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

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Citation

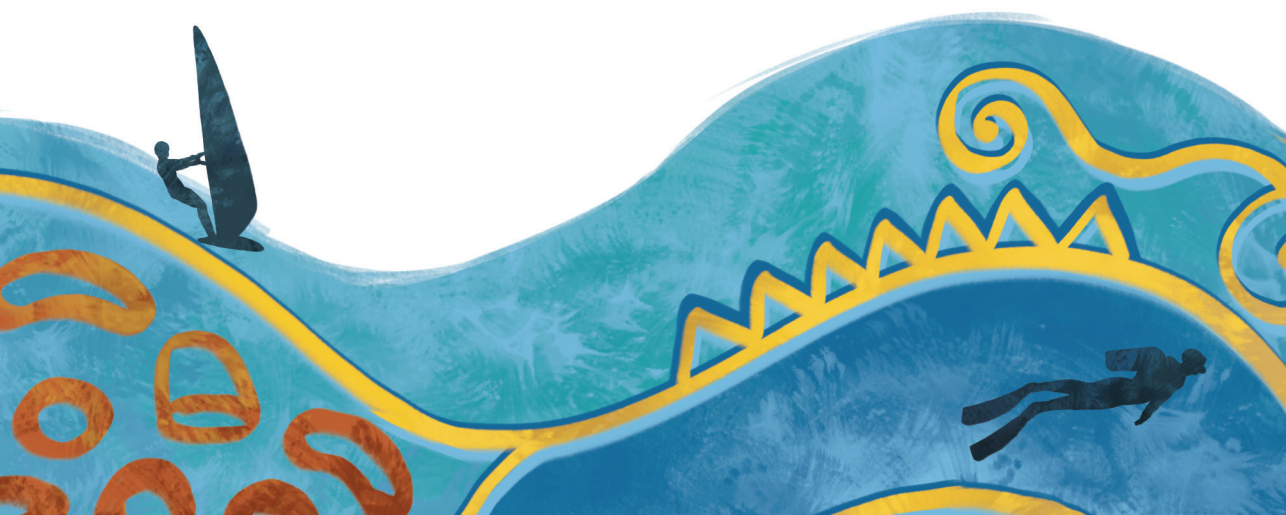
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CHAPTER 3

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

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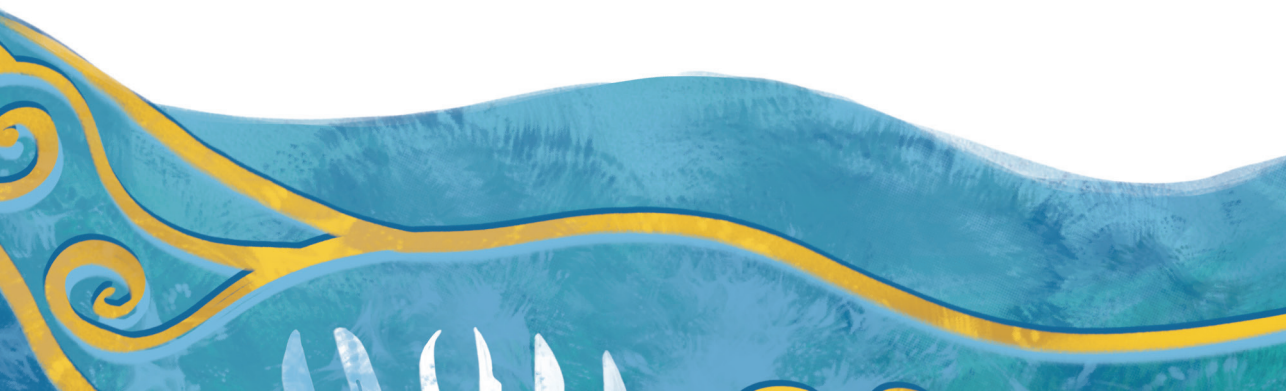
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Abstract

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

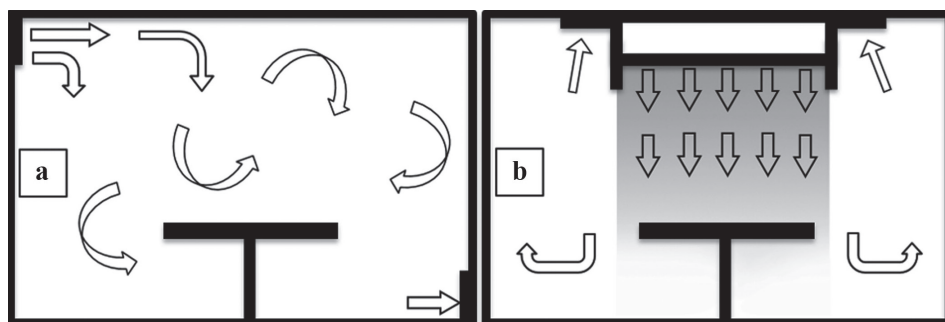


Figure 1. Turbulent Mixed Airflow (a) and Unidirectional Airflow (b).¹¹

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).

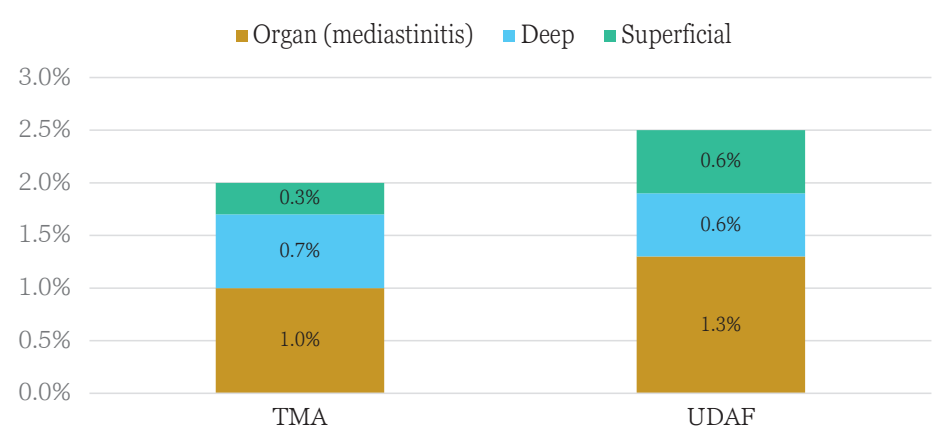


Figure 2. Frequency of SSI distributed by depth Centers for Disease Control (CDC) classification. TMA, turbulent mixed airflow; UDAF, unidirectional airflow.

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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