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Reduction of Airborne Bacterial Burden in the OR by Installation of Unidirectional Displacement Airflow (UDF) Systems

Authors' Contribution:
Study Design A
Data Collection B
Statistical Analysis C
Data Interpretation D
Manuscript Preparation E
Literature Search F
Funds Collection G

ACDEF 1 **Sebastian Fischer**
ADF 2 **Martin Thieves**
ADE 3 **Tobias Hirsch**
DE 1 **Klaus-Dieter Fischer**
ABCD 4 **Helmine Hubert**
ABD 4 **Steffen Bepler**
ACDEF 4 **Hans-Martin Seipp**

1 Department of Hand, Plastic, and Reconstructive Surgery, Burn Center, BG Trauma Center Ludwigshafen, University of Heidelberg, Ludwigshafen, Germany
2 Division of Hospital Hygiene, Darmstadt Clinic, Darmstadt, Germany
3 Department of Plastic and Reconstructive Surgery, Burn Centre, BG University Hospital Bergmannsheil, Ruhr University Bochum, Bochum, Germany
4 Department of Hygiene, University of Applied Science, Giessen-Friedberg, Germany

Corresponding Author: Hans-Martin Seipp, e-mail: Hans-Martin.Seipp@tg.fh-giessen.de

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Background: Intraoperative bacterial contamination is a major risk factor for postoperative wound infections. This study investigated the influence of type of ventilation system on intraoperative airborne bacterial burden before and after installation of unidirectional displacement air flow systems.

Material/Methods: We microbiologically monitored 1286 surgeries performed by a single surgical team that moved from operating rooms (ORs) equipped with turbulent mixing ventilation (TMV, according to standard DIN-1946-4 [1999], ORs 1, 2, and 3) to ORs with unidirectional displacement airflow (UDF, according to standard DIN-1946-4, annex D [2008], ORs 7 and 8). The airborne bacteria were collected intraoperatively with sedimentation plates. After incubation for 48 h, we analyzed the average number of bacteria per h, peak values, and correlation to surgery duration. In addition, we compared the last 138 surgeries in ORs 1-3 with the first 138 surgeries in ORs 7 and 8.

Results: Intraoperative airborne bacterial burden was 5.4 CFU/h, 5.5 CFU/h, and 6.1 CFU/h in ORs 1, 2, and 3, respectively. Peak values of burden were 10.7 CFU/h, 11.1 CFU/h, and 11.0 CFU/h in ORs 1, 2, and 3, respectively). With the UDF system, the intraoperative airborne bacterial burden was reduced to 0.21 CFU/h (OR 7) and 0.35 CFU/h (OR 8) on average ($p<0.01$). Accordingly, peak values decreased to 0.9 CFU/h and 1.0 CFU/h in ORs 7 and 8, respectively ($p<0.01$). Airborne bacterial burden increased linearly with surgery duration in ORs 1–3, but the UDF system in ORs 7 and 8 kept bacterial levels constantly low (<3 CFU/h). A comparison of the last 138 surgeries before with the first 138 surgeries after changing ORs revealed a 94% reduction in average airborne bacterial burden (5 CFU/h *vs.* 0.29 CFU/h, $p<0.01$).

Conclusions: The unidirectional displacement airflow, which fulfills the requirements of standard DIN-1946-4 annex D of 2008, is an effective ventilation system that reduces airborne bacterial burden under real clinical conditions by more than 90%. Although decreased postoperative wound infection incidence was not specifically assessed, it is clear that airborne microbiological burden contributes to surgical infections.

MeSH Keywords: **Environment, Controlled • Operating Rooms • Ventilation**

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Background

Postoperative wound infections are one of the most common complications after surgery. In Germany, 225 000 postoperative wound infections are recorded annually, representing 1.8% of all performed surgeries [1]. Besides a prolonged healing process, extended in-patient hospital stay, and additional surgeries, wound infections can lead to serious complications such as sepsis or even death. Although their origin is not clearly defined, wound infections are most likely due to multiple causes. The systemic distribution of microbial pathogens and intraoperative bacterial contamination are highly suspected to be the main factors causing surgical infections. Whether airborne or attached to skin particles of the OR team, these pathogens directly or indirectly reach the surgical field during surgery [2]. Cecsey et al. showed that a square centimeter of skin carries 2300 microorganisms on average, and that a person loses about 10 000 dead skin scales per day [3]. Although these data were not assessed in an intraoperative setting, they provide a reference value for the expected OR team-related bacterial burden in the surgical field.

Contamination of the surgical field occurs not only directly, but also indirectly, for example, through instruments or gloves. However, indirect contamination depends on air quality as well. Chosky et al. demonstrated that sterilized OR instrument are contaminated to a higher extent depending on the ventilation system [4]. Therefore, a lower bacterial burden in the air of the OR should reduce direct and indirect contamination of the surgical field.

Two types of OR ventilation systems are currently available: turbulent mixing ventilation (TMV) and laminar airflow (LAF). While the former (TMV) reduces bacterial concentration by streaming sterile and filtered inlet air into the surgical field and thereby provokes turbulent mixing with contaminated air, laminar airflow (LAF) follows the opposite principle [5,6] with sterile filtered inlet air flowing with low turbulence from the ceiling, displacing the contaminated air without cross-contamination [7]. In contrast, LAF systems with very low turbulence (<5%) are established for cleanrooms, and a comparable ventilation system is available for ORs – the unidirectional displacement airflow (UDF) systems. Although UDF has higher turbulence (5–20%) compared to LAF, they are still able to achieve an airborne bacterial burden of less than 1 CFU/m^3 under experimental conditions [8,9. However, the extent of pathogen reduction compared to other OR ventilation systems and under real clinical conditions is hard to evaluate. The type of surgery, the number of attending staff, and the individual approach to performing surgery differ significantly among hospitals, making valid comparison of evaluated bacterial numbers difficult.

In our previous study, we demonstrated that bacterial contamination of the surgical field under real clinical conditions is significantly lower with unidirectional displacement airflow (UDF) compared to turbulent mixing ventilation (TMV) systems [10]. However, ORs included in the study were each situated in different hospitals, leading to differences in the OR team as well as their surgical approach and spectrum, and, thus, are factors that can significantly influence intraoperative bacterial contamination.

The purpose of this study was to assess the intraoperative airborne bacterial burden in surgeries performed by a single surgical team that initially utilized ORs ventilated by turbulent mixing ventilation systems and subsequently switched to ORs with ventilation systems according to the principle of unidirectional displacement airflow. As there were no other changes, except of the ventilation system, the effects shown are only based on this technical change. To the best of our knowledge, no study thus far has compared has these 2 ventilation systems in such a controlled setting.

Material and Methods

Theatres

The following ORs were included in this study:

ORs 1–3 were equipped with air canopies with supported nozzles in a special turbulent mixing ventilation (TMV) system, according to DIN-Standard 1946-4 (1999) [11]. Each TMV system was installed 3.1 m above the floor. The supply air volume was 2200 m^3/h in OR 1 and OR 2 and 1600 m^3/h in OR 3. ORs 1–3 had an ambient volume of 103 m^3 each.

After construction of the new surgical wing of the hospital, 2 ORs with new ventilation systems were created (ORs 7 and 8), which functioned according to the principle of unidirectional displacement airflow (DIN-Standard 1946-4, annex D 2008) [9]. The size of the each ceiling was 3.2×3.2 m^2 and supply air volume was 9000m^3/h. In both ORs, flow stabilizers were installed at the ceiling 2.1 m above floor level. OR 7 had an ambient volume of 94 m^3 and OR 8 had an ambient volume of 112 m^3 and both were connected to vestibules. OR equipment, including medical devices, clothes, supplies, and instruments, remained the same after moving into the new ORs.

According to DIN 1946-4, each ventilation system involved in this study was maintained on a regular basis (every 3 years) by means of particle number measurements as well as inspections of tightness of fit and integrity of all filter components to warranty optimal performance, efficacy, and safety, and to facilitate comparison over the entire study period.

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Table 1. Overview of operating room (OR).

System		Turbulent mixing ventilation (TMV)			Unidirectional displacement airflow (UDF)	
Name		OR-1	OR-2	OR-3	OR-7	OR-8
Ceiling size [m²]			–		3.2×3.2	3.2×3.2
Supply air [m³/h]		2.200	2.200	1.600	9.000	9.000
Ambient volume [m³]		103	103	103	94	112
Number of surgeries		243	465	440	62	76
IC-time	Mean value [min]	77	102	92	114	88
	Standard deviation	68	81	73	80	68
	Variation coefficient	88%	79%	80%	70%	78%

TMV – turbulent mixing ventilation; UDF – unidirectional displacement airflow; IC-time – incision-to-closure time.

Sedimentation

Sterile sedimentation plates (ICR plates, item number: 03075e Heipha Dr. Müller GmbH Co., Eppelheim, Germany) were exposed on the instrument table. Scrub nurses positioned and opened the plates in the sterile area. Plates were opened at the beginning of surgical incision and were closed at the end of suturing (sedimentation period = incision-to-closure time [IC time]) in accordance with the objectives of the standards DIN-1946-4 [9] and ISO-14698-1 [12]. The cover plates were affixed with tape and labeled immediately after surgery. Accompanying data sheets included the documentation of patient information, duration of surgery (IC time), surgical procedures, and plate numbers.

For 48 h, ICR plates were incubated at a temperature of 37°C (Incubator type B12, Heraeus Holding GmbH Co., Hanau, Germany). The colonies grown were then counted numerically as colony-forming units (CFUs).

Statistics

The primary result parameter of the CFUs was matched to the analyzed ORs. The calculation of mean value, median, variation coefficient, and standard deviation was completed. The determination of the trimmed mean value (percentile range 85–95%) was used to eliminate outliers. IC time was harmonized to 60 min and the bacterial count was calculated (CFU/h) in accordance with the objective of the standard DIN-1946 (annex F) to compare the airborne bacterial burden (in CFUs) between the various ORs. The t test was used for pairwise comparison of harmonized CFUs.

Three groups were created, based on different IC times and for comparison of the intraoperative bacterial transmission of the 5 ORs with their respective ventilation systems: short (<35 min), middle (36–75 min), and long (>75 min) IC time. Variance comparison was verified by Levene test (F-test). Mean value discrepancies were then tested for statistical significance by t test; $p<0.05$ was defined as significant and $p<0.005$ as highly significant.

To increase comparability of the situation before and after switching ORs, the last 138 surgeries in ORs 1–3 were compared to the first 138 surgeries in ORs 7 and 8. Thereby, the airborne bacterial burden in each OR and each surgery was calculated and correlated to the IC time.

Results

For the comparison of both ventilation systems, we performed measurements in 5 ORs over a period of 6 years in the same hospital. A total of 1286 surgeries were performed and a corresponding number of sedimentation plates were used (1 plate for each surgery). The mean value of IC time was 94.6 min and varied between 77 min (OR 1) and 114 min (OR 7) (Table 1).

Bacterial contamination

Turbulent mixing ventilation (TMV)

In ORs 1, 2, and 3, we analyzed 243, 465, and 440 surgeries, respectively. IC time ranged from 77 min (OR 1) to 102 min (OR 2) on average. Mean bacterial burdens were 6.5, 8.1, and 7.5 CFU in ORs 1, 2, and 3, respectively, and reached a maximum of 121 CFU (OR 2). Trimmed mean values were 16.6, 18.5, and 17.1 CFU in ORs 1, 2, and 3, respectively. Detailed results are given in Table 2. Comparing ORs 1–3 with each other, no statistically significant differences in airborne bacterial burden or harmonized bacterial burden were detectable ($p>0.05$).

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Table 2. System comparison of ventilation systems.

system		Turbulent mixing ventilation (TMV)			Unidirectional displacement airflow (UDF)	
Name		OR-1	OR-2	OR-3	OR-7	OR-8
Mean IC-time [min]		77	102	92	114	88
CFU	Mean value	6.5	8.1	7.5	0.3	0.4
	Standard deviation	7.0	9.3	7.8	0.6	0.6
	Median	4	5	5	0	0
	Minimum	0	0	0	0	0
	Maximum	36	121	58	2	2
	Trimmed SD (0.85–0.95)	16.6	18.5	17.1	1.0	1.0
CFU/h	Mean value	5.4	5.5	6.1	0.2	0.4
	Standard deviation	4.3	6.3	9.2	0.4	0.9
	Median	4	4	4	0	0
	Minimum	0	0	0	0	0
	Maximum	23	101	96	1.7	6.7
	Trimmed SD (0.85–0.95)	10.7	11.1	11.0	0.9	1.0

TMV – turbulent mixing ventilation; UDF – unidirectional displacement airflow; IC-time – incision-to-closure time; CFU – colony-forming units.

Unidirectional displacement airflow (UDF)

In OR 7, 62 surgeries were performed, with a mean IC time of 114 min. In OR 8, the 76 surgeries performed had an average IC time of 88 min. Therefore, mean airborne bacterial burdens were 0.3 and 0.4 CFU for OR 7 and 8, respectively, reaching a maximum of 2 CFU in both ORs 7 and 8. Trimmed mean value was 1 CFU for both ORs 7 and 8. Detailed results are shown in Table 2. In contrast, both OR 7 and OR 8 had no statistically significant differences in airborne bacterial burden or harmonized bacterial burden ($p>0.05$).

Comparison of ventilation systems

IC time was harmonized to 60 min and a calculation of the corresponding bacterial count was performed to compare the 2 different ventilation systems. For turbulent mixing ventilation (TMV), bacterial burdens harmonized to 1 h were 5.4, 5.5, and 6.1 CFU/h for ORs 1, 2, and 3, respectively, and reached maxima of 23, 101, and 96 CFU/h, respectively. Trimmed mean values of harmonized airborne bacterial burden were 10.7, 11.1, and 11 CFU/h for ORs 1, 2, and 3, respectively. In contrast, airborne bacterial burden of ORs with unidirectional displacement airflow (UDF) varied from 0.2 CFU/h in OR 7 to 0.4 CFU/h in OR 8, and reached a maximum of 6.7 CFU/h in OR 8. Trimmed mean values of harmonized airborne bacterial burden were 0.9 and 1 CFU/h in ORs 7 and 8, respectively. Detailed results are presented in Table 2. Each OR with turbulent mixing ventilation (ORs 1–3) demonstrated a statistically significant ($p<0.005$) higher bacterial burden per hour compared to both ORs with unidirectional displacement airflow (ORs 7 and 8, Figure 1).

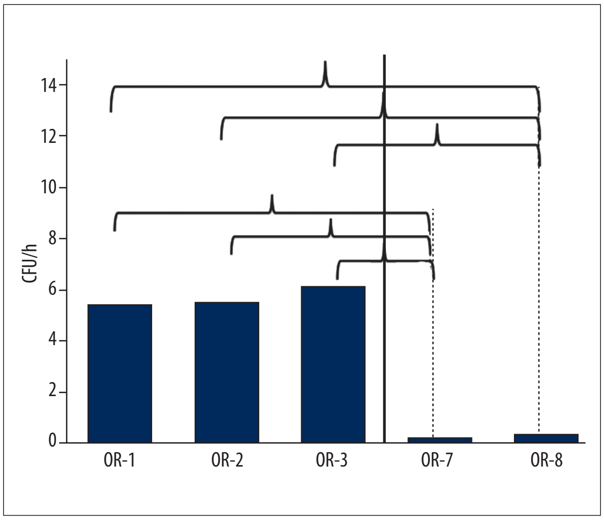

Figure 1. Comparison of bacterial burden in ORs 1–3 (turbulent mixing ventilation) with ORs 7 and 8 (unidirectional displacement airflow). Brackets indicate statistical significance ($p<0.05$).

Table 3. Comparison of the last 138 surgeries in ORs 1–3 with the first 138 surgeries in OR 7 and 8.

system		Turbulent mixing ventilation (TMV)	Unidirectional displacement airflow (UDF)
Name		OR1–3	OR7+8
Number of surgeries		138	138
IC-time	Mean [min]	89	100
	Standard deviation	74	75
CFU	Mean value	6.1	0.4
	Standard deviation	5.7	0.6
	Median	4.3	0
	Minimum	0	0
	Maximum	26.3	2
	Trimmed SD (0.85–0.95)	13.6	1
CFU/h	Mean value	5	0.3
	Standard deviation	5.3	0.7
	Median	3.8	0
	Minimum	0	0
	Maximum	31.9	6.7
	Trimmed SD (0.85–0.95)	10.8	1

TMV – turbulent mixing ventilation; UDF – unidirectional displacement airflow; IC-time – incision-to-closure time; CFU – colony-forming units; SD – standard deviation.

Importantly, the large differences in maximum values of airborne bacterial burden per h within the same study group were based on outliers.

To increase reliability of comparing the 2 ventilation systems, the last 138 surgeries of ORs 1-3 (group A) were compared to the first 138 surgeries of ORs 7 and 8 (group B). Thereby, mean IC times were 89 min and 100 min for groups A and B, respectively. Mean airborne bacterial burden in group A was 6.1 CFU, ranging from 0 to 26.3 CFU and a trimmed value of 13.6 CFU. For group B, mean airborne bacterial burden was 0.35, with a minimum of 0 CFU and a maximum of 2 CFU, and a trimmed value of 1. Mean bacterial burden harmonized to 1 h was 5 CFU/h and 0.29 CFU/h for groups A and B, respectively. Detailed results are presented in Table 3. Comparing the 2 groups, group A had a significantly higher ($p<0.005$) airborne bacterial burden than group B (Figure 2).

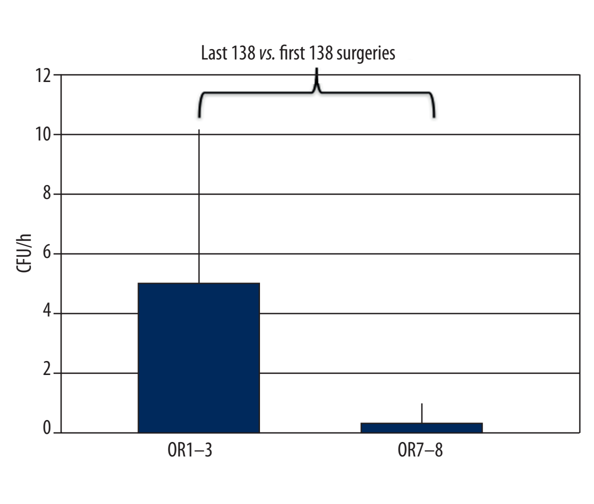

Figure 2. Comparison of bacterial transmission of the last 138 surgeries in ORs 1–3 with the first 138 surgeries in ORs 7 and 8. Brackets indicate statistical significance ($p<0.05$).

Impact of surgical procedure duration (IC) on bacterial burden

The gathered data were analyzed. Surgical procedure duration (IC time) was divided into 3 groups: short (<35 min), middle (35–75 min), and long (>75 min) surgical procedures (Table 4). These groups were compared with the data collected. In relation to increased IC time, the bacterial burden constantly rose in ORs with turbulent mixing ventilation (ORs 1–3), whereas bacterial burden in ORs with unidirectional displacement airflow (ORs 7 and 8) remained low over the study period (Figures 3, 4).

Table 4. System comparison with respect to surgery durations.

System		Turbulent mixing ventilation (TMV)			Unidirectional displacement airflow (UDF)	
Name		OR-1	OR-2	OR-3	OR-7	OR-8
Short IC-time (<35 min.)	Number of surgeries	61	73	88	7	13
	Mean value IC-time [min]	26	26	25	21	21
	Standard deviation IC-time	6	7	8	8	8
	Mean value CFU	2.5	2.8	3.5	0	0.3
	Standard deviation CFU	1.9	2.2	5	0	0.6
Middle IC-time (36 to 75 min.)	Number of surgeries	115	160	149	17	26
	Mean value IC-time [min]	56	56	55	54	52
	Standard deviation IC-time	11	12	12	9	11
	Mean value CFU	4.9	5.7	4.7	0.4	0.3
	Standard deviation CFU	4.4	10	3.9	0.6	0.5
Long IC-time (>75 min.)	Number of surgeries	66	220	191	38	37
	Mean value IC-time [min]	143	162	151	159	137
	Standard deviation IC-time	80	79	73	71	68
	Mean value CFU	12.9	11.8	11.8	0.4	0.4
	Standard deviation CFU	9	8.9	9.2	0.6	0.6

TMV – turbulent mixing ventilation; UDF – unidirectional displacement airflow; IC-time – incision-to-closure time; CFU – colony-forming units.

Discussion

It is obvious that bacterial contamination of surgical wounds should be avoided as much as possible. As postulated by Soots et al. 30 years ago, 98% of bacteria found in wound infections originated directly or indirectly from airborne contamination [13]. In this context, Fitzgerald and Washington reported that the degree of airborne contamination depends on the number of persons and the physical activity of the OR team [14]. Strong physical activity during surgery leads to liberation of about 10 000 particles per min and 10% of these bacteria persist in the air longer than half an hour. According to Salvigni et al., presence of humans in the OR is without dispute the biggest source of contamination [15]. Reducing the number of medical personnel in the OR is difficult, so optimization of ventilation systems is the best option to reduce bacterial contamination in the OR. In our latest study we also used sedimentation plates according to national and internationals standards [9,12] and demonstrated that unidirectional displacement airflow (UDF) significantly reduces bacterial burden in the OR compared to other ventilation systems [10]. Besides having the lowest bacterial counts per h, the UDF system was

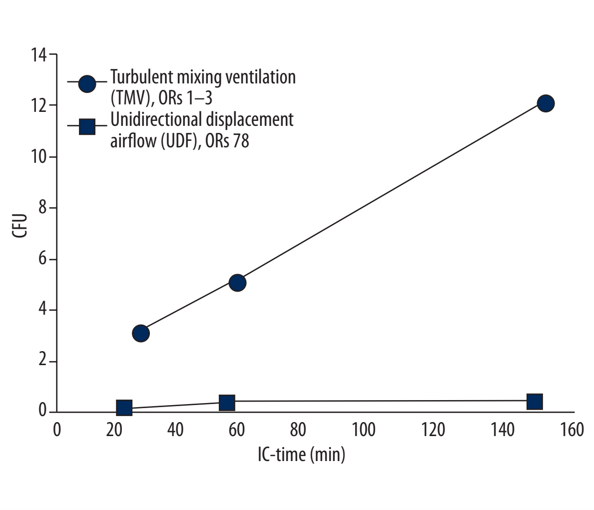

Figure 3. Comparison of turbulent mixing airflow systems (mean values of ORs 1–3) with unidirectional displacement airflow systems (mean values of ORs 7 and 8) in correlation to surgery durations. IC-time – incision-to-closure time, CFU – colony-forming units.

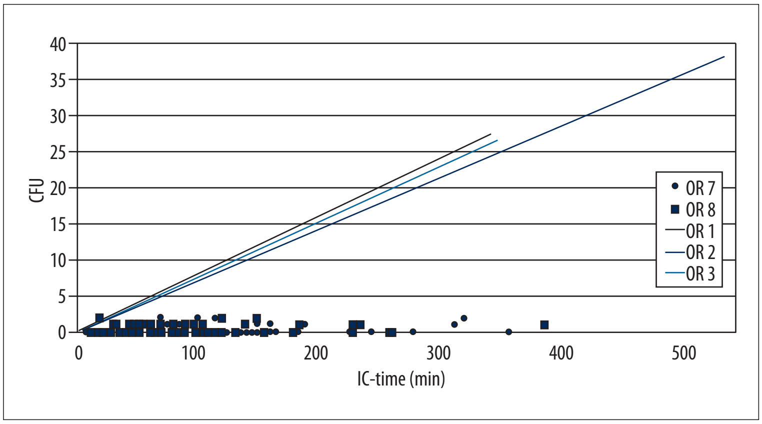

Figure 4. Comparison of turbulent mixing airflow in ORs 1–3 with unidirectional displacement airflow in ORs 7 and 8, both in correlation to surgery durations. IC-time – incision-to-closure time, CFU – colony-forming units.

able to constantly maintain airborne bacterial burden independent of surgery duration. Furthermore, in agreement with the results of Thomas and Meierhans, we found the highest airborne bacterial burden in ORs equipped with a window-based ventilation system without filters or prevention of turbulence [16]. Although our results showed the superiority of UDF, some limitations were seen retrospectively. Because investigations were simultaneously performed in different ORs and, especially, with different OR teams, reduction of bacterial burden cannot be attributed solely to the ventilation system.

The aim of the present study was to determine the impact of ventilation system type on bacterial burden by comparison under similar conditions. Therefore, we performed investigations in the same institution involving the same OR team before and after switching from ORs with turbulent mixing ventilation (TMV) to ORs with unidirectional displacement airflow ventilation systems (UDF). Thereby, the surgical spectrum and procedures remained identical and reduction of airborne contamination was solely attributed to the ventilation system.

The main principle of UDF is to replace contaminated air by discharging sterile filtered air coming from the ceiling into the protection zone (PZ) [7]. The PZ is defined as the area beneath the ceiling in which the surgical procedure is performed, including personnel and instrument table. Discharge occurs with low velocity to avoid turbulence and to replace the potentially contaminated air without mixture and without cross-contamination. The latter is the main difference from turbulent mixing ventilation systems (TMV), which have been the criterion standard in ORs for several decades. Directly streaming sterile filtered air via outlets into the surgical field (with different types depending on the manufacturer, e.g., iron pipes) is the only way to reduce bacterial burden by TMV [6]. A reduction of bacterial burden is thus required by mixing sterile filtered air with contaminated air. To provide the maximum mixture, TMV systems create turbulences by streaming with high velocity out of the supply air. High turbulences, however, make the bacteria become airborne and induce drafts that are uncomfortable for the OR team [17]. The dependence of TMV systems on the room volume is also disadvantageous because inflow of sterile filtered air aims to reduce of bacterial burden, not to replace contaminated air [18].

To confirm compliance with the current standard for TMV systems, a 99% reduction in airborne bacterial burden in ORs must be achieved within 25 min (recovery time). In contrast, the same reduction is obtained by UDF systems in less than 8 s by a flow velocity of 25 cm/s out of the ceiling [19].

We demonstrated that UDF significantly reduces airborne bacterial contamination of the surgical site in comparison to TMV (0.29 *vs.* 4.98 CFU/h). Whereas TMV leads to linear increase over time, UDF was able to maintain airborne bacterial burden at constantly low levels. Considering the conditions of measurement (identical surgical spectrum, equipment, and staff), this effect results mainly from the installation of the UDF ventilation system.

Limitations of this study include lack of specification regarding bacterial pathogenicity and relevance for the clinical outcome after surgery. The significant reduction of bacterial contamination might be clinically irrelevant because obvious wound infections probably do not depend on bacterial counts in the surgical field, but rather on concomitant diseases or the general condition of the patient. OR wound infections only occur at a certain threshold of bacterial counts in the surgical field, which is not achieved by TMV or UDF ventilation systems. Therefore, further studies are necessary to evaluate the effect of ventilation systems on postoperative wound infections. Investigations in the literature have not accounted for co-morbidities, limiting the usefulness of results.

Nevertheless, the results of the present study clearly show the significant impact of ventilation systems on airborne bacterial burden during surgery.

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Conclusions

The unidirectional displacement airflow, which fulfills the requirements of standard DIN-1946-4 annex D of 2008, is an effective ventilation system that reduces the airborne bacterial burden under real clinical conditions by more than 90%. Although we did not specifically assess the incidence of postoperative wound infections, it is clear that microbiological contamination causes these infections.

Conflict of interest

The authors state no conflict of interest.

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