



Universiteit
Leiden
The Netherlands

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

Friedericy, H.J.

Citation

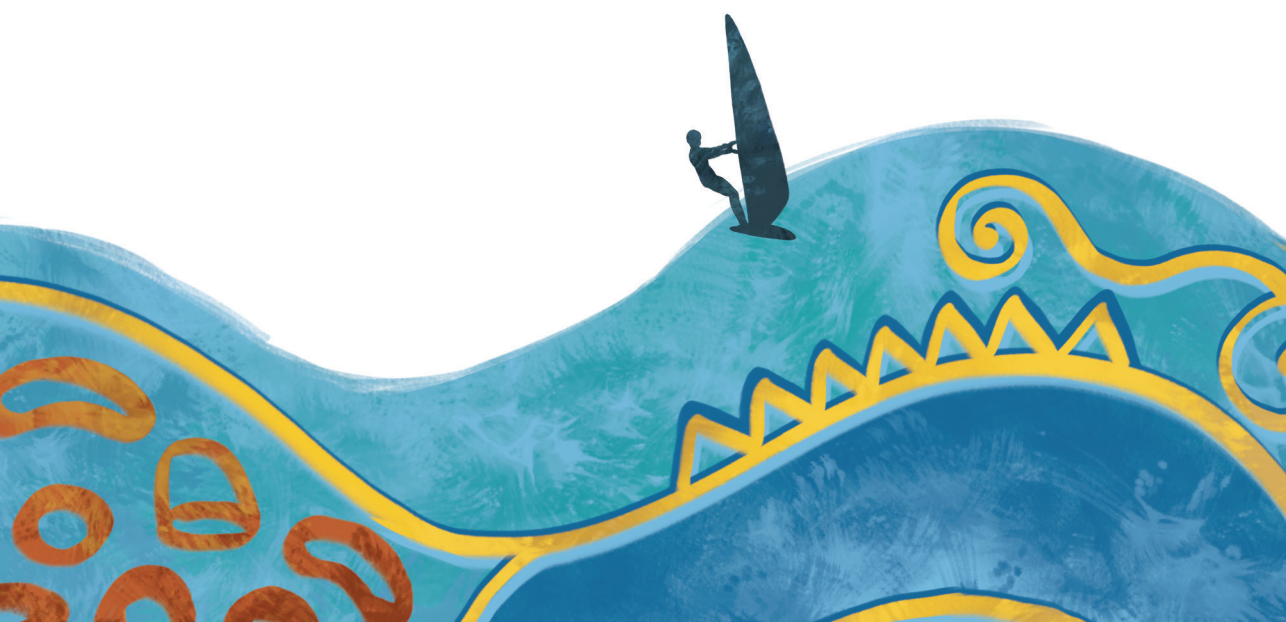
Friedericy, H. J. (2026, September 30). *Carbon footprint reduction of the operating room: tools to mitigate the environmental impact of surgical practice*. Retrieved from <https://hdl.handle.net/1887/4310441>

Version: Publisher's Version

License: [Licence agreement concerning inclusion of doctoral thesis in the Institutional Repository of the University of Leiden](#)

Downloaded from: <https://hdl.handle.net/1887/4310441>

Note: To cite this publication please use the final published version (if applicable).



CHAPTER 5

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

Authors:

Herman J. Friedericy¹, Maëlle J. Lustig², Florine de Haes³, Frank van der Kley⁴, Lauran F.C.M. van Oers⁵, Anne C. van der Eijk^{6,7}, Frank Willem Jansen⁷

Affiliations:

1. Department of Anaesthesiology, Leiden University Medical Centre, Leiden, The Netherlands
2. Faculty of Medicine, Leiden University, Leiden, The Netherlands
3. Centre for Sustainable Healthcare, Amsterdam UMC, Amsterdam, The Netherlands
4. Department of Cardiology, Leiden University Medical Centre, Leiden, The Netherlands
5. Institute of Environmental Sciences (CML), Leiden University, Leiden, The Netherlands
6. Operating Room Department & Central Sterile Supply Department, Leiden University Medical Centre, Leiden, The Netherlands
7. Faculty of Biomedical Engineering, Delft University of Technology, Delft, The Netherlands

Published in:

Heart, 2026



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

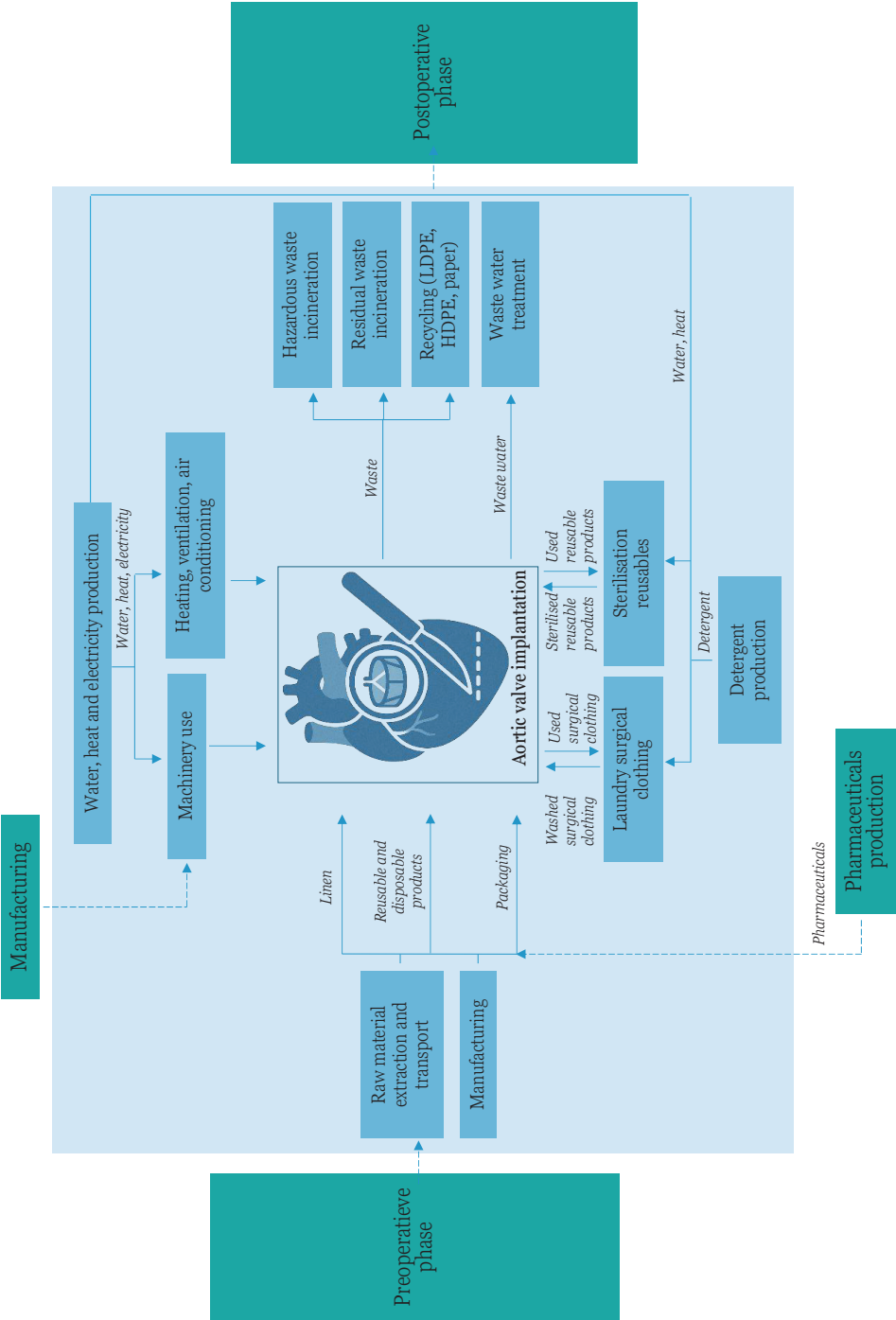
Study design

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.

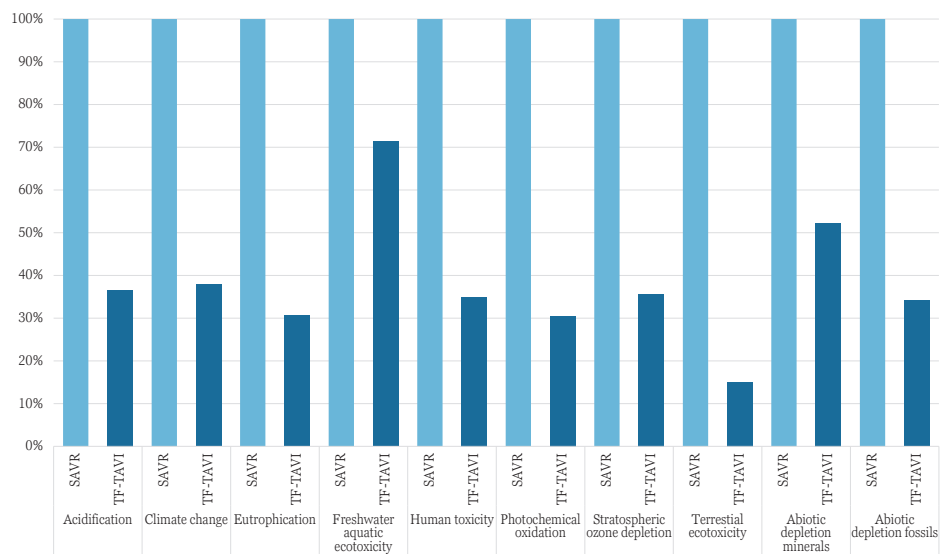


Figure 2. Comparative characterisation results impact categories. Results are normalised to 1 for the largest characterisation result per category.

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

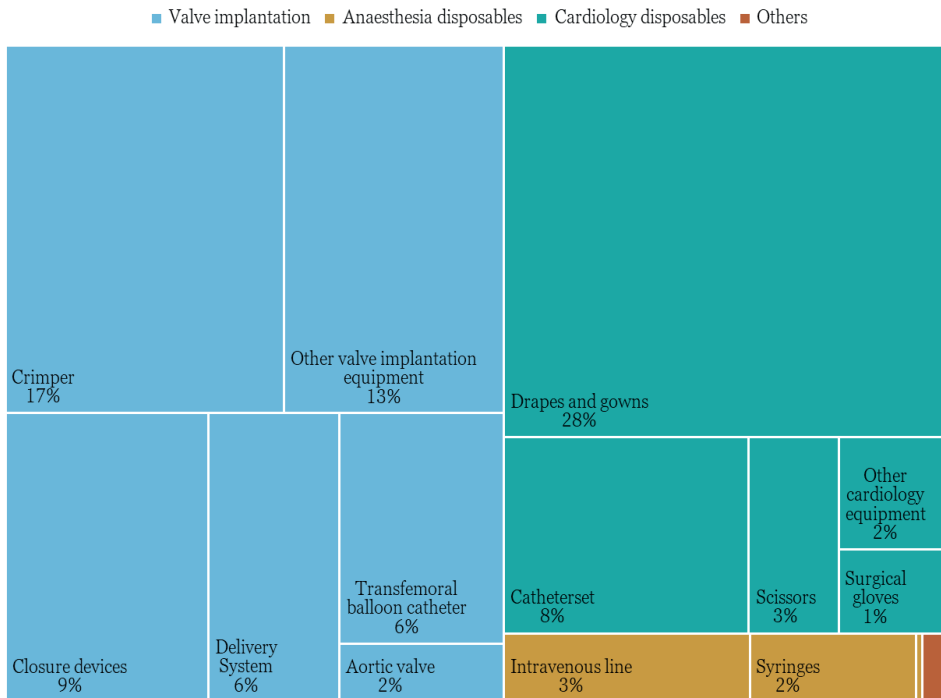


Figure 3. Carbon footprint of disposables used in TF-TAVI. Percentage of 35.5 kg CO₂-eq total.

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.

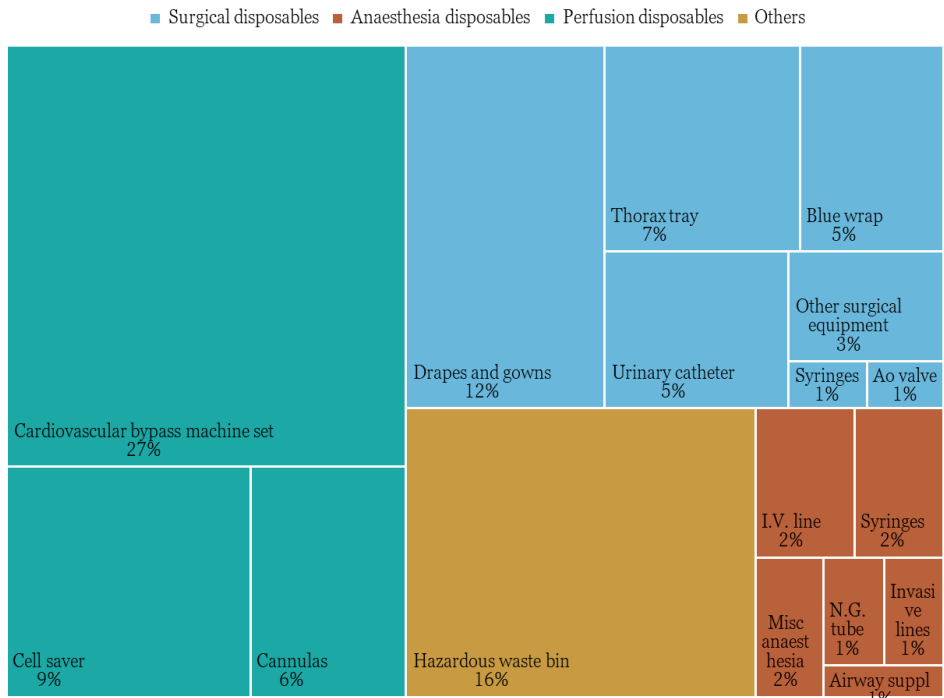


Figure 4. Carbon footprint of disposables used in SAVR. Percentage of 104.0 kg CO₂-eq total.

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 Blitzer 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.

References

1. Keil M, Frehse L, Hagemeister M, et al. Carbon footprint of healthcare systems: a systematic review of evidence and methods. *BMJ Open*. 2024;14(4):e078464.
2. Pichler PP, Jaccard IS, Weisz U, Weisz H. International comparison of health care carbon footprints. *Environ Res Lett*. 2019;14(6):064004.
3. MacNeill AJ, Lillywhite R, Brown CJ. The impact of surgery on global climate: a carbon footprinting study of operating theatres in three health systems. *Lancet Planet Health*. 2017;1(9):e381–e388.
4. Eckelman MJ, Sherman JD. Estimated Global Disease Burden From US Health Care Sector Greenhouse Gas Emissions. *Am J Public Health*. 2018;108(S2):S120–S122.
5. de'Angelis N, Conso C, Bianchi G, et al. Systematic review of carbon footprint of surgical procedures. *J Visc Surg*. 2024;161(2S):7–14.
6. Barratt AL, Li Y, Goorooadoo I, et al. Environmental impact of cardiovascular healthcare. *Open Heart*. 2023;10:e002279.
7. van Bree EM, Stobernack T, Boom T, et al. Assessing the environmental impact of coronary artery bypass grafting to decrease its footprint. *Eur J Cardiothorac Surg*. 2025;67(2):e2af054.
8. Fong KY, Yap JLL, Chan YH, et al. Network Meta-Analysis Comparing Transcatheter, Minimally Invasive, and Conventional Surgical Aortic Valve Replacement. *Am J Cardiol*. 2023;195:45–56.
9. Petrou P. The economics of TAVI: A systematic review. *Int J Cardiol Heart Vasc*. 2023;44:101173.
10. Finkbeiner M, Inaba A, Tan R, Christiansen K, Klüppel H-J. The New International Standards for Life Cycle Assessment: ISO 14040 and ISO 14044. *The International Journal of Life Cycle Assessment*. 2006;11(2):80–85.
11. Ecoinvent. <https://ecoinvent.org/database/>. Accessed 23-06, 2026.
12. CMLCA-Leiden. <https://www.universiteitleiden.nl/en/research/research-output/science/cml-cmlca>. Accessed 23-06, 2026.
13. Leiden A, Cerdas F, Noriega D, Beyerlein J, Herrmann C. Life cycle assessment of a disposable and a reusable surgery instrument set for spinal fusion surgeries. *Resources, Conservation and Recycling*. 2020;156:104704.
14. Parvatker AG, Tunceroglu H, Sherman JD, et al. Cradle-to-Gate Greenhouse Gas Emissions for Twenty Anesthetic Active Pharmaceutical Ingredients Based on Process Scale-Up and Process Design Calculations. *Acs Sustain Chem Eng*. 2019;7(7):6580–6591.
15. Davies JF, McAlister S, Eckelman MJ, et al. Environmental and financial impacts of perioperative paracetamol use: a multicentre international life-cycle assessment. *Br J Anaesth*. 2024;133(6):1439–1448.
16. McAlister S, Ou Y, Neff E, et al. The Environmental footprint of morphine: a life cycle assessment from opium poppy farming to the packaged drug. *BMJ Open*. 2016;6(10):e013302.
17. Hibbs SP, Thomas S, Agarwal N, et al. What is the environmental impact of a blood transfusion? A life cycle assessment of transfusion services across England. *Transfusion*. 2024;64(4):638–645.
18. McGain F, Moore G, Black J. Steam sterilisation's energy and water footprint. *Aust Health Rev*. 2017;41(1):26–32.
19. Blitzer D, Meinrenken CJ, Apelgren NB, et al. Carbon emission analysis of aortic valve replacement: the environmental footprint of transcatheter vs. surgical procedures. *Eur Heart J*. 2025;46(44):4810–4819.



20. Thiel C, Collins A, Vukelich D. The Case for Hospitals to Boost Single-Use Device Reprocessing Programs. *National Academy of Medicine* 2025; <https://nam.edu/perspectives/the-case-for-hospitals-to-boost-single-use-device-reprocessing-programs/>. Accessed 23-06, 2026.
21. Kirchherr J, Reike D, Hekkert M. Conceptualizing the circular economy: An analysis of 114 definitions. *Resour Conserv Recy*. 2017;127:221–232.
22. Schulte A, Maga D, Thonemann N. Combining Life Cycle Assessment and Circularity Assessment to Analyze Environmental Impacts of the Medical Remanufacturing of Electrophysiology Catheters. *Sustainability-Basel*. 2021;13(2):898.
23. Boussuge-Roze J, Boveda S, Mahida S, et al. Current practices and expectations to reduce environmental impact of electrophysiology catheters: results from an EHRA/LIRYC European physician survey. *Europace*. 2022;24(8):1300–1306.
24. McGrath N, Waldron C, Farragher A, Walsh C, Polisen J. Safety, cost and environmental impact of reprocessing high risk single-use medical devices: a systematic review and meta-analysis. *GMS Hyg Infect Control*. 2025;20:Doc25.
25. Ditac G, Cottinet PJ, Quyen Le M, et al. Carbon footprint of atrial fibrillation catheter ablation. *Europace*. 2023;25(2):331–340.
26. Lalman C, Karunathilake H, Ruparathna R. To Dispose or to Reuse? Analyzing the Life Cycle Impacts and Costs of Disposal, Sterilization, and Reuse of Electrophysiological Catheters. *Sustainability-Basel*. 2023;15(6):5363.
27. Vozzola E, Overcash M, Griffing E. An Environmental Analysis of Reusable and Disposable Surgical Gowns. *AORN J*. 2020;111(3):315–325.
28. Friedericy HJ, van Egmond CW, Vogtländer JG, van der Eijk AC, Jansen FW. Reducing the Environmental Impact of Sterilization Packaging for Surgical Instruments in the Operating Room: A Comparative Life Cycle Assessment of Disposable versus Reusable Systems. *Sustainability-Basel*. 2022;14(1):430.
29. Vosschenrich J, Mangold D, Aberle C, et al. Interventional Imaging Systems in Radiology, Cardiology, and Urology: Energy Consumption, Carbon Emissions, and Electricity Costs. *AJR Am J Roentgenol*. 2024;222(6):e2430988.
30. Eussen MMM, Logghe E, Bluminck S, et al. Reducing surgical instrument usage: systematic review of approaches for tray optimization and its advantages on environmental impact, costs and efficiency. *BJS Open*. 2025;9(3):zraf030.
31. van Nieuwenhuizen KE, van Trier T, Friedericy HJ, Jansen FW, Dankelman J, van der Eijk AC. Optimising Surgical Instrument Trays for Sustainability and Patient Safety by Combining Actual Instrument Usage and Expert Recommendations. *Sustainability-Basel*. 2024;16(16):6953.