expertise on environmental impacts within their field – defined a 'standard OR'. Consensus was hierarchically

reached, either supported by literature or through group discussion in cases where empirical data lacked (Table 1). Some variables were common surgical practice (e.g. work days per week). The standard OR integrated variables on energy consumption, type of anaesthesia, number of medical products in the OR, and decontamination services.

Carbon footprint calculations

Building upon the standard OR, carbon footprints were calculated using LCA-derived data for every item and process. An example calculation is provided below:

$$\begin{aligned} & \text{Weekly kg CO}_2\text{-eq emitted by surgical gowns per OR} \\ &= \text{GWP sterile surgical gown (disposable or reusable)} \\ & \quad * 3.5 \text{ gowns per surgery} * 5 \text{ surgeries per day} * 5 \text{ days per week} \end{aligned}$$

Carbon emissions factors of fossil fuels and renewable energy were obtained from independent research firms (Gupta Strategists, CE Delft).

Sustainable OR benchmark

To determine the carbon footprint reduction potential of an individual OR, the most 'sustainable OR' scenario (SOR) was used as a benchmark. The SOR represented the lowest achievable carbon footprint for every item and process, according to the obtained literature. Individual OR results were compared with the SOR to identify ten priority interventions to achieve the OR-level reduction potential. From December 2023 onward, each participating surgical centre received an individualised advisory report outlining its performance and recommending what measures to implement.

Data collection

In this cross-sectional study, pilot questionnaires on hospital specific practices across the five themes mentioned above were initially distributed among sustainability officers. Additionally, they were asked to provide data, such as energy contracts, to enhance objectivity. Sustainability officers reported that delivering objective data sources, such as procurement records, required excessive time and effort, and that data gathering was challenging from their position. They suggested that OR managers would have better access to the necessary data across different departments (e.g. procurement). Subsequently, final versions (Appendix A, Table 1) were distributed among OR managers and personnel from 60 Dutch hospitals and five private clinics in June 2023. The OR managers were not asked to provide further objective data but were given instructions on how to collect all required data. By August 2023, 31 hospitals and two clinics had completed the forms. Reminders were sent to the remaining centres. Seven centres replied that they were still occupied, of which three finalised



the forms by December 2023. Four hospitals reinitiated contact and completed questionnaires in 2024. In the case of missing data, hospitals were contacted with a request of completion. Responses up to December 2024 were included in the analysis.

Table 1. *Defined variables included in SCALE.*

	Unit	Boundaries standard OR	Practice in sustainable OR	Source
Nr. of surgeries	/day	5	-	CSP
Hrs. of surgery (energy consumption)	/day	6	100% renewable energy 100% ORs with heat recovery 100% ORs with active night strategy	EC
Nr. of workdays per week	/wk	5	-	CSP
Active weeks per year	/yr	52	-	CSP
Anaesthesia with inhalational anaesthetic agents (MAC hours)	hrs/wk	15	Sevoflurane (carrier gas air) No nitrous oxide VCT End-tidal control	EC
Anaesthesia with TIVA	hrs/wk	15	-	EC
Nr. of sterile surgical instrument trays	/surgery	2	Reusable trays	EC
Nr. of sterile surgical gowns	/surgery	3.5	Reusable gowns	EC
Nr. of m ² surgical drapes	/surgery	4	Reusable drapes	EC
Nr. of laryngoscope handles	/surgery	0.5	Reusable handles	EC
Nr. of laryngoscope blades	/surgery	0.5	Reusable blades	CSP + FGC
Nr. of laryngeal masks	/surgery	0.5	Reusable masks	CSP + FGC
Nr. of blood pressure cuffs	/surgery	1	Reusable cuffs	CSP
Nr. of laparoscopic trocars	/surgery	0.2	Reusable trocars	Literature ²⁰ + FGC
Nr. of laparoscopic scissors	/surgery	0.05	Reusable scissors	Literature ²⁰ + FGC
Nr. of laparoscopic clippers	/surgery	0.05	Reusable clippers	Literature ²⁰ + FGC
Nr. of needle containers	/surgery	0.04	Reusable containers	EC
Nr. of anaesthesia drugtrays	/surgery	1	Reusable trays	CSP

The standard operating variables in average surgical practice, modelled by the focus group, are indicated as boundaries of a standard OR. The most sustainable choice per variable deducted from the included articles in the literature search and the source of the defined variables are also provided. OR, operating room; SOR, sustainable operating room; VCT, vapour capture technology; MAC, minimal alveolar concentration; total intravenous anaesthesia, TIVA; common surgical practice, CSP; expert consensus, EC; focus group consensus, FGC.

Sensitivity analysis

A Monte Carlo simulation with 5,000 iterations was performed to assess the impact of uncertainty in key parameters (Table 1) on the total OR carbon footprint. The surgical hours per day were varied from 4 to 8 ($\pm 50\%$). Similarly, the amount of surgical gowns and sterile trays were ranged $\pm 71\%$ and 50% , respectively, to prevent the average amount needed per surgery from being lower than one. The number of days per week and weeks per year were excluded. All other variables were modelled within clinical ranges ($\pm 80\%$), taking into account different hospital sizes and surgical subspecialties. All parameters were uniformly ranged. The Pearson correlation coefficient of every parameter to the carbon footprint was determined.

All calculations for the tool and Monte Carlo simulations were performed in Microsoft Excel. Statistical analyses were conducted using SPSS Statistics version 29.0.

Results

Literature inclusion

Twelve studies quantifying the carbon footprint of OR-related processes and products were included. These studies assessed (1) the electricity consumption of mixing ventilation and laminar flow, heat recovery, and active night mode; (2) propofol and inhalational gases (desflurane, sevoflurane, and nitrous oxide) and the impact of vapour capture technology (VCT) or end-tidal control (Et Control); (3) both single-use and reusable products such as sterile drapes, laryngeal masks, sharps containers, anaesthetic drug trays, laparoscopic trocars, scissors, and clippers, blood pressure cuffs, laryngoscope blades and handles, surgical gowns; and (4) decontamination packaging.²⁰⁻³¹ Products or services not routinely used across surgical practice, such as bronchoscopes, were excluded. One Dutch study by Bijleveld and Uijttewaai (2022) was identified through the snowballing method.²⁴ An overview of all included items and system boundaries of the standard OR and SOR is provided (Table 1). Incorporating studies with lower-emission alternatives only meant that the model encompassed a defined subset of the OR carbon footprint rather than total emissions. Absolute values should, therefore, not be interpreted as a complete inventory. Detailed information on the included studies is provided (Appendix A, Table 2).

Participating hospitals

Questionnaires were completed by 38 hospitals (63.3%) and two private clinics. The participating surgical centres in our study included 7 out of the 8 Dutch academic hospitals (87.5%), 18 out of 27 top-clinical hospitals (66.7%), and 13 out of 38 (34.2%) regional hospitals. A total of 594 ORs were represented: 172 (29.0%) in academic



hospitals, 310 (52.2%) in top-clinical (high-level non-academic) hospitals, 110 (18.5%) in regional hospitals, and 2 (0.3%) in private clinics. Public data on the total number of ORs in the Netherlands is not available. Figure 1 presents the rate of participating hospitals per province, in which 11 of the 12 Dutch provinces represented. A detailed overview of hospital types can be found in Appendix A, Table 3.

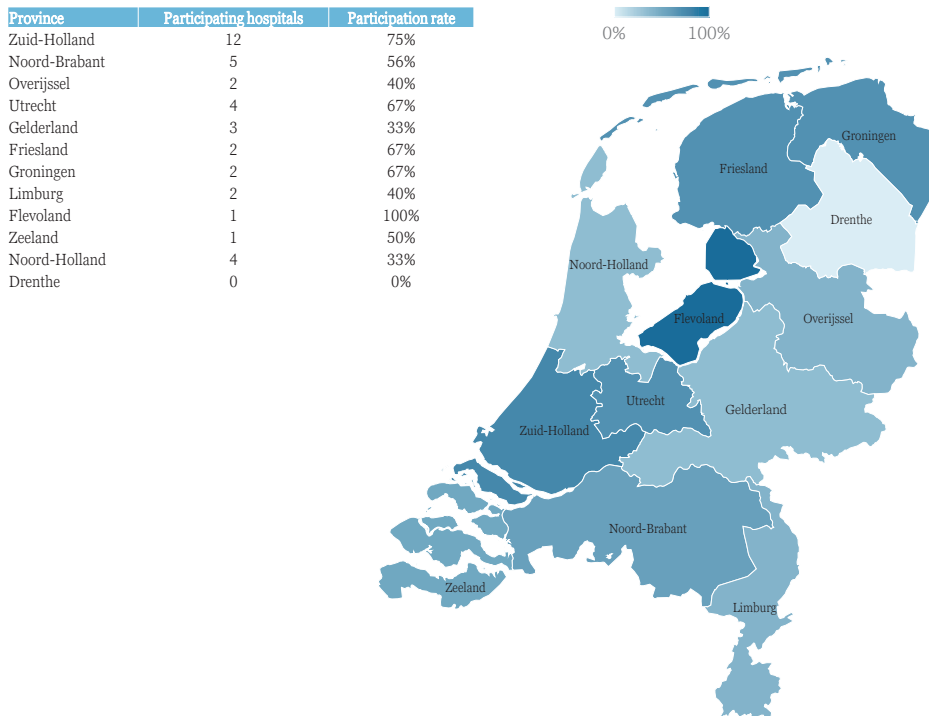


Figure 1. Included hospitals of total per province in the Netherlands.

Evaluated parameters

The category ‘organisation and reporting’ was evaluated in terms of qualitative indicators of organisational practices, such as hospital-level strategy on sustainability instead of carbon footprint. All participating surgical centres reported targets aimed at reducing their environmental footprint. Sustainability was incorporated into staff training in a minority of the hospitals (37.5%), and over one-third (37.5%) of the hospitals did not integrate sustainability in procurement processes. Still, organisational frameworks integrating sustainability in procurement and education did not always align with a lower carbon footprint. The evaluated indicators in this category are provided (Appendix A, Table 4).

In our model, the electricity source (either fossil fuel-based or renewable) was relevant to the carbon footprint of heating, ventilation, and air conditioning (HVAC). In the Netherlands, ORs use three types of HVAC systems: mixing ventilation, laminar airflow, ultra-clean laminar airflow, with increasing hourly air changes and energy consumption, and a decreasing number of particles per m³. In 21 hospitals (52.5%), multiple HVAC systems were available in individual ORs. Energy-limiting measures related to HVAC, including an active night mode – an energy-saving mode – and heat recovery technology, were also assessed.

With respect to anaesthetics, parameters included vapour capture technology (VCT) – a method to recapture inhalational anaesthetics – and Et Control, in which the inhalational anaesthetic dose is precisely regulated. While two-thirds of the ORs had anaesthetic equipment facilitating Et Control, VCT was present in a limited proportion.

Regarding medical products, all evaluated medical products, with the exception of surgical drapes, were reusable in at least one participating OR. At the time of study, laparoscopic trocars and clippers were either hybrid – meaning partly reusable – or single-use. Aiming to prevent unnecessary waste production, products were unpacked exclusively when needed in the majority of the ORs.

Most decontamination services were on hospital premises, and approximately half had water- or energy-saving modes in place. Sterile surgical instrument trays were wrapped in blue wrap rather than reusable containers in most decontamination services. All evaluated categories are presented (Table 2).

Carbon footprint Dutch OR

Within the scope of SCALE, focusing on processes and products with lower-emission alternatives, the average Dutch OR emitted 956.7 kg CO₂-eq/week. The carbon footprint was primarily driven by energy consumption and anaesthetics, contributing a mean (standard deviation) of 377.1 kg CO₂-eq/week (355.4) and 366.2 kg CO₂-eq/week (211.9) respectively. Medical products and waste emitted 196.1 kg CO₂-eq/week (19.3). Decontamination packaging of sterile reusable surgical products contributed 17.3 kg CO₂-eq/week (4.4).

Figure 2 shows the relative impact of individual processes and products to an individual Dutch OR. Fossil fuel-based energy was responsible for the largest share, accounting for 44.8% of the energy used in OR complexes. Desflurane contributed to 7.5% (27.3 kg CO₂-eq/week) of anaesthesia-related emissions and 2.9% of the average per-OR emissions, despite being used in only 15 ORs.



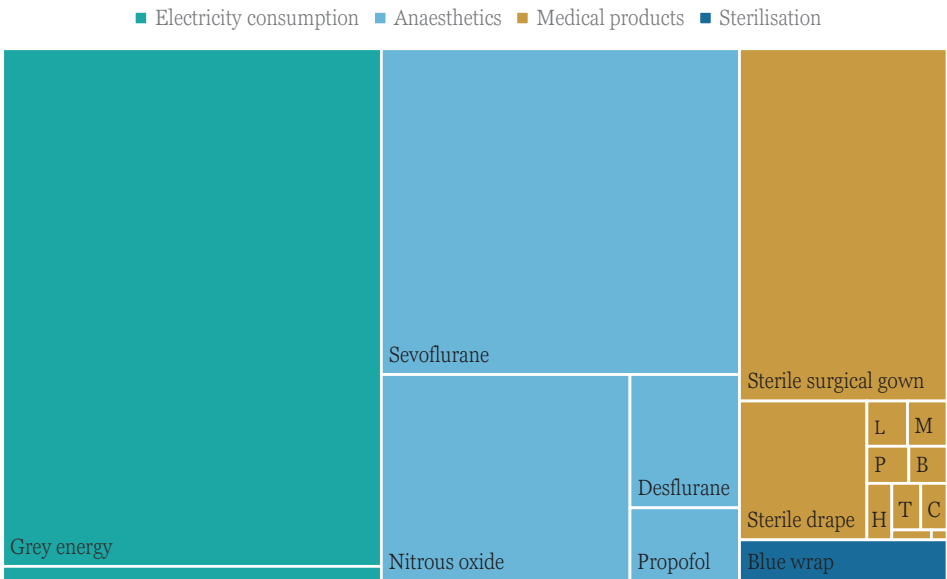


Figure 2. *Per-hospital average emissions per category.* The average carbon footprint related to processes and products in the four categories electricity consumption, anaesthetics, medical products, and decontamination, on a per-hospital level. M= laryngeal mask, L= laparoscopic trocar, B= laryngoscopy blade, T= medication tray, C= laparoscopic clipper, P= blood pressure cuff, H= laryngoscopy handle).

Due to their widespread single-use, sterile drapes and gowns made the greatest contribution to the material-related carbon footprint related. Sterile gowns emitted 140.8 kg CO₂-eq/week per OR and sterile drapes were responsible for 34.0 kg CO₂-eq/week. Laryngoscopy emitted 2.7 kg CO₂-eq/week per handle and blade. Laryngeal masks had a carbon footprint of 3.5 kg CO₂-eq/week. Laparoscopic trocars, scissors, and clippers emitted a total of 6.6 kg CO₂-eq/week, 3.5, 0.8, and 2.4 kg CO₂-eq/week, respectively. Packaging sterile surgical trays with single-use blue wrap caused 18.7 kg CO₂-eq/week, over six times more than sterile surgical instrument trays, which emitted 2.9 kg CO₂-eq/week. Medication trays were responsible for 2.6 kg CO₂-eq/week, and blood pressure cuffs 3.0 kg CO₂-eq/week.

Variation across surgical centres

The five hospitals with the highest and lowest carbon footprints, along with the SOR, are presented in Figure 3. None of the hospitals met the SOR profile fully, indicating a reduction potential across all centres. The two lowest-emitting surgical centres (on a per-OR basis) matched the SOR carbon footprint in the categories energy, anaesthetics, and decontamination. Among the five highest emitting surgical centres, the greatest carbon mitigation could be achieved in the categories energy consumption and

anaesthetics. An OR in the most sustainable hospital in our study had an average weekly carbon footprint of 367.0 kg CO₂-eq, compared to 2,044.9 kg CO₂-eq emitted in the highest-emitting centre. The per-category carbon footprint significantly differed in the anaesthetics, materials, and decontamination categories depending on hospitals sizes, as shown in Table 3.

Reduction potential

On average, transitioning to the SOR led to a yearly carbon footprint decrease of 37,955.3 kg CO₂-eq (76.3%) per OR. Annually, all ORs in our study combined could save 22.5 million kg CO₂-eq. The top ten priority actions in transitioning to a SOR identified by SCALE are presented in Figure 4.

The largest reduction in carbon footprint could be achieved by transitioning from fossil fuel-based to renewable energy, annually saving 18,715.4 kg CO₂-eq per OR. The second most impactful adjustment was the implementation of anaesthetic machines equipped with VCT and Et Control. Eliminating nitrous oxide as a carrier gas could save over 5,000 kg CO₂-eq/year. Switching from single-use to reusable sterile gowns is the fourth most impactful intervention. Adopting these, together with the implementation of heat recovery technology and the phase-out of desflurane would obtain over 95% of the reduction potential of carbon emissions. The carbon footprint related to heat recovery technology is co-independent of the type of energy.

Uncertainty analysis

The uncertainty analysis revealed that the OR carbon footprint had the strongest correlation with the inhalational anaesthesia/TIVA ratio, operating hours per week, and number of surgeries per day. Pearson correlation coefficients for every parameter are provided in Appendix A, Figure 1. Figure 5 presents the carbon footprint distribution of 5,000 iterations. The mean carbon footprint of all simulations was 956.5 kg CO₂-eq/week (95%-confidence interval 949.6 – 963.5 kg CO₂-eq/week) and was nearly identical to the calculated carbon footprint based on the key parameters (956.7 kg CO₂-eq/week).



Table 2. *Evaluated parameters questionnaires.*

	Number of ORs or hospitals
Energy	
Fossil fuel based energy	9 fully, 13 partly (fossil fuel based and renewable)
Renewable energy	18 fully, 13 partly (fossil fuel based and renewable)
Self-generated renewable energy (hospitals)	19 hospitals
Externally purchased renewable energy (hospitals)	30 hospitals
Active night mode	433 ORs
Heat recovery technology	383 ORs
Equipment turned off at night	477 ORs
Mixing ventilation	47 ORs
Laminar flow	202 ORs
Ultra-clean laminar flow	357 ORs
No air handling system	8 ORs
Anaesthesia	
Desflurane	15 ORs
Sevoflurane	<i>Defined variable: 50% anaesthesia hours</i>
Nitrous oxide	311 ORs
Propofol	<i>Defined variable: 50% anaesthesia hours</i>
VCT	42 ORs
Et Control	406 ORs
Low flow	557 ORs
Prefilled syringe	392 ORs
Medication wastage monitoring	84 ORs
Medical products and waste	
Conscious unpacking products	570 ORs
Conscious unpacking integrated in OR protocol	312 ORs
Hazardous and residual waste separation	471 ORs
Paper waste separation	555 ORs
Plastic waste separation	439 ORs
Metal waste separation	296 ORs
Surgical drapes ^a (single-use/reusable/both/none)	594/0/0/0 ORs
Sterile gowns ^a (single-use/reusable/both/none)	553/15/26/0 ORs
Laryngoscope handles ^a (single-use/reusable/both/none)	19/528/47/0 ORs
Laryngoscope blades ^a (single-use/reusable/both/none)	178/233/183/0 ORs
Laryngeal mask ^a (single-use/reusable/both/none)	510/15/69/0 ORs

Total responding ORs or hospitals	Percentage of total responders	Mean related carbon footprint (kg CO ₂ -eq/week) in Dutch OR
40 hospitals	44.8%	366.2
40 hospitals	55.2%	10.9
40 hospitals	47.5%	NA
40 hospitals	75.0%	NA
594 ORs	72.9%	9.8
583 ORs	65.7%	38.7
594 ORs	80.3%	NA
594 ORs	7.9%	Dependent of heat-recovery technology and active night mode
594 ORs	34.0%	Dependent of heat-recovery technology and active night mode
594 ORs	60.1%	NA
594 ORs	1.3%	NA
594 ORs	2.5%	27.3
-		224.6
594 ORs	52.4%	99.2
-		15.2
594 ORs	7.1%	Dependent of inhalational gas used and end-tidal control
594 ORs	68.4%	Dependent of inhalational gas used and VCT
594 ORs	93.8%	NA
594 ORs	66.0%	NA
594 ORs	14.1%	NA
594 ORs	96.0%	NA
594 ORs	52.5%	NA
594 ORs	79.3%	NA
564 ORs	98.4%	NA
568 ORs	77.3%	NA
594 ORs	49.8%	NA
594 ORs	-	34.0
594 ORs	-	140.7
594 ORs	-	2.7
594 ORs	-	2.7
594 ORs	-	3.5



Table 2. *Continued*

	Number of ORs or hospitals
Blood pressure cuffs ^a (single-use/reusable/both/none)	129/396/69/0 ORs
Laparoscopic trocar ^b (single-use/reusable/both/none)	309/18/239/28 ORs
Laparoscopic clipper ^b (single-use/reusable/both/none)	226/53/313/2 ORs
Laparoscopic scissors ^b (single-use/reusable/both/none)	76/171/345/2 ORs
Needle containers ^a (single-use/reusable/both/none)	559/35/0/0 ORs
Medication trays ^a (single-use/reusable/both/none)	99/448/0/47 ORs
Decontamination	
On site CSD	34 hospitals
Blue wrap	542 ORs
Sterile surgical instrument trays	52 ORs
Blue wrap collection	319 ORs
Decontamination equipment turned off	6 hospitals
Decontamination equipment standby	23 hospitals
Energy or water saving modus	20 hospitals

All items included in the final questionnaires, the per OR and hospital answers depending on best suitability. Additionally, the mean related carbon footprint if applicable.) ^aThe single-use/reusable ratio was provided by hospitals.

Total responding ORs or hospitals	Percentage of total responders	Mean related carbon footprint (kg CO ₂ -eq/week) in Dutch OR
594 ORs	-	3.0
594 ORs	-	3.5
594 ORs	-	2.4
594 ORs	-	0.8
594 ORs	-	0.3
594 ORs	-	2.6
40 hospitals	85.0%	NA
594 ORs	91.2%	17.1
594 ORs	8.8%	0.2
594 ORs	53.7%	NA
40 hospitals	15.0%	NA
40 hospitals	57.5%	NA
40 hospitals	50.0%	NA

^bHybrid instruments (partly reusable). CSD, central sterilisation department; VCT vapour capture technology; OR, operating room; NA, not applicable (for example, no quantified related carbon footprint).



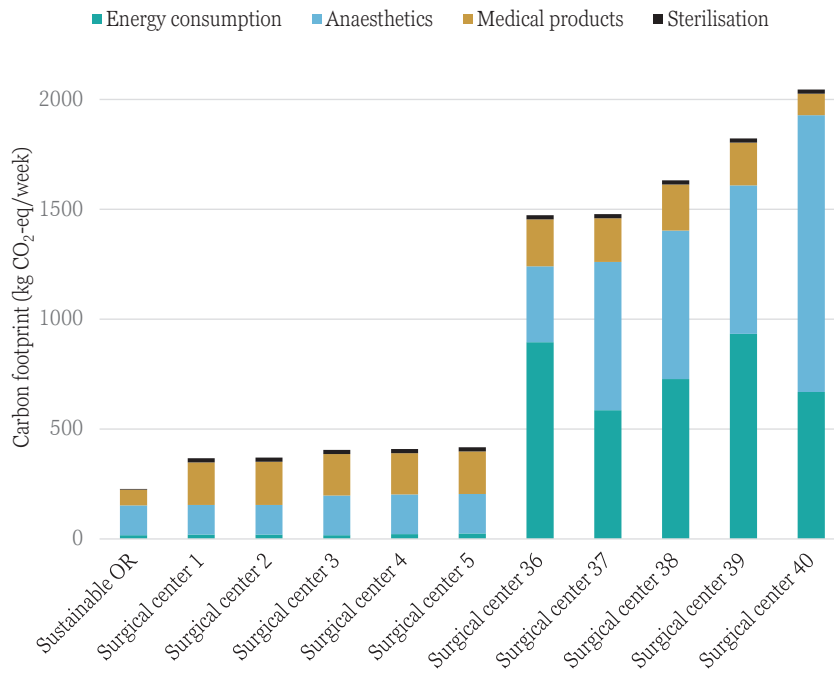


Figure 3. Five surgical centres with the lowest and five the highest carbon footprint compared to the sustainable OR. The total and per-category carbon footprint of the sustainable OR, as well as an OR in the five surgical centres with the lowest and highest-emitting ORs.

Table 3. Average carbon footprint per category in different hospital types.

Carbon footprint OR (Mean kg CO ₂ -eq/ week (range))	Academic hospitals	Top-clinical hospitals	Regional hospitals	Difference in means (p-values)
Energy consumption	382.2 (17.2 – 787.8)	380.9 (17.2 – 933.7)	355.4 (17.2 – 859.7)	0.803
Anaesthetics	365.3 (180.2 – 675.2)	408.6 (135.2 – 1260.2)	248.5 (135.2 – 675.2)	<0.001
Materials	205.5 (190.6 – 229.3)	191.7 (97.6 – 213.7)	194.1 (188.0 – 198.2)	<0.001
Decontamination	16.0 (2.9 – 18.7)	17.6 (2.9 – 18.7)	17.7 (2.9 – 18.7)	0.002

The mean carbon footprint in energy consumption did not differ across hospital types (academic, top-clinical and, regional). The largest relative difference was found in the anaesthetics category.

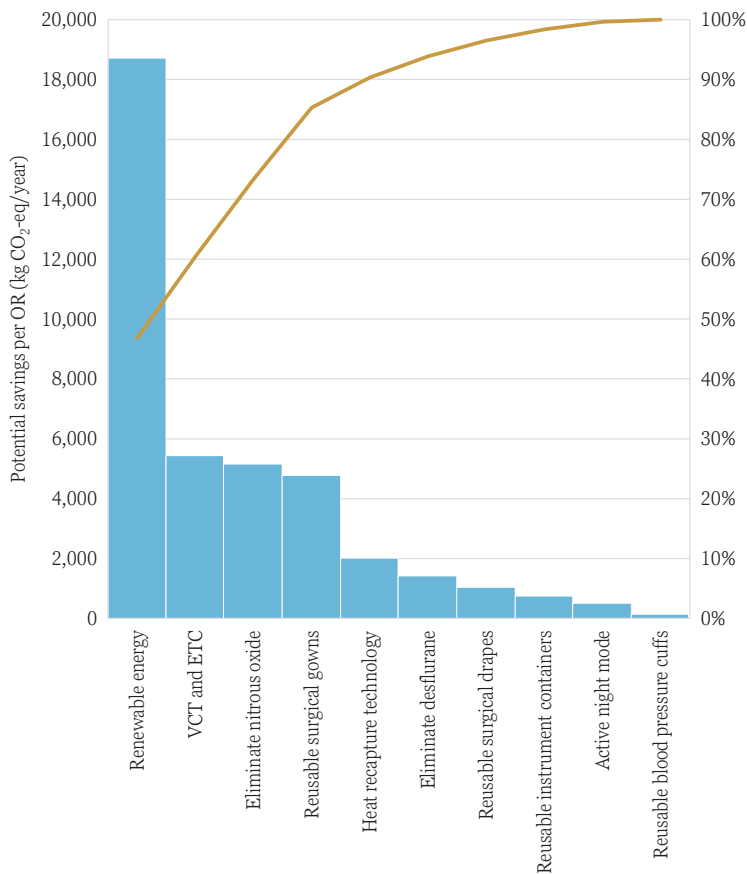


Figure 4. Ten interventions with the largest reduction potential in carbon emissions. Interventions with the largest carbon footprint reduction potential: (1) transition to renewable energy, (2) use vapour capture technology (VCT) and end-tidal control on the anaesthetic machine, (3) eliminate nitrous oxide as a carrier gas, (4) switch to reusable sterile surgical gowns, (5) use heat recovery technology, (6) phase out desflurane, (7) switch to reusable sterile drapes, (8) use reusable sterile instrument trays for decontamination, (9) activate night mode, (10) switch to reusable blood pressure cuffs.



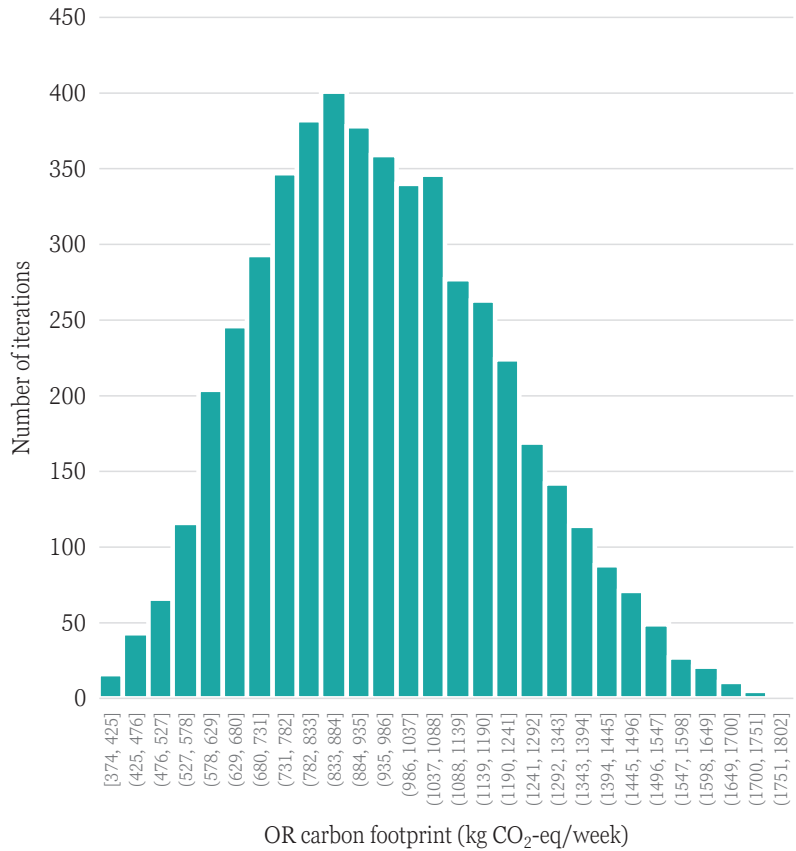


Figure 5. Monte Carlo simulation of variation in base parameters of the SCALE model (standard OR and SOR). The carbon footprint of an individual OR is emitted on a weekly basis when varying the key parameters by a maximum of $\pm 80\%$. The mean carbon footprint in the sensitivity analysis was 956.6 kg CO₂-eq/week (95%-confidence interval 949.6 – 963.5 kg CO₂-eq/week).

Discussion

SCALE provides an evidence-based model to quantify the carbon footprint reduction potential of ORs and identify interventions for sustainable surgical practice. By combining existing LCAs with hospital-specific surgical practice, SCALE eliminates the need for labour-intensive de novo LCAs for individual ORs. To our knowledge, it is the first carbon auditing tool assessing mitigation potential at both individual and national levels.

Main findings

Our findings show that sustainable measures can reduce the carbon footprint by 76.3%, saving 729.9 kg CO₂-eq per OR weekly, equivalent to a one-way flight from Amsterdam to Singapore.³² Six implementations accounted for 95% of the total carbon footprint reduction potential: transition to renewable energy, anaesthetic machines with VCT and Et Control, phase-out of nitrous oxide as a carrier gas, use of heat recovery technology, and reusable sterile surgical gowns. Nearly all SOR parameters were in place in at least one of the ORs, indicating that the SCALE recommendations were both realistic and achievable interventions. Part of the interventions can be sustained by immediate practice change, such as the switch from disposable to reusable products, while other measures, e.g., the procurement of renewable energy, require departmental decisions or might even be policy-dependent. As necessary efforts are expected to differ across hospitals, SCALE enables hospitals to weigh the carbon footprint reduction potential against the expected implementation burden.

Altogether, energy and anaesthetics were carbon footprint hotspots within ORs. Fossil fuel-based energy accounted for 44.8% of the total energy in OR complexes. HVAC systems are known to serve as the main energy consumer in ORs.⁵ In the Netherlands, national protocols indicate HVAC requirements for specific surgical interventions. While Dutch hospitals reported that less than half of the performed surgeries required ultra-clean air, its highly energy-consuming supply system was in place in 94% of the ORs.³³ As we concluded, at least two types of HVAC were available in 21 hospitals, providing surgical teams with a choice. This finding indicates that energy can be saved on an extensive scale by rightly adjusting the classification.

Anaesthetics represented the second hotspot. A study on the carbon footprint of ORs in three academic centres in the UK, Canada, and the USA reported anaesthetics as the largest contributor, with 62% being caused by desflurane and isoflurane.⁵ Despite the rare use of desflurane in Dutch practice (2.5% of the ORs), its phase-out is the fifth most impactful transition to reduce an ORs carbon footprint. This finding aligns with a study reporting that while desflurane and nitrous oxide made up merely 4.1% and 4.6% of purchased inhalational anaesthetics, respectively, their emissions were responsible for 41% and two thirds of the carbon footprint of volatile gases in the Netherlands. The high impact of desflurane and nitrous oxide is explained by their high global warming potential and low potency (nitrous oxide).⁸ The anaesthetic-related emissions were predominantly driven by the use of inhalational anaesthetics. In the sensitivity analysis, the inhalational-to-TIVA ratio had the strongest correlation with the OR's total carbon footprint. Accordingly, shifting to TIVA, when clinically feasible, represents the most impactful anaesthesia-related intervention.



Our results are consistent with a process-based analysis of the carbon footprint of five surgeries, showing that single-use drapes and surgical gowns were among the products with the largest contributions to surgical carbon footprint.⁹ Regarding patient safety, the World Health Organization Surgical Site Infection (SSI) Prevention Guidelines summarize studies comparing the rate of infections in disposable and reusable drapes and gowns across a variety of surgical sub-specialties (e.g. cardiac surgery, orthopaedics). None of the studies, with low to moderate evidence, identified a statistically significant difference in SSI.³⁴ Based on this, the Dutch guideline for infection prevention of SSIs mentions both disposable and reusable surgical drapes and gowns as feasible options.³⁵

We concluded that an integrated hospital-wide sustainable strategy was, in itself, not an indicator of the carbon footprint. This highlights that current improvements were mostly realised through grassroot sustainability initiatives such as 'green teams'. Almukhtar and colleagues found that a lack of knowledge is one of the main challenges for implementation.³⁶ This was confirmed by 42.5% of the hospitals in our study, alongside a lack of time, high costs, and existing contracts with suppliers. Therefore, institutional commitment is required to address complex challenges such as collaboration with procurement and suppliers.

Tools for sustainable practice

Sustainability in healthcare has gained momentum, and various frameworks have been developed. The Greenhouse Gas Protocol provides guidance to practitioners wanting to measure emissions related to medical products and pharmaceuticals.³⁷ It highlights the importance of the LCA approach and serves as the basis for the SCALE design. A practical tool for sustainable surgical practice is the 'Greening the Operating Room Checklist'.³⁸ It identifies opportunities for sustainable practice in the OR in four categories: organisational development, waste, purchasing, and built environment. A similar checklist by the American Society of Anaesthesiologists focuses on both interventions in organisational sustainability meetings and anaesthesiology.³⁹ While these tools highlight mostly intraoperative interventions, the RCSEd Intercollegiate Green Theatre Checklist integrates preoperative, postoperative, intraoperative, and anaesthesia-related recommendations.⁴⁰ These checklists provide extensive suggestions that can serve as useful guides for sustainable surgical practice. However, the impact of the interventions is not quantified. To distinguish high- and low-impact measures supporting decision-making, SCALE calculates the environmental impact of (part of) these interventions and adjusts it to individual levels. Still, SCALE covers only part of the interventions in the abovementioned checklists, as it does not include interventions for which carbon footprint data remain unavailable.

Limitations

Several limitations should be noted. First, the environmental impact is broader than carbon footprint.⁴¹ SCALE reported only on the carbon footprint as a result of the 'Green Deal for Sustainable Healthcare', an agreement for the Dutch healthcare sector distilled from the national climate agreement, aiming to reduce carbon footprint by 55% before 2030.⁴² Dutch healthcare institutions are focusing on carbon emission reduction as a result of this agreement, and SCALE facilitates this goal. Furthermore, the carbon footprint is generally consistently reported upon in environmental studies in healthcare. Limiting the outcome to carbon footprint enhanced the amount of studies included in the tool and provided single-way results. Still, we encourage other scientists to integrate as many environmental impact categories as possible to provide complete conclusions on sustainable practice.

Secondly, integrating LCAs from multiple sources in one tool limits strict comparability and introduces uncertainty in carbon footprint values. The intent of this first-generation tool was to identify high-impact strategies for sustainable surgical practice. Exact carbon footprint figures may be influenced by the differences in LCA scope and methodology, meaning that caution in interpretation is required. The tool does, however, still offer the ability to identify and distinguish high- versus low-impact interventions for carbon footprint reduction. Moreover, the structure of the tool provides the possibility of adaptation to new insights, both operational and environmental impact-wise. The incorporated literature was specifically tailored to the Dutch context for this national benchmark, and further practice-based refining is both necessary and feasible before implementation in another country.

Another limitation is the possible variability in reporting of the questionnaires. While the questionnaires were accompanied by instructions on where to obtain accurate information, the reported data was not complemented by objective sources such as procurement records. Due to the extensive profile of the questionnaires, we attempted to limit their extent to enhance maximal participation.

Lastly, real-time results may deviate from our conclusions as the model was based on a standardised set of variables. These are an inherent simplification of highly variable surgical practice, considering case-mix, hospital size, and complexity of procedures. This standardisation ensured a fair comparison of carbon footprint based on sustainable choices and organisation rather than volume. The uncertainty analysis showed a limited impact of variations in the key parameters on the carbon footprint outcome. Moreover, this standardisation ensured a fair comparison of carbon footprint based on sustainable choices and organisation rather than surgical volume.



Future perspectives

Following this measurement, the Dutch Ministry of Health, Welfare, and Sport received a report providing hotspots and focus points on a national scale, aimed at facilitating sustainable surgical practice from a higher policy level. SCALE has been incorporated in national certification for sustainable practice in healthcare institutions.

Future research should focus on evaluating the adoption of recommended interventions and motives driving their uptake, as well as barriers to implementation, including economic trade-offs. As SCALE is a dynamic model, it will be updated with emerging literature potentially integrating more environmental indicators. A follow-up measurement will be performed approximately two years after baseline – providing a window to implement the advised interventions. Lastly, an international upscale of SCALE represents an opportunity for even greater environmental benefits.

Conclusion

In conclusion, if we want to counteract the paradoxical role of the highly emitting healthcare sector and advocate for better human health, high impact interventions should be pursued in the resource- and energy-intensive OR environment. SCALE identified these measures on both a local and national level. The national framework ‘Sustainability in guidelines: Adding sustainability aspects in guideline development for the OR’ can facilitate their embedding in surgical guidelines.⁴³ Integration of the most effective SCALE measures in these guidelines presents an evidence-based approach and stimulation of clinical action toward enhancing both planetary and human health. Without urgent actions to counteract the surgical carbon footprint, healthcare will continue to have a detrimental effect on the very health it intends to protect.³

Appendix A.

Supplemental digital content.

<https://links.lww.com/JS9/H528>

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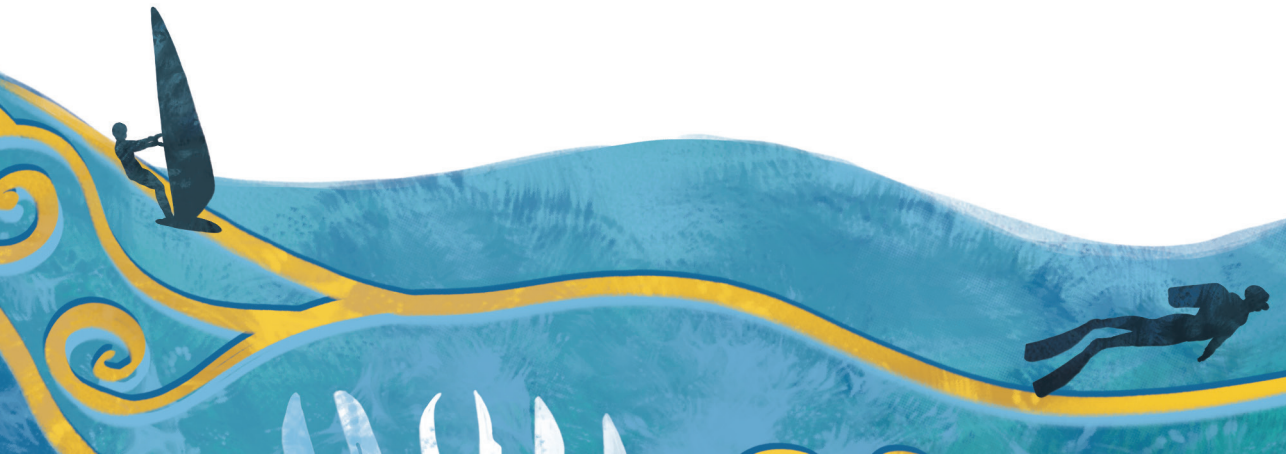
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CHAPTER 8

**General Discussion, Future
Perspectives and Conclusion**



General Discussion

Our research has focussed on the low-hanging fruit, sources of greenhouse gas (GHG) emissions that have the greatest impact on the carbon footprint of the OR. In doing so, we are contributing to the WHO goals of increasing environmental sustainability in healthcare facilities and the Dutch Green Deal 3.0 goal of reducing GHG emissions in healthcare by 55% by 2030 and becoming climate neutral by 2050.^{1,2}

The results are discussed in the framework of the GHG Protocol, which divides emissions into three scopes: direct emissions (Scope 1), indirect emissions due to energy consumption (Scope 2), and indirect emissions due to procurement of goods and waste generation (Scope 3) (Figure 3, Chapter 1).³ Part II of this thesis allows us to distil twelve practical solutions for reducing carbon emissions in the OR. Therefore, we used the evidence-based mitigation measures from the SCALE auditing tool in **Chapter 7** and the results of the HSMEA (**Chapter 6**) to discuss carbon footprint mitigation strategies for the OR. To this end we used the 10R Framework, a model for transitioning from a linear to a circular economy based on hierarchical measures.⁴ This comprehensive model is a refinement of the 3R concept (Reduce, Reuse, Recycle) to preserve value in a circular economy. The 10R Framework has three main objectives: avoiding waste, extending product life and recycling waste, listed here in order of preference. Figure 1 shows which R strategies lead to these three main objectives and explains the strategies. Finally, in the chapter on future perspectives, we will discuss follow-up questions arising from this thesis and indicate the direction in which OR sustainability research should proceed.



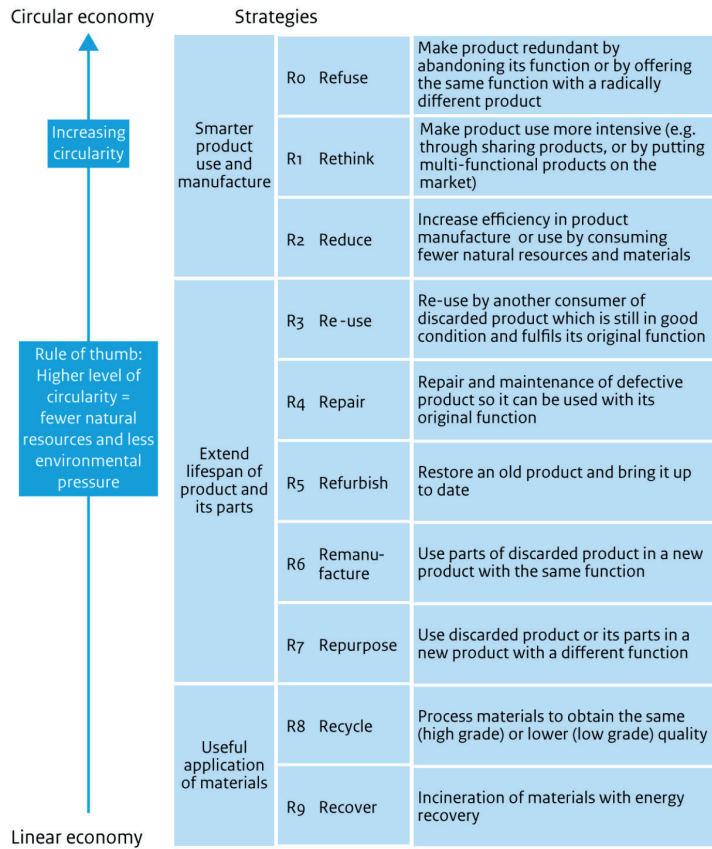


Figure 1. 10R strategy to increase circularity⁵ The higher the strategy is on the ladder, the higher the degree of circularity.

Main results

In Part I of this thesis, reduction of the major determinants of Scopes 1, 2 and 3 of the OR are investigated: inhalation anaesthetic use, energy consumption due to air treatment, waste generation resulting from widely used sterilisation packaging material for surgical instruments and in addition the reduction of the carbon footprint of an aortic valve replacement procedure.

Our results show that direct emissions from volatile anaesthetics (VAs) (**Scope 1**) in the Netherlands are relatively low due to the fact that desflurane is hardly used and that 70% of Dutch anaesthesiologists use propofol as their first choice for general anaesthesia.

However, we did observe that nitrous oxide remains a significant source of Scope 1 emissions, despite there being much less need for its clinical use.

Indirect emissions resulting from energy consumption (**Scope 2**) account for 35% of the carbon footprint of an aortic valve replacement in our study, due to HVAC, sterilisation and electronic devices. In our findings into surgical site infections (SSI) in open heart surgery, the use of an energy-efficient TMA airflow system does not lead to more sternal wound infections or mediastinitis compared to the use of a high flow UDAF airflow system.

The LCA on aortic valve replacement shows that, regardless of the method used, more than 50% of the carbon footprint of these procedures is attributable to single-use items (**Scope 3**). Our LCA of packaging methods for surgical instruments shows that replacing blue wrap, a major contributor to OR waste, with rigid reusable containers reduces the carbon footprint of sterilisation packaging by 85%.

The practical tools presented in Part II of this thesis provide data on where and how to reduce the carbon emissions of the OR. The HSMEA presents a structured way to reduce emissions and is easily applicable in practice for a variety of surgical procedures (**Scope 3**). The SCALE auditing tool for OR complexes demonstrates that just six of the eighteen evidence-based interventions implemented together in Dutch ORs account for 95% of the model's calculated carbon footprint reduction potential of 730 kg CO₂-eq/week/OR (Figure 3, Chapter 5) (**Scopes 1,2, and 3**).



Interpretation of main results and mitigating 'R' strategies

Scope 1

Volatile anaesthetics

Volatile anaesthetics are potent GHGs and responsible for 0.004% of all GHG emissions emitted globally each year.⁶ In **Chapter 2** our results show that annual emissions from VAs in the Netherlands with 0.22 kg CO₂-eq/capita are relatively low. The average per capita emissions of VAs in 2023 for all high-income countries was 1.03 kg CO₂-eq/capita, with Japan and South Korea at the top of the list with 2.51 and 2.28 kg CO₂-eq/capita respectively.⁶ Desflurane, with a global warming potential measured over 100 years (GWP₁₀₀) of 2,540 greater than CO₂, accounted for 70% of total global VA emissions.

Our 2019 bottom-up consumption data showed that only 4.1% of the purchased volume of VAs in the Netherlands was desflurane. Worldwide, the use of desflurane is considerably higher, particularly in countries with high incomes.⁶ Awareness among anaesthesiologists of the harmful effects of desflurane has already led to a reduction of GHG impact due to desflurane of 52% over the past 10 years in these high-income countries. However, a trend was observed whereby middle- and low-income countries actually showed an increase in GHG impact due to desflurane in that period.

Internationally, steps have already been taken to phase out desflurane (*Ro, Refuse*), with the EU strictly limiting its use from 2026 onwards. Given its more favourable overall risk-benefit ratio, it is preferable to choose sevoflurane over desflurane if inhalation anaesthesia is opted for.⁷ Simulations have shown that if anaesthetists worldwide had used only sevoflurane as VA, global GHG emissions from VAs would have fallen by 73% over the past decade.⁶

Choosing propofol over VA for general anaesthesia by anaesthesiologists will reduce Scope 1 emissions (*R3, Reduce*). Unlike VA, the intravenous anaesthetic propofol has virtually negligible GHG emissions.^{8,9} Our results of **Chapter 2** show that 70% of anaesthesiologists in the Netherlands prefer the intravenous drug propofol as their first-choice agent for general anaesthesia, which partly explains the relatively low GHG impact of inhalation anaesthetics in the Netherlands compared to other countries.

When using VA, it is not only important to opt for sevoflurane instead of desflurane, but also to use sevoflurane responsibly (*R3, Reduce*) in order to limit its GHG impact. Two important technical developments are available for this purpose: automated low flow target administration (Et Control) and vapour capture technology (VCT). The former ensures economical administration of VA, while the latter allows part of the exhaled sevoflurane to be captured before it is vented into the atmosphere.^{10,11} In **Chapter 7**, we used the SCALE auditing tool to show that VCT, the capture of VA before it enters the atmosphere, is the second most important factor in reducing the carbon footprint of Dutch ORs. Once VAs have been captured, it is technically possible to recover them (*R8, Recycle*) for re-use in humans which is already permitted under the regulations in Canada, Austria and Germany.¹¹ Although the technique undoubtedly has potential, there is currently controversy in the literature about how much of the administered VA can be recovered. Future multi-centre studies will have to demonstrate its value in daily practice.¹¹

We believe that there is no longer any place for desflurane in anaesthetic practice, but that sevoflurane should remain part of the anaesthesiologist's armamentarium, as the intravenous drug propofol is the only other option available for general anaesthesia. In this context, we have to consider that during the COVID-19 pandemic, a shortage of propofol occurred, and it became clear that an alternative was needed. In addition, the administration of VA requires a unique expertise in daily practice that would otherwise be lost to future anaesthesiologists. When sevoflurane is chosen for general anaesthesia, it is mandatory that administration takes place via Et Control administration and that VCT is used to capture sevoflurane, so that the amount released into the atmosphere remains minimal. Manufacturers must equip their ventilators with these modifications as a standard feature.

Nitrous oxide

Although there is a decreasing need for anaesthesiologists to use nitrous oxide (N_2O), its low potency, which means it must be administered in high concentrations, combined with its atmospheric lifetime of 109 years and resulting GWP₁₀₀ of 298, makes it a significant source of medically attributable GHG emissions. Exact figures are not known, but rough estimates suggest that 1-3% of global N_2O emissions originate from healthcare.^{12,13} This would correspond to 0.1% of total global GHG emissions, which is 25 times the above-mentioned figure for VAs.¹⁴ In accordance with these estimates we found in **Chapter 2** that emissions of medical N_2O in the Netherlands were twice as high as those originating from VAs. These figures correspond to countries such as Ireland and Austria, where N_2O accounts for more than 80% of emissions due to inhalation anaesthetics.^{15,16}

Phasing out (*Ro, Refuse*) N_2O from the anaesthesiologist's armamentarium would be an effective measure to reduce the carbon footprint of the OR. For the administration of general anaesthesia, N_2O has traditionally been used in combination with older VAs to reduce their side effects and speed up induction and recovery. However, with the introduction of sevoflurane in the 1990s, this role of N_2O became redundant. Furthermore, a recent study demonstrated that the use of N_2O had no effect on post-operative mortality or most morbidity outcomes.¹⁷ In addition, it has become clear that widespread large-scale losses of N_2O occur due to leaks in centralised systems which can be prevented by using portable cylinders (*R2, Reduce*).¹⁴

Societies for Anaesthesia must make it clear to their members that N_2O is obsolete in modern anaesthesiology practice, and hospitals must ensure that N_2O connections in operating rooms are dismantled to prevent accidental leaks.



Scope 2

Energy consumption in ORs is high due to the stringent requirements for air quality and the extensive use of electronic equipment. A recent systematic review of the carbon footprint of surgical procedures demonstrated that energy consumption (together with anaesthetic gases) was the main source of GHG emissions.¹⁸ However, the environmental impact of Scope 2 emissions is highly dependent on the type of electricity used. Moving away from (*Ro, Refuse*) electricity generated by burning fossil fuels has a major impact on reduction of the carbon footprint of the OR. In **Chapter 7**, we demonstrated that more than 90% of the calculated reduction potential of Dutch hospitals could be achieved if only energy from renewable sources was used.

Air treatment by HVAC systems accounts for 90-99% of energy consumption in operating rooms.¹⁹ However, these systems often consume energy unnecessarily when they are left on after working hours or when they are not in use during the day. Our results in **Chapter 7** show that applying HVAC setback strategies during unoccupied periods is one of the five most effective evidence-based measures for reducing the carbon footprint of the OR. Setback strategies are an accepted method of reducing energy consumption (*R2, Reduce*).²⁰ Research has shown that this energy-saving strategy can reduce energy consumption by up to 70%.^{21,22} Also in **Chapter 7**, we demonstrate that heat recovery (*R3, Reuse*) from the exhaust air of the HVAC is an important evidence-based method for reducing the carbon footprint of the OR. Fresh outside air is drawn in by a HVAC system and then conditioned (temperature, humidity) before being distributed into the OR. After the air has left the OR again, it is expelled either completely or partially to the exterior. The heating energy can at that moment be recovered and used to pretreat the newly incoming fresh air so that less energy is required to achieve the desired OR temperature. In a case study on the suitability of different air distribution strategies the potential energy savings of heat recovery strategy were twice as high as those of a setback strategy.²³

In addition, the energy consumption of HVAC systems is highly dependent on the degree of air cleanliness.^{23,24} In **Chapter 3**, our results show that, for open-heart surgery, ultra-clean air conditions created by unidirectional airflow ventilation (UDAF) does not reduce the incidence of SSI and that consideration should be given to choosing more energy-efficient systems for these operations (*R2, Reduce*). The use of ultra-clean air to prevent SSIs has been a topic of debate in the scientific community for decades. The low incidence and multifactorial causes of SSIs make it difficult to demonstrate a causal link between the two and has resulted in conflicting results. One possible explanation for this is that much of the research has been conducted using large databases (registries)

involving large patient groups, but without controlling for confounding factors that may also influence the risk of SSI. In our study, air cleanliness was the only variable for the risk of SSI. The only other study with the same study design similarly showed that UDAF did not reduce the risk of SSI, in this case in total joint arthroplasty.²⁵

In conclusion, hospitals must decarbonise their electricity supply and prioritise energy efficiency. Societies of medical specialists must ensure, through guidelines, that unnecessarily high standards regarding clean air in ORs are not imposed if there is no scientific evidence to support them. Facilities Management Departments in hospitals must ensure that HVAC systems are energy efficient by implementing measures such as air recirculation, setback strategies, and heat recovery.

Scope 3

Emissions from the supply chain belong to scope 3 and include hidden emissions from upstream activities such as purchasing goods and generating waste (figure 1, Chapter 1). A carbon footprint assessment of the National Healthcare Service (NHS) in England showed that 62% of total healthcare emissions were attributable to the supply chain.²⁶ ORs are known for their use of large quantities of disposable items and the associated waste production resulting in large Scope 3 emissions.¹⁹ Our results from **Chapter 6** show that in 57% and 53% of respectively SAVR and TF-TAVI the carbon footprint was attributable to disposable items. These outcomes are consistent with the findings of a systematic review of surgical procedures, which found that more than 50% of the carbon footprint of operations is due to Scope 3 emissions.¹⁸

Surgical gowns

Our SCALE auditing tool from **Chapter 7** demonstrates that the most significant Scope 3 reduction can be achieved by replacing disposable surgical gowns with reusable ones (*R3, Reuse*). This measure has been shown to lead to a 64% reduction in energy consumption, a 66% reduction in GHG emissions, an 85% reduction in water consumption and an 84% reduction in waste production.²⁷ A performance comparison showed that reusable surgical gowns offered better protection and performance than disposable gowns.²⁸ User experience shows that reusable gowns are perceived as superior in terms of comfort, ventilation and temperature control, functionality and barrier function.²⁹ Despite these clear advantages of reusable surgical gowns, a study into their implementation revealed a number of obstacles. A global survey of perioperative professionals in 134 countries showed that financial constraints were a particular barrier to implementation. In high-income countries, there were in addition



institutional barriers such as resistance to change and changing working methods. In lower and lower-middle income countries, the sterilisation process was a particular barrier due to inadequate or poor sterilisation facilities and/or lack of clean water.³⁰

Disposable sterilisation packaging

Another major contributor to OR waste is the disposable packaging of surgical instrument trays (blue wrap), thus presenting an opportunity to reduce Scope 3 emissions.³¹ In **Chapter 4**, using an in-depth life cycle assessment, we found that replacing blue wrap with a reusable rigid sterilisation container (RSC) reduced the carbon footprint of sterilisation packaging by 85%.

Carbon footprint estimates of steam sterilisation and packaging of reusable surgical instruments by Rizan et al. yielded conflicting results with ours. In that study, the carbon footprint of blue wrap was lower than that of aluminium RSCs.³² There are a number of possible explanations for these differences. First of all, our results are based on 5,000 usage cycles of the RSC, as opposed to 1,000 in Rizan et al. This will result in an increase in the carbon footprint of the RSC, as four additional containers need to be manufactured and destroyed. In addition, a different type of blue wrap was used, for which 40% less polypropylene was modelled than in our study. Instead, paper was used as a second layer, resulting in a lower carbon footprint for blue wrap. The method used to determine the carbon footprint can also influence the results. To this end, we used three different indicators in our study (carbon footprint, ReCiPe and eco-costs), with all three methods a lower environmental impact was demonstrated for RSC.

Scope 3 emissions can thus be reduced by switching from blue wrap to RSC (*R₃, Reuse*). Aluminium containers are ideally suited as a circular solution for packaging surgical instruments. The containers can be manufactured from recycled aluminium and, at the end of their life, can be used as raw material for new containers. The two packaging systems are comparable in terms of patient safety.³³ However, switching to RSC may have financial and practical consequences. Research shows that the total cost of ownership of the two systems is quite similar, but the implementation of RSC requires long-term investments, which can be an obstacle.³⁴ In addition, additional physical space is required for storage of containers and washing machines.

Operating room waste

Operating rooms produce large quantities of waste, mainly because of the extensive use of disposable items. There are two main waste streams in ORs: hazardous and non-hazardous. For the former, only incineration is possible given the regulations for hazardous infectious waste. The non-hazardous waste stream, on the other hand, is

comparable to household waste. This allows for the reutilising (*R8, Recycle*) of packaging materials in particular, while the remainder is either incinerated or landfilled. The HSEMA tool from **Chapter 6** can be used to identify recyclable waste in the OR, create separate waste streams for it and calculate the carbon footprint reduction by doing so. Applying the HSEMA to waste from 18 orthopaedic operations in a Dutch university hospital showed that of the average amount of 7.8 kg of waste, 23% was non-recyclable. The remaining 77% recyclable portion consisted of plastic, paper, cardboard, and aluminium.³⁵

When the non-recyclable surgical waste is incinerated, heat can still be recovered from the burning process (*R9, Recover*). However, destruction of materials is not in line with the principles of a circular economy and should therefore be seen as a last resort. Table 1 provides an overview of all the above-mentioned practical implications.

In order to reduce the large amounts of concealed CO₂ emissions and waste from consumables in the OR, the purchasing department must include the sustainability of products in tenders, in addition to price. Preference should be given to reusable products such as surgical gowns and rigid sterilisation containers instead of disposables. Staff on the work floor must be vigilant about wasting materials, water, and energy, as this is where the greatest gains can be made in terms of reducing GHG emissions. Finally, the infection prevention department must ensure that no unnecessarily strict hygiene requirements are imposed if there is no scientific evidence to support them, this allows for significant savings in personal protective equipment usage.



Table 1. *Overview of practical implications.*

Main objective	Scope	Strategy	Subject	Method
Avoiding waste	1	<i>R₀ Refuse</i>	Desflurane	Use sevoflurane or propofol
	1	<i>R₀ Refuse</i>	N ₂ O	Phase out from anaesthetic practice
	1	<i>R₂ Reduce</i>	VA emission	Prefer propofol or use Et Control + VCT
	1	<i>R₂ Reduce</i>	N ₂ O	Prevent systemic losses
	2	<i>R₀ Refuse</i>	Fossil fuel energy	Use renewably generated energy
	2	<i>R₂ Reduce</i>	HVAC energy demand	Implement setback strategies
Extending product life	2	<i>R₃ Reuse</i>	HVAC heat recovery	Install exhaust air heat exchanger
	3	<i>R₃ Reuse</i>	Surgical gowns	Reusable instead of disposable
	3	<i>R₃ Reuse</i>	Sterilisation Packaging	RSC instead of blue wrap
Recycling waste	1	<i>R₈ Recycle</i>	VA	VCT
	3	<i>R₈ Recycle</i>	Surgical waste	Plastic, paper, cardboard, aluminium
	3	<i>R₉ Recover</i>	Surgical waste	Incineration

N₂O, nitrous oxide; VA, volatile anaesthetic; HVAC, heating ventilation, and air conditioning; RSC, rigid sterilisation container; VCT, vapour capture technology

Strengths & limitations

In our research, we use carbon footprinting as the main method for quantifying environmental impact. An important reason for doing so is that this measure is now widely used for this goal and also because it is familiar to the general public. This method has proven to be very effective in making healthcare more sustainable by: 1) establishing baseline values and monitoring changes; 2) identifying carbon hotspots that offer opportunities for substantial improvements; 3) enabling comparisons between products; and 4) optimising processes.³⁶ However, there is significant heterogeneity in the various methods, which means that caution should be exercised when comparing the absolute outcomes of studies with different methods. In addition, when comparing studies, it is important to consider whether there are any differences in the functional unit, system boundaries and included life cycle stages.³⁷ A recognised limitation of the carbon footprint is that it is a measure of climate change and not of all other forms of environmental impact, such as human and eco-toxicity, acidification, resource depletion, and so on. This carries the risk that the focus on reducing the carbon footprint could shift the problem to other environmental impacts, as the carbon footprint and other impact categories often do not correlate.³⁸

Future perspectives / research

In order to contribute to the global goal of zero GHG emissions by 2050, the healthcare sector must also take its responsibility as indicated by the WHO. In this thesis, we demonstrate that it is possible to significantly reduce GHG emissions from ORs. Both Scope 1 and Scope 2 emissions are largely influenced by hospitals and can therefore be reduced to virtually zero with the right measures. However, Scope 3 emissions are estimated to account for over 71% of the emissions of the entire healthcare sector.³⁹ These are the concealed emissions contained in the products and services as a result of upstream and downstream activities and are therefore difficult to measure and influence by the healthcare sector.⁴⁰ The main sources of Scope 3 emissions in the OR are disposables, equipment and pharmaceuticals. The majority of items used in ORs today are single-use. In this thesis (**Chapter 5**), we demonstrate that in both types of aortic valve replacement, 99% of the materials used are disposable and account for more than 50% of the carbon footprint of the procedure. It is crucial for future research to focus on reducing Scope 3 emissions in healthcare.

The most important way to achieve this is through the transition from a linear to a circular economy. A circular economy aims to preserve the value of products, materials and resources for as long as possible (Figure 2). This not only results in less raw material consumption, but also lower CO₂ emissions because fewer materials and products need to be manufactured, which means less energy consumption for production. In addition, less waste is produced, which also results in a reduction in GHG emissions due to incineration or landfill. Hence, a circular economy and decarbonisation are intrinsically intertwined. We will discuss two areas that have not yet been sufficiently researched: refurbishing single-use devices and the concept of product as a service.

Reprocessing single use devices

One way to reuse single-use devices (SUDs) is through reprocessing. This involves the regulated cleaning, testing, sterilisation and repackaging of SUDs so that they can be reused by hospitals. In Europe reprocessing has been legally authorised since 2021 but is subject to strict (national) regulations to ensure patient safety. Although several medical devices can already be reprocessed, there are many more that cannot, as is the case with many laparoscopic instruments and instruments for robotic surgery. Future research should focus on circular product design for medical applications. Product manufacturers must collaborate with technical researchers and healthcare professionals to design durable products that are easy to disassemble, repair and reprocess, with features such as modularity, adaptability, and versatility.⁴² Examples include laparoscopic instruments, robotic instruments, and endoscopes.



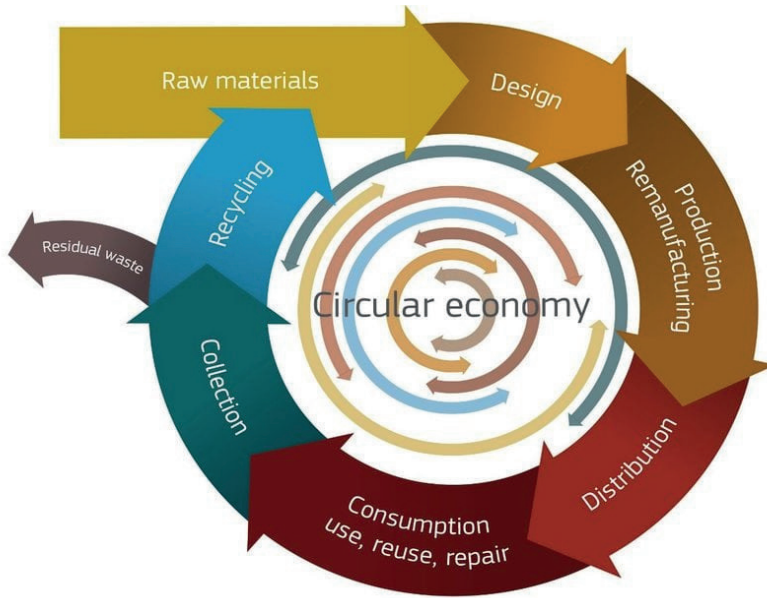


Figure 2. Simple circular economy model.⁴¹

Product as a service

In a linear economy, original equipment manufacturers (OEMs) benefit from high volume consumption, which is why products are designed with characteristics such as: rapid obsolescence, a short lifespan, difficulty in dismantling and poor cleanability.⁴² However, it is sometimes also possible to supply a product as a service, also known as 'servicisation'. An example of this is Philips supplying light as a service rather than light bulbs as a product (Circular Lighting). In this concept, the supplier remains the owner of the product and pays for the electricity, maintenance and end-of-life disposal. As a result, Philips has innovated the lamps so that they have the longest possible lifespan, are energy efficient and have a modular design.⁴³ All characteristics that align with a circular economy. There are also opportunities for servicisation in healthcare, where consumers receive high-quality medical devices that are durable and easy to clean, and where use is facilitated by technical support and product servicing.⁴⁴ This concept provides OEMs with a new revenue model based on usage rather than ownership.⁴³

Future research by technical researchers, healthcare professionals and financial experts, in collaboration with product manufacturers should investigate the possibilities for servicisation in the OR, where many devices could be eligible, such as ventilators, defibrillators, electrocautery devices and operating lights.

Conclusion

To meet the Green Deal 3.0 target of reducing CO₂ emissions in healthcare by 55% by 2030 and ultimately to zero by 2050, the OR has a potential contribution. To achieve considerable reductions in carbon emissions in the short term through quick wins, our results show that significant effective reductions are possible in all three scopes with practical implications based on the 10R strategy. However, given the scale and complexity of Scope 3 emissions, there is still much to be gained to ultimately achieve a zero-emission, circular healthcare economy. Future research should focus on OR circularity, with Reuse, Repair, Refurbish, Remanufacture and Repurpose strategies playing an important role in extending the lifespan of, what are currently mainly disposable, products.

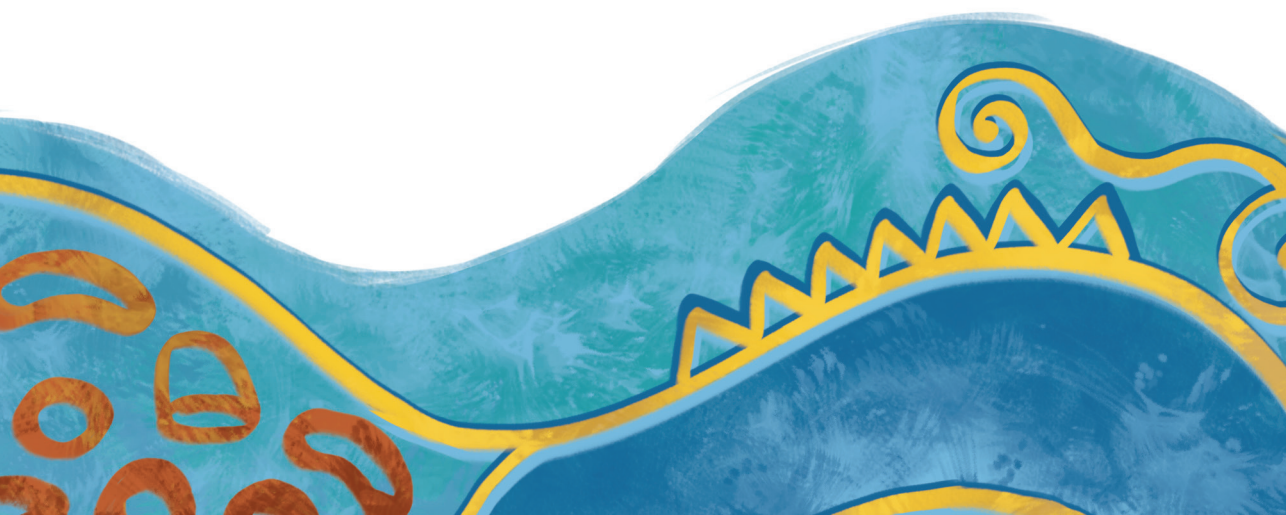
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APPENDICES



Nederlandse samenvatting

Achtergrond

Het tijdperk waarin we momenteel leven, wordt doorgaans het Antropoceen genoemd: het tijdperk dat wordt gekenmerkt door ingrijpende menselijke invloeden, zoals de uitstoot van broeikasgassen, grootschalige ontbossing en de verspreiding van microplastics.¹ Sinds de jaren vijftig is de impact van de mens op het milieu versneld, wat heeft geleid tot een dramatische toename van de hoeveelheid broeikasgassen in de atmosfeer, met als gevolg dat de mondiale temperatuur vandaag de dag bijna 1,5 °C (boven het pre-industriële niveau) is gestegen. Klimaatverandering wordt veroorzaakt door de opwarming van de aarde als gevolg van broeikasgasemissies en heeft grote gevolgen voor het welzijn van de mens. Extreme weersomstandigheden zoals hittegolven, extreme neerslag en extreme droogte hebben onmiskenbare gevolgen voor de menselijke gezondheid en eisen wereldwijd steeds meer levens en brengen de gezondheid van mensen in gevaar. Paradoxaal genoeg draagt de gezondheidszorgsector aanzienlijk bij aan de uitstoot van broeikasgassen zoals CO₂ in de atmosfeer en is daardoor medeverantwoordelijk voor de negatieve effecten van klimaatverandering op de volksgezondheid.

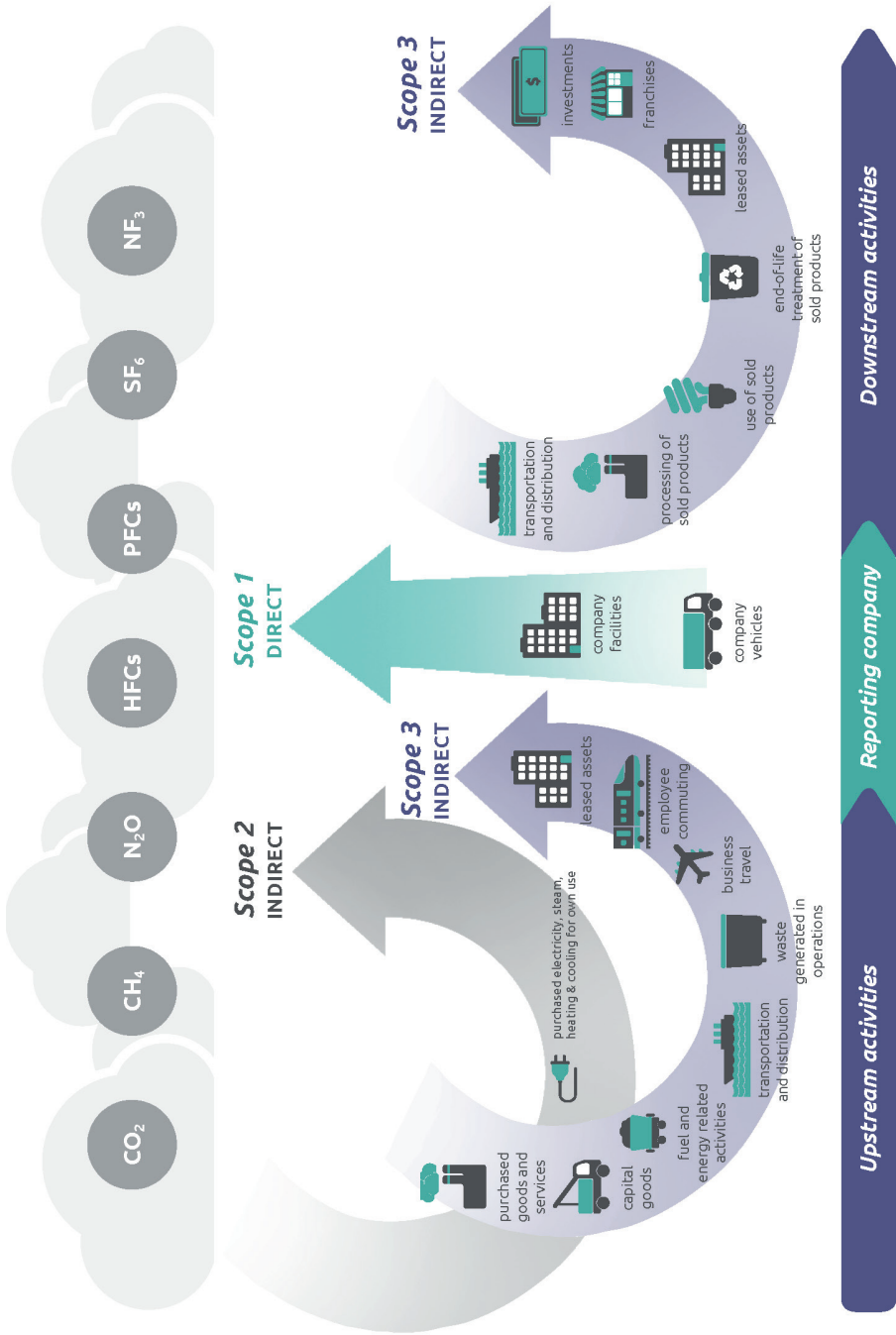
De gezondheidszorg duurzamer maken

De Wereldgezondheidsorganisatie (WHO) heeft aangegeven dat klimaatverandering een van de ernstigste wereldwijde bedreigingen voor de volksgezondheid van de 21e eeuw is en benadrukt dat het koolstofarm maken (de-carboniseren) van gezondheidszorgstelsels wereldwijd essentieel is om zowel de klimaatverandering tegen te gaan als de volksgezondheid te beschermen. Operatiekamers (OK's), die bekend staan om hun hoge energieverbruik, groot verbruik van goederen en aanzienlijke afvalproductie, bieden kansen met een grote impact voor het verminderen van uitstoot van broeikasgassen in de gezondheidszorg. Dit plaatst ze in het hart van strategieën voor het de-carboniseren van ziekenhuizen met maatregelen zoals energie-efficiëntie, vermindering van vervuiling, duurzaam afvalbeheer en efficiënt gebruik van hulpbronnen.

Het meten en berekenen van CO₂-uitstoot (CO₂-voetafdruk)

Om de CO₂-uitstoot van een product, organisatie of activiteit te kwantificeren, kan een CO₂-voetafdruk worden berekend. Een CO₂-voetafdruk wordt gedefinieerd als 'de hoeveelheid directe en indirecte CO₂-uitstoot die door een activiteit wordt veroorzaakt of die tijdens de levenscyclus van een product wordt gegenereerd'.² De berekening kan worden uitgevoerd door middel van een levenscyclusanalyse (LCA). Met deze 'van wieg tot graf'-methode ('cradle-to-grave') wordt de milieu-impact gedurende de gehele levenscyclus van een product berekend, van de winning van grondstoffen tot productie, transport, gebruik en afvalverwerking. De CO₂-voetafdruk wordt uitgedrukt in CO₂-equivalenten (CO₂-eq), een meeteenheid die wordt gebruikt om de klimaateffecten van verschillende





Figuur 1. Overzicht van de scopes van het GHG Protocol.³

broeikasgassen te standaardiseren. Het 'Greenhouse Gas Protocol' is de standaard voor het rapporteren van de CO₂-voetafdruk van bedrijven en organisaties.³ Volgens dit protocol worden broeikasgasemissies ingedeeld in drie scopes: Scope 1 omvat directe emissies van broeikasgassen; Scope 2 omvat indirecte emissies die voortvloeien uit de opwekking van ingekochte elektriciteit of warmte; en Scope 3 omvat alle andere indirecte emissies die voortvloeien uit de productie van goederen, afvalverwerking en het vervoer van personeel en patiënten (Figuur 1).

De CO₂-voetafdruk van de operatiekamer

Scope 1. Directe uitstoot als gevolg van inhalatie-anesthetica

Inhalatie-anesthetica worden al sinds de eerste etherverdoving in 1846 door William Morton gebruikt om algehele anesthesie voor operaties op te wekken. Deze middelen zijn krachtige broeikasgassen die vrijwel niet door het lichaam worden geklaard en na de operatie onveranderd via de uitgeademde lucht in de atmosfeer terechtkomen, waar ze verblijven totdat ze zijn afgebroken. Lachgas blijft bijvoorbeeld 114 jaar in de atmosfeer voordat het wordt afgebroken en is een 298 keer sterker broeikasgas dan CO₂. Het moderne inhalatie-anestheticum desfluraan is zelfs een 2540 keer sterker broeikasgas dan CO₂.

Scope 2. Indirecte emissies als gevolg van de luchtbehandeling

Om besmetting van de wond via de lucht te voorkomen, zijn operatiekamers uitgerust met verwarmings-, ventilatie- en airconditioningsystemen (HVAC). Frequentie en hoogwaardige luchtfiltering vermindert de concentratie van ziekteverwekkers in de lucht afkomstig van de huid en neus-keelholte van de aanwezigen op de OK, waardoor de kans op besmetting van de wond via de lucht wordt verminderd. Vanwege de hoge eisen die aan de luchtkwaliteit in de OK worden gesteld, is 90-99% van het energieverbruik van het OK-complex toe te schrijven aan de luchtbehandeling.⁴

Scope 3. Indirecte emissies als gevolg van de inkoop van goederen en de productie van afval

Voor het uitvoeren van medische handelingen is vaak een breed scala aan verbruiksartikelen nodig. Hieronder vallen persoonlijke beschermingsmiddelen, chirurgische instrumenten, wondverzorgingsproducten, anesthesiebenodigdheden, steriele afdekmaterialen et cetera. Het merendeel van deze chirurgische producten is momenteel bedoeld voor eenmalig gebruik (disposable), vanuit de gedachte dat wegwerpartikelen veiliger, zuiniger en handiger in het gebruik zouden zijn. Dit blijkt veelal niet het geval te zijn, maar voor wegwerpartikelen is wel een aanzienlijke



hoeveelheid grondstoffen nodig. De productie, verpakking, het transport en de afvalverwerking ervan genereren grote hoeveelheden verborgen CO₂-emissies, die zich gedurende de gehele levenscyclus van het product opstapelen. In een onderzoek in drie grote Westerse ziekenhuizen bleek het afval van verschillende operaties gemiddeld 14,5 kg per operatie te bedragen.⁴

Doel en opzet van dit proefschrift

Het doel van dit proefschrift is te onderzoeken hoe de CO₂-voetafdruk van OK's kan worden verminderd om de impact van de gezondheidszorg op het milieu te verminderen, zonder de patiëntveiligheid daarbij in gevaar te brengen. Daartoe zullen we ons richten op die gebieden die een grote impact hebben op de CO₂-voetafdruk van een OK, het zogenaamde 'laaghangend fruit'. Door deze potentiële snelle successen aan te pakken, willen we bijdragen aan de doelstelling van de WHO om tegen 2050 een klimaat neutrale gezondheidszorg te realiseren.

In deel I van dit proefschrift wordt gekeken naar het terugdringen van de belangrijkste factoren binnen Scope 1, 2 en 3 van de OK: het gebruik van inhalatie-anesthetica, het energieverbruik als gevolg van luchtbehandeling en de afvalproductie door veelgebruikt sterilisatieverpakkingsmateriaal voor chirurgische instrumenten. Daarnaast wordt onderzocht of de CO₂-voetafdruk van een hartklepvervanging – een ingrijpende operatie waarbij veel materialen en energie wordt verbruikt – kan worden verminderd.

In deel II van dit proefschrift worden twee instrumenten ontwikkeld om de CO₂-uitstoot te kwantificeren en 'hotspots' te identificeren, zodat de CO₂-uitstoot efficiënt kan worden verminderd. Het eerste instrument werkt op microniveau (specifieke operaties) en het andere op macroniveau (OK-complexen op nationale schaal).

Deel I. Onderzoek naar manieren om de CO₂-uitstoot in de operatiekamer te verminderen

In hoofdstuk 2 brengen we de omvang van de klimaatimpact van inhalatie-anesthetica in Nederland in kaart. Daarnaast inventariseren we de voorkeuren van Nederlandse anesthesiologen voor anesthesietechnieken en onderzoeken we mogelijkheden om de uitstoot van broeikasgassen als gevolg van de anesthesiepraktijk te verminderen. We stellen een relatief lage uitstoot van broeikasgassen als gevolg van inhalatie-anesthetica in de Nederlandse gezondheidszorg vast die kan worden verklaard door het beperkte gebruik van lachgas en desfluraan door Nederlandse anesthesiologen en hun sterke voorkeur voor intraveneus (via de bloedbaan) toegediend propofol als anestheticum.

In hoofdstuk 3 onderzoeken we of het risico op postoperatieve wondinfecties na openhartchirurgie is afgenomen na de overstap van een luchtbehandelingssysteem met luchtstroming o.b.v. turbulente menging (TMA) naar een systeem o.b.v. unidirectionele luchtstroming (UDAF). Van de laatste is bekend dat de lucht in de OK schoner is, maar dat dit gepaard gaat met een energieverbruik dat wel twee maal zo hoog is.^{5,6} Op basis van onze resultaten lijkt er geen aanwijzing te zijn dat UDAF wondinfecties van het borstbeen en/of de weefsels daarachter (mediastinitis) bij openhartchirurgie vermindert. Het gebruik van UDAF bij openhartoperaties moet daarom worden afgewogen tegen de lage kosteneffectiviteit ervan en de negatieve gevolgen voor het milieu als gevolg van het hoge elektriciteitsverbruik. Door gebruik te maken van TMA bij openhartchirurgie kan energieverspilling worden tegengegaan en kan de CO₂-voetafdruk van OK's worden verkleind.

Het veel voorkomende gebruik van wegwerpverpakkingen voor de sterilisatie van chirurgische instrumenten (blue wrap) is een belangrijke bron van plastic afval op een OK. Harde (aluminium) sterilisatiecontainers (RSC's) vormen qua kwaliteit en prijs een goed alternatief dat in veel landen buiten Nederland wordt gebruikt. In hoofdstuk 4 onderzoeken wij het milieuvoordeel van RSC bij grote volumes in grote ziekenhuizen, en voor kleine ziekenhuizen het break-evenpunt waarbij het milieuvoordeel optreedt. We gebruiken een LCA om de twee systemen te vergelijken. De door ons geanalyseerde RSC heeft een 85% lagere CO₂-voetafdruk dan blue wrap, er is al sprake van een milieu-break-evenpunt na 98 van de 5.000 gebruikscycli. Gezien het feit dat deze twee alternatieve verpakkingssystemen vergelijkbare kosten en kwaliteit hebben, blijkt uit onze resultaten dat de CO₂-voetafdruk van OK's significant gereduceerd kan worden wanneer RSC de voorkeur krijgt boven blue wrap als verpakkingssysteem voor steriele chirurgische instrumenten.

Openhartoperaties zijn uitgebreide ingrepen die lang duren en waarbij veel materialen worden gebruikt. Een vervanging van de aortaklep wordt meestal chirurgisch gedaan (SAVR) via het openen van het borstbeen, maar sinds een aantal jaren is het ook mogelijk om dat via de liesvaten te doen (TF-TAVI). Bij ernstige aortaklepvernauwing is gebleken dat TF-TAVI een voordeel oplevert wat betreft sterfte en kosten, en bovendien in meer kwaliteit gecorrigeerde levensjaren resulteert.^{7,8} Voor een afweging tussen de klinische en financiële voordelen enerzijds en de milieu-impact anderzijds is tot nu toe onvoldoende informatie beschikbaar. Het doel van ons onderzoek in hoofdstuk 5 is het uitvoeren van een uitgebreide vergelijkende LCA van deze twee ingrepen. In ons onderzoek heeft TF-TAVI een CO₂-voetafdruk die 38% lager is dan die van SAVR. Bij TF-TAVI wordt 51% minder materiaal, 52% minder energie en 97% minder water gebruikt.



Deel II. Het ontwikkelen van praktische hulpmiddelen om de CO₂-voetafdruk van de operatiekamer te verkleinen

Hoofdstuk 6 beschrijft een nieuwe methode waarmee de milieu-impact van operatiekamers op een systematische manier effectief kan worden verbeterd. Bij deze nieuwe methode, de zogenaamde Healthcare Sustainability Mode and Effect Analysis (HSMEA), inventariseert een multidisciplinair team aan de hand van een gestructureerde, stapsgewijze aanpak systematisch chirurgisch afval, kwantificeert het de milieueffecten ervan, brengt het knelpunten in kaart en biedt het oplossingen voor verbetering. De HSMEA is een praktisch hulpmiddel voor op de werkvloer dat helpt bij het verminderen van de milieu-impact van chirurgisch afval en dat bij alle soorten operaties kan worden toegepast.

In hoofdstuk 7 hebben we de Surgical Carbon Footprint Auditing Tool for Less Emissions (SCALE) ontwikkeld, een op onderzoek gebaseerd model dat wetenschappelijk gepubliceerde LCA's combineert met de dagelijkse chirurgische praktijk om de CO₂-uitstoot in OK's (op landelijk niveau) te kwantificeren en effectieve verbeteringsstrategieën te identificeren. De zes meest impactvolle maatregelen zijn het overstappen van grijze naar groene stroom, de uitfasering van lachgas en desfluraan, het gebruik van dampafvangtechnologie voor inhalatie-anesthetica, geautomatiseerde efficiënte toediening van inhalatie-anesthetica, het overgaan op herbruikbare steriele operatiejassen en warmteterugwinning uit uitlaatlucht van de luchtbehandeling. Tezamen waren deze zes maatregelen goed voor meer dan 95% van de door ons model berekende haalbare CO₂-emissiereductie op OK's.

Strategieën om de CO₂-voetafdruk van de OK te verminderen

In hoofdstuk 8 bespreken we strategieën voor het terugdringen van de CO₂-uitstoot van de OK. Hiervoor hebben we gebruik gemaakt van de R-ladder ('Reduce, Reuse, Recycle'), een model voor de overgang van een lineaire naar een circulaire economie op basis van hiërarchische maatregelen.⁹ Deze R-ladder heeft drie hoofddoelstellingen: afval vermijden, de levensduur van producten verlengen en afval recycleren.

Scope 1. Verminderen van uitstoot van inhalatie-anesthetica

Anesthesiologen moeten voor algehele narcose het middel propofol verkiezen boven inhalatie-anesthetica. Dit narcosemiddel, dat via de bloedbaan wordt toegediend, veroorzaakt vrijwel geen broeikasgasuitstoot.^{10,11} Indien anesthesiologen toch voor inhalatie-anesthesie kiezen, moeten ze de voorkeur geven aan het middel sevofluraan in plaats van desfluraan. Desfluraan heeft een aardopwarmingsvermogen dat 2540 keer

zo hoog is als dat van CO₂ en is verantwoordelijk voor 70% van de totale wereldwijde uitstoot van inhalatie-anesthetica.¹² Internationaal zijn er inmiddels maatregelen genomen om desfluraan uit te faseren; de EU legt vanaf 2026 strenge beperkingen op aan het gebruik ervan. Daarnaast moeten anesthesiologen het inhalatie-anestheticum sevofluraan op verantwoorde wijze gebruiken om de uitstoot van dit broeikasgas te beperken. Hiervoor zijn twee belangrijke technische ontwikkelingen beschikbaar: geautomatiseerde efficiënte toediening en dampafvangtechnologie. De eerste zorgt voor een zuinige toediening van sevofluraan, terwijl de tweede het mogelijk maakt een deel van het uitgeademde sevofluraan op te vangen voordat het in de atmosfeer terechtkomt met zelfs de mogelijkheid tot recycling voor hergebruik.^{13,14} Fabrikanten moeten deze aanpassingen standaard in hun beademingsapparaten inbouwen.

Lachgasgebruik is een belangrijke bron van aan de medische sector toe te schrijven broeikasgasemissies. Het verwijderen van lachgas uit het armamentarium van de anesthesioloog zou een doeltreffende maatregel zijn om de CO₂-uitstoot van de OK te verminderen. Verenigingen voor anesthesiologie moeten hun leden duidelijk maken dat lachgas in de moderne anesthesiologiepraktijk achterhaald is.

Scope 2. Verminderen van CO₂-uitstoot t.g.v. elektriciteitsverbruik

Ziekenhuizen moeten hun elektriciteitsvoorziening decarboniseren (groene stroom inkopen) en prioriteit geven aan energie-efficiëntie. Afdelingen Facilitair Beheer van ziekenhuizen moeten ervoor zorgen dat hun luchtbehandelingssystemen energiezuinig zijn door maatregelen te nemen zoals luchtrecirculatie, warmteterugwinning en het terugregelen van luchtbehandeling tijdens periodes dat de OK niet in gebruik is. Hiervan is aangetoond dat deze energiebesparende strategie het energieverbruik tot wel 70% kan verminderen.^{15,16}

Verenigingen van medisch specialisten moeten er via richtlijnen voor zorgen dat er geen onnodig strenge normen voor de luchtzuiverheid in OK's worden opgelegd als daar geen wetenschappelijk bewijs voor is. Voor veel operaties geldt dat ultra-zuivere luchtomstandigheden die worden gecreëerd door ventilatie met eenrichtingsluchtstroom (UDAF) het aantal gevallen van postoperatieve wondinfecties niet verminderen, en dat er bij deze operaties gekozen moet worden voor energiezuinigere instellingen of systemen zoals TMA.

Scope 3. Verminderen van indirecte CO₂-uitstoot t.g.v. producten en afval

Om de grote hoeveelheden verborgen CO₂-uitstoot en afval van verbruiksartikelen in de OK terug te dringen, moet de inkoopafdeling bij aanbestedingen naast de prijs ook de duurzaamheid van producten meewegen. Er moet de voorkeur worden gegeven



aan herbruikbare producten, zoals bijvoorbeeld steriele operatiejassen en aluminium containers, in plaats van wegwerpartikelen. Het personeel op de werkvloer moet alert zijn op verspilling van materialen, water en energie, aangezien hier de grootste winst te behalen valt wat betreft het terugdringen van de uitstoot van broeikasgassen. Ten slotte moet de afdeling infectiepreventie ervoor zorgen dat er geen onnodig strenge hygiëne-eisen worden opgelegd als er geen wetenschappelijk bewijs is om deze te ondersteunen; dit maakt aanzienlijke besparingen mogelijk in het gebruik van bijvoorbeeld persoonlijke beschermingsmiddelen.

Toekomstperspectieven & onderzoek

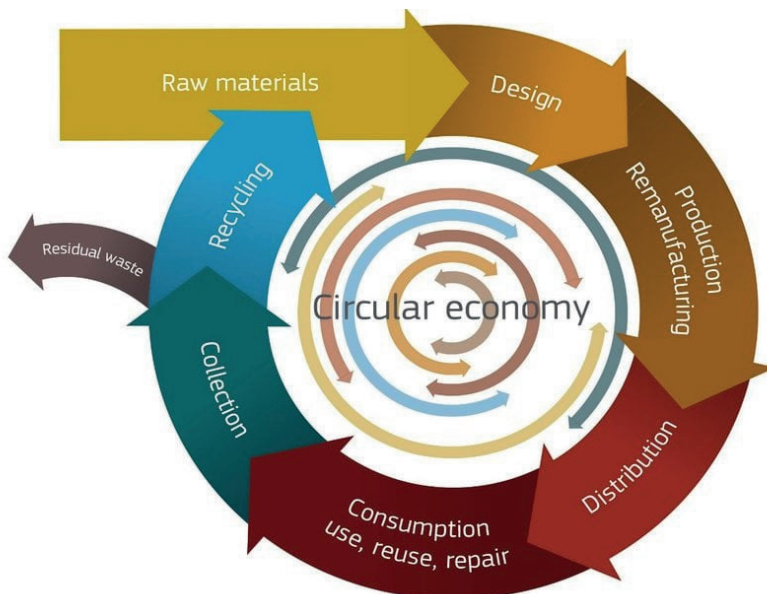
In dit proefschrift tonen we aan dat het mogelijk is de uitstoot van broeikasgassen door OK's aanzienlijk te verminderen. Zowel de Scope 1- als de Scope 2-uitstoot worden grotendeels beïnvloed door ziekenhuizen en kunnen daarom met de juiste maatregelen tot vrijwel nul worden teruggebracht. De Scope 3-uitstoot maakt naar schatting echter meer dan 71% uit van de totale uitstoot van de gezondheidszorgsector.¹⁷ Het is daarom van cruciaal belang dat toekomstig onderzoek zich richt op het terugdringen van Scope 3-emissies in de gezondheidszorg.

De belangrijkste manier om dit te bereiken is door de overgang van een lineaire naar een circulaire economie. Een circulaire economie heeft tot doel de waarde van producten, materialen en hulpbronnen zo lang mogelijk te behouden (Figuur 2). Dit leidt niet alleen tot een lager verbruik van grondstoffen, maar ook tot lagere CO₂-emissies omdat er minder materialen en producten hoeven te worden vervaardigd, wat betekent dat er minder energie wordt verbruikt voor productie en transport. Bovendien wordt er minder afval geproduceerd, wat ook resulteert in een vermindering van de broeikasgasemissies als gevolg van verbranding of vuilstorting.

Toekomstig onderzoek zou zich moeten richten op circulair productontwerp voor medische toepassingen. Productfabrikanten moeten samenwerken met technische onderzoekers en zorgprofessionals om duurzame producten te ontwerpen die eenvoudig te demonteren, te repareren en herbruikbaar zijn en die kenmerken vertonen zoals modulariteit, aanpasbaarheid en veelzijdigheid.¹⁹ Voorbeelden hiervan zijn laparoscopische instrumenten, robotinstrumenten en endoscopen.

Toekomstig onderzoek door technische onderzoekers, zorgprofessionals en financiële experts, in samenwerking met fabrikanten, zou de mogelijkheden voor het concept 'product as a service' in de OK moeten onderzoeken. Een voorbeeld hiervan is dat het

bedrijf Philips licht als dienst aanbiedt in plaats van gloeilampen als product (Circular Lighting). In dit concept blijft de leverancier eigenaar van het product en draagt het de kosten voor de elektriciteit, het onderhoud en de afvalverwerking aan het einde van de levensduur. Daartoe heeft Philips lampen en armaturen zodanig geïnnoveerd dat ze een zo lang mogelijke levensduur hebben, energiezuinig zijn en een modulair ontwerp hebben.²⁰ Dit zijn allemaal kenmerken die passen bij een circulaire economie. Onderzocht moet worden of apparaten op OK's hiervoor in aanmerking zouden kunnen komen, zoals beademingsapparaten, defibrillatoren, elektrocauterisatieapparaten en operatielampen.



Figuur 2. Eenvoudige weergave circulaire economie.¹⁸

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Curriculum Vitae

Herman Jan (Hans) Friedericy was born on 17 March 1963 in Amsterdam, the Netherlands. After finishing secondary school at het Rhedens Lyceum in Rozendaal in 1982, he completed his propaedeutic year in physiotherapy at Jan van Essen in Amsterdam and subsequently began medical school at the University of Amsterdam in 1983. After graduating in 1991, he entered a PhD programme on reflex dynamics through provocation of cardiovascular reflexes at the Department of Physiology at the University of Amsterdam, which he ended prematurely in 1994 to focus on a career in anaesthesiology.

In 1995, he began his training as an anaesthesiologist at Leiden University Medical Centre. After completing his training in 2000, he worked as an anaesthesiologist at St. Lucas Andreas Hospital in Amsterdam, UMC Utrecht in Utrecht, and Horacio Oduber Hospital in Aruba. Since 2009, he has been working as a cardiothoracic anaesthesiologist at LUMC in Leiden, where he started his current PhD programme, 'The Sustainable Operating Room', under the guidance of Prof. dr. Frank Willem Jansen in 2019.



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List of abbreviations

BMI	body mass index
CABG	coronary artery bypass grafting
CDC	Centers for Disease Control
CPB	cardiopulmonary bypass
DALY	disability-adjusted life year
DSWI	deep sternal wound infection
FGF	fresh gas flow
GHG	greenhouse gas
GWP ₁₀₀	global warming potential over 100 years
HFC	hydrofluocarbons
HFMEA	healthcare failure mode and effect analysis
HSMEA	healthcare sustainability mode and effect analysis
HVAC	heating, ventilation, and air conditioning
LCA	life cycle assessment
OR	operating room
RSC	rigid sterilisation container
SAVR	surgical aortic valve replacement
SCALE	surgical carbon footprint auditing tool for less emissions
SOR	sustainable operating room
SSI	surgical site infection
TF-TAVI	transfemoral transcatheter aortic valve implantation
TMA	turbulent mixed airflow
UDAF	unidirectional air flow
VA	volatile anaesthetic
VCT	vapour capture technology

Reference scale for CO₂-equivalent emissions

CO ₂ -eq	Order of magnitude	Approximate real-world equivalent
1 kg	10 ⁰ kg	Driving 5 km by car
100 kg	10 ² kg	One way flight Amsterdam-London
1 tonne (t)	10 ³ kg	One way flight Amsterdam-NYC
1 kilotonne (kt)	10 ⁶ kg	Annual CO ₂ emission from 90 Dutch citizens
1 megatonne (Mt)	10 ⁹ kg	~9% of Tata Steel's annual CO ₂ emissions
1 gigatonne (Gt)	10 ¹² kg	~2% of global CO ₂ emissions

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