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What is the effect of reducing the air change rate on the ventilation effectiveness in ultra-clean operating rooms?

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SUMMARY

Background: The operating room (OR) department is one of the most energy-intensive departments of a hospital. The majority of ORs in the Netherlands have an air-handling installation with an ultra-clean ventilation system. However, not all surgeries require an ultra-clean OR.

Aim: To determine the effect of reducing the air change rate on the ventilation effectiveness in ultra-clean ORs.

Methods: Lower air volume ventilation effectiveness (VE_{Lv}) of conventional ventilation (CV), controlled dilution ventilation (cDV), temperature-controlled airflow (TcAF) and unidirectional airflow (UDAF) systems were evaluated within a 4 × 4 m measuring grid of 1 × 1 m. The VE_{Lv} was defined as the recovery degree (RD), cleanliness recovery rate (CRR) and air change effectiveness (ACE).

Findings: The CV, cDV_{Lv} and $TcAF_{Lv}$ ventilation systems showed a comparable mixing character in all areas (A, B and AB) when reducing the air change rate to 20/h. Ventilation effectiveness decreased when the air change rate was reduced, with the exception of the ACE. At all points for the UDAF-2_{Lv} and at the centre point (C3) of the $TcAF_{Lv}$, higher RD_{10Lv} and CRR_{Lv} were measured when compared with the other examined ventilation systems.

Conclusions: The ventilation effectiveness decreased when an ultra-clean OR with an ultra-clean ventilation air-supply system was switched to an air change rate of 20/h. Reducing the air change rate in the OR from an ultra-clean OR to a generic OR will reduce the recovery degree (RD_{10}) by a factor of 10–100 and the local air change rate (CRR) by between 42% and 81%.

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Introduction

Energy consumption in healthcare is high. Worldwide, hospitals account for about 6% of total building energy consumption [1]. An operating room (OR) department is three to six times more energy-intensive than all other hospital departments combined. Heating, ventilation and air conditioning (HVAC) energy requirements account for 90–99% of the total energy consumption of the OR [2]. The main objectives of an air-handling system in the OR and an ultra-clean air-supply ventilation (UCV) system are to create a safe and comfortable working environment for surgical staff by controlling the temperature and, in some cases, the relative humidity, diluting the concentration of harmful substances and minimizing the incidence of surgical site infections [3].

The Dutch Federation of Medical Specialists (FMS) [4] introduced a new guideline for air handling in operating and treatment rooms. The guideline recommends that major orthopaedic implant surgeries, primary and revision prostheses and major spinal surgery (e.g., scoliosis), should be performed in an OR class1+ [4]. The indoor air quality of an OR class 1+ should comply with the internationally accepted definition of ultra-clean air, which is defined as air which contains less than 10 colony forming units per cubic meter of air (cfu/m^3) [5–9]. This is in line, for infection prone surgery, with international standards and guidelines [10–13] as well as with the recommendation of the Dutch Orthopedic Association (NOV) [14]. In an ultra-clean OR with the highest classification, a UCV system should be installed, according to the standards and guidelines [4,10–13], which results in a higher air change rate to achieve the required number of $\leq$10 cfu/m^3 in the ultra-clean or protected [11] area. In the Netherlands, the average air change rate per hour (ACH) of ultra-clean ORs with a UCV system is 69 [15]. Practically all ORs in Dutch hospitals are designed and equipped as an ultra-clean OR (FMS OR class 1+ [4]). However, not all ORs in an OR department are used for major (orthopaedic) implant surgeries or large joint procedures. One of the possibilities to reduce energy consumption of an HVAC system for ORs is to reduce the number of air changes (air volume) [16,17] of the OR air-handling installation and air-supply system when the type of surgery does not require an ultra-clean OR.

International standards and guidelines [4,10–13] recommend for generic surgeries or other than the major orthopaedic implant and spinal surgeries [4], an air change rate of $\geq$20 which is in line with the WHO [18] and other international standards and guidelines [4,10,12]. In an ultra-clean OR, the number of air changes per hour or the required outside air (ODA) volume varies in different international standards and guidelines.

The goal of this study was to provide insight into what the effect is on ventilation effectiveness (VE) [19] when the air change rate in ultra-clean ORs is reduced to approximately 20/h. We assessed the VE of a conventional ventilation (CV), a controlled dilution ventilation (cDV), a temperature-controlled airflow (TcAF) and a uni directional airflow (UDAF) in the ultra-clean area when the ventilation system was switched to approximately 20 air changes per hour as advised for generic surgery [4,10–12].

Methods

This study was performed in five ORs of four hospitals and one clinic in the Netherlands. To reduce the number of air changes per hour the setpoints of the supply air (SUP) [20] of the air-handling installation via the building management system were changed. SUP was the sum of ODA and secondary air (SEC). SUP is defined according to the EN-16798–3:2017 [20] as airflow entering the treated room, or air entering the system after any treatment. SEC is airflow taken from a room and returned to the same room after any treatment. ODA is defined as air entering the system or opening from outdoors before any air treatment. In this study, ODA remained the same for CV, cDV, TcAF and UDAF-2 and SEC was reduced. For the UDAF-1, ODA was reduced and the SEC air system turned off.

OR ventilation systems

As in our previous study [19], four different ventilation systems were selected. The selected ventilation systems are categorized as unidirectional and non-unidirectional airflow ORs according to the ISO 14644-3 [21]. To understand the VE and air distribution of the compared OR ventilation systems technical dissimilarities and working principles are explained in our previous study [19].

Before measurements were performed, a technical inspection of the ventilation performance with the systems working on a lower air volume was carried out to ensure that the system was functioning as intended for this study.

The measurements were performed in the same hospitals in order to be able to compare the VE_{Lv} with the VE out of our previous study. Because it was not possible, without major modifications, to reduce the number of ACH of the UDAF system used in our previous study, we assessed another UDAF system as well to be able to compare equally the VE_{Lv} with the other CV and UCV systems. The UDAF from the former study is called UDAF-1 and the newly assessed UDAF, UDAF-2. The number of air changes per hour in our previous study [19] for the examined ultra-clean ventilation systems varied from 45 to 73 ACH (see Table I). In the current study this number of ACH was reduced to approximately 21 ACH per OR for all systems except for the CV system, for which the number of ACH was 24 (see Table II).

Measurements

The measurement methodology used was based on the recovery test described in ISO 14644-3; B.12 [21]. Within a 4 $\times$ 4 m square measuring grid of 1 $\times$ 1 m, three measuring areas were defined, Area A with nine measuring locations, Area B with 16 measuring locations, Area AB with 25 measuring locations (see Figure 1). Each measuring grid, with measuring locations at a height of 1.20 m above floor level, was situated with its centre (point C3) in the middle of the operating field. Measuring locations were at a distance of 1 m from each other and were performed per row. At each measuring row, five Lighthouse 3016 handheld particle counters with a flow rate of 2.83 L/min (0.1 ft^3/min) were placed at the measuring locations (grid positions). On each point per row the particle

Table I
Results of our previous study, descriptive examined operating ventilation systems, Areas A, B and AB

Ultra-clean area	CV	cDV	TcAF	UDAF
Air volume (m^3/h)	3.220–3.344	9.800	6.848–7.180	10.032–10.379
Number of air changes per hour	24–26	69	45–53	66–73
Area A				
N	45	54	45	54
RD_{10}	2.22 (1.72–3.42)	4.18 (3.67–4.49)	2.96 (2.75–3.61)	6.00 (5.00–5.00)
CRR	0.50 (0.38–0.66)	1.21 (1.11–1.34)	0.73 (0.58–0.86)	5.41 (3.20–5.96)
ACE	1.20 (0.91–1.58)	1.07 (0.98–1.18)	0.97 (0.74–1.11)	4.62 (2.96–5.05)
Area B				
N	80	96	80	96
RD_{10}	1.82 (1.59–2.33)	4.60 (4.02–5.58)	2.91 (2.34–3.98)	4.45 (3.86–5.00)
CRR	0.38 (0.33–0.42)	1.21 (1.09–1.30)	0.67 (0.55–0.73)	1.10 (0.96–1.29)
ACE	0.93 (0.81–1.05)	1.06 (0.96–1.14)	0.81 (0.73–0.96)	0.96 (0.84–1.15)
Area AB				
N	125	150	125	150
RD_{10}	1.94 (2.52–5.00)	4.40 (3.95–4.95)	2.92 (2.41–3.86)	5.20 (4.16–5.00)
CRR	0.41 (0.54–1.27)	1.21 (1.10–1.31)	0.70 (0.55–0.77)	1.34 (1.02–3.45)
ACE	0.98 (0.87–1.21)	1.07 (0.97–1.15)	0.87 (0.73–1.00)	1.17 (0.95–3.21)

Results are presented as median and interquartile range. ACE, air change effectiveness; cDV, controlled dilution ventilation; CRR, cleanliness recovery rate; CV, conventional ventilation; RD_{10}, recovery degree within 10 min; TcAF, temperature-controlled airflow; UDAF, unidirectional airflow.

counters measured, with a measuring cycle of 1 min for 10 min, the quantity of particles with a particle size of $\geq$0.5 μm. During the measurements, medical equipment, respirators, and operating lights (switched on) were positioned in the operational position. The operating lights were positioned according to VCCN RL7 and DIN 1946-4 [12,22]. Before the measurements started, particles were emitted in the whole OR with a calibrated Topas aerosol generator (model ATM 226, aerosol Emery 3004). The emitting stopped when all particle counters in the measuring row displayed a background concentration between $\geq 10^7$ and 10^9 particles ($\geq$0.5 μm) per m^3. The exact route of the emitted particles cannot be indicated with these measurements. From the number of particles measured at each point, the recovery degree (RD), cleanliness recovery rate (CRR) and the air change effectiveness (ACE) were calculated.

Table II
Descriptives examined operating room ventilation systems, Areas A, B and AB

Ultra-clean area	CV_{Lv}	cDV_{Lv}	$TcAF_{Lv}$	UDAF-1_{Lv}	UDAF-2_{Lv}
Air volume (m^3/h)	2678	3000	3500	1750	2400
Number of air changes per hour	24	21	21	12	22
Area A					
N	9	9	9	9	9
RD_{10Lv}	1.86 (1.21–2.52)	1.45 (1.22–1.69)	1.63 (1.21–2.05)	0.96 (0.47–1.46)	4.24 (1.46–7.02)
CRR_{Lv}	0.39 (0.28–0.50)	0.35 (0.29–0.40)	0.30 (0.19–0.40)	0.20 (0.04–0.36)	0.91 (0.56–1.26)
ACE_{Lv}	0.98 (0.71–1.26)	1.09 (0.85–1.17)	0.85 (0.56–1.15)	0.99 (0.23–1.74)	2.47 (1.52–3.41)
Area B					
N	16	16	16	16	16
RD_{10Lv}	1.69 (1.17–2.22)	1.59 (1.06–2.13)	1.57 (1.02–2.12)	1.36 (0.80–1.91)	3.75 (2.96–4.54)
CRR_{Lv}	0.37 (0.32–0.43)	0.33 (0.27–0.39)	0.32 (0.27–0.38)	0.26 (0.20–0.31)	0.75 (0.66–0.83)
ACE_{Lv}	0.93 (0.80–1.06)	0.97 (0.79–1.14)	0.97 (0.80–1.13)	1.25 (0.99–1.52)	2.02 (1.80–2.25)
Area AB					
N	25	25	25	25	25
RD_{10Lv}	1.71 (1.13–2.29)	1.49 (1.06–1.93)	1.58 (1.20–1.96)	1.27 (0.67–1.87)	3.75 (2.76–4.75)
CRR_{Lv}	0.37 (0.32–0.43)	0.34 (0.28–0.39)	0.32 (0.24–0.39)	0.25 (0.16–0.34)	0.77 (0.62–0.91)
ACE_{Lv}	0.94 (0.80–1.07)	0.98 (0.82–1.13)	0.94 (0.73–1.15)	1.23 (0.80–1.66)	2.08 (1.68–2.48)

Results are presented as median and interquartile range. ACE_{LV}, air change effectiveness low volume; cDV_{LV}, controlled dilution ventilation low volume; CRR_{LV}, cleanliness recovery rate low volume; CV_{LV}, conventional ventilation low volume; RD_{10LV}, recovery degree within 10 min low volume; $TcAF_{LV}$, temperature-controlled airflow low volume; UDAF-1_{LV}, unidirectional airflow-1 low volume; UDAF-2_{LV}, unidirectional airflow-2 low volume.

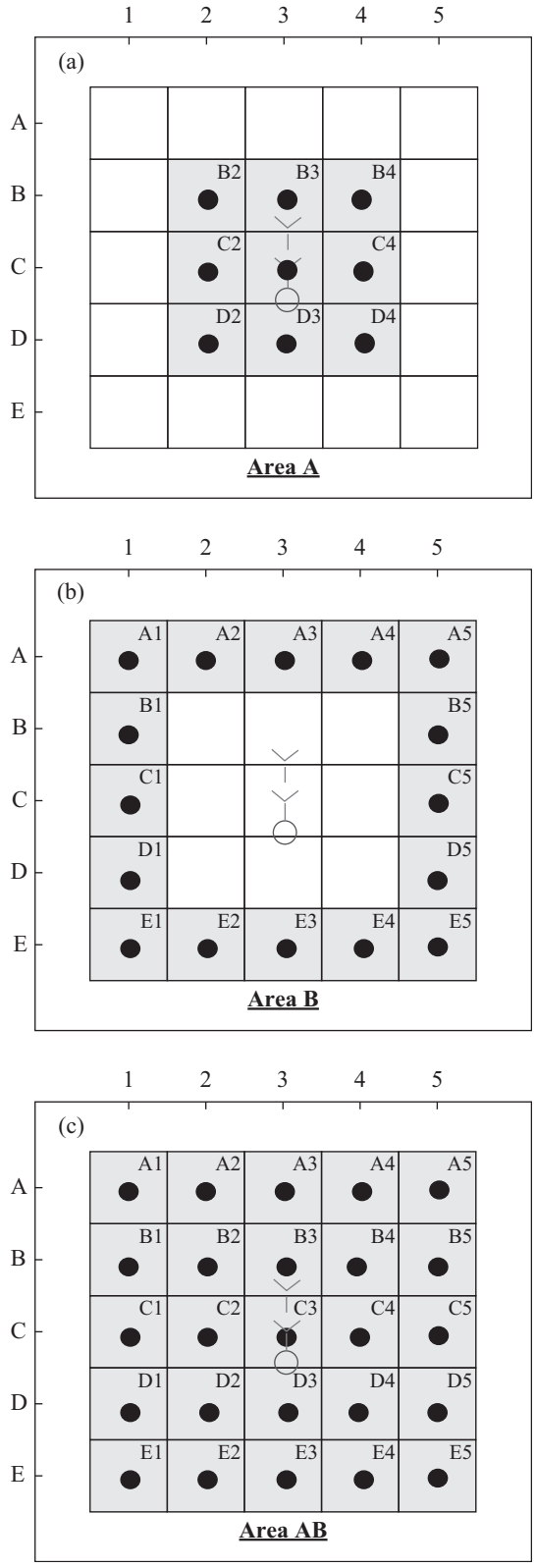

Figure 1. Measuring location, dots are the position of particle counters. (a) Area A, nine measuring locations (B2–B3, C2–C3, D2–D4). (b) Area B, 16 measuring locations (A1–A5, B1 and B5, C1 and C5, D1 and D5, E1–E5). (c) Area AB, 25 measuring locations (A1–A5, B1–B5, C1–C5, D1–D5, E1–E5).

RD

The RD shows the ability of the OR ventilation system to eliminate or reduce the quantity of airborne particles, at the measuring locations, from the maximum concentration after emitting within 10 min (RD_{10}). The RD [19] shows the ability of the ventilation system to eliminate or reduce the quantity of airborne particles, at the measuring locations, from the maximum concentration after emitting. The RD is defined as the logarithm of the quotient (ratio) of the number of particles $\geq$0.5 μm per m^3. In this study RD is measured every minute for 10 min and therefore RD_{10} is used in this study. RD_{10Lv} is the RD over a period of 10 min with a lower air change rate.

The RD is derived from the recovery test as described in the ISO 14644-3: B12 [21]. An RD of 2 means that the number of particles at the measuring locations is a factor 100 times ($^{10}\log 100 = 2$) lower than at the start of the measurement during the period of 10 min.

RD is calculated by Equation 1:

$$RD_{tx} = -log\ \frac{C_{tx}}{C_{t0}} \quad (1)$$

where RD_{tx} is the RD after time tx, C_{tx} is the concentration of particles at location at time tx, and C_{t0} is the initial concentration at start measurement t_0, directly after emitting.

CRR

The CRR is used as a method [23] to determine the local air change rate at the measuring locations. CRR, or decay rate, is closely related to the RD. The CRR is used as a method [23] to determine the local air change rate at the measuring locations. Local air change rate per minute is equal to the CRR. Calculation of the CRR, as given in ISO 14644-3, was carried out over the period of exponential decay. This period is ascertained by plotting the particle concentration over time [23] and defines the inclination angle of the particle decay. In this study the CRR_{Lv} is used to compare the air distribution in the OR of the different ventilation systems with a lower air change rate.

CRR (local air change rate) can be calculated Equation 2:

$$CRR = -\frac{1}{t}\ln\left(\frac{C1}{C0}\right) = -2.3\ \frac{1}{t}log\frac{C_1}{C_0} \quad (2)$$

where t is the time in minutes, elapsed between the first and last measurement in the measurement interval, C_0 is the concentration at the start of the exponential decay, and C_1 is the concentration at the end of the exponential decay.

ACE

The VE is determined by the ACE [23–25]. This study compares the average CRR per system in the measured areas A, B and AB with the overall average air change rate. The overall average air change rate is the total air volume (m^3/h) introduced in the OR divided by the OR's volume (m^3). If introduced, HEPA-filtered air and room air volume are perfectly mixed, the ACE will have a value of 1 at all measuring locations. If less introduced air reaches the measuring location than the OR volume average the ACE will be below 1. If more introduced air reaches the measuring location, the ACE index will be above 1.

The aim of a UCV system is to have a higher ACE (>1) in the ultra-clean area [23].

The ACE is calculated by Equation 3.

$$ACE = \frac{\textit{local air change rate per minute (CRR) at measuring location x 60}}{\textit{overall average air change rate } \left(\frac{m3}{h}\right) \textit{ operating room}} \quad (3)$$

where local air change rate per minute is the average CRR per measuring location per system, overall average air change rate in the OR is the total air volume introduced (m^3/h)/OR's volume (m^3).

In this study the VE was defined as the RD, CRR and ACE. Because the number of air changes per hour in this study was reduced, lower air volumes were introduced in the OR. The lower air volume VE (VE_{Lv}) of the four ventilation systems was determined for three different ultra-clean protected areas: standard protected area (A), area outside standard protected area (B) and large protected area (AB).

In Table II the characteristics of the examined OR ventilation systems as well as the VE in Areas A, B and AB are shown.

Statistical analysis

To determine differences between the ventilation systems regarding RD, CRR and ACE, a Kruskal–Wallis test was performed, because a normal distribution could not be assumed. As post hoc analysis, a Mann–Whitney *U*-test was performed, with Bonferroni correction.

IBM SPSS version 25 (IBM Corp. Armonk, NY: IBM Corp) was used. A *P*-value of 0.05 or less was considered statistically significant.

Results

Results of the VE low volume (VE_{Lv}) in Areas A, B and AB are presented in Table II. The CV, cDV and TcAF ventilation systems show a comparable and stable RD and CRR over time in Areas A, B and AB when reducing the air change rate. Airborne particle concentration and RD_{10Lv} per minute for the four ventilation systems of the middle row (C1–C5, Area AB) are shown in Figure 2. At all points for the UDAF-2_{Lv} and at the centre point (C3) of the $TcAF_{Lv}$, higher RD_{10Lv} and CRR_{Lv} were seen when compared with the measuring locations of the other examined ventilation systems (Figure 2e). In the centre of the OR, at measuring location C3 (Figure 1c) a higher RD_{10Lv} (3.5) CRR_{Lv} (0.8) and ACE_{Lv} (2.1) were measured for the TcAF due to the working principle and design of this UCV system [19].

Comparison of the four types of ventilation systems in area AB is shown in Figure 3. The VE_{Lv} (RD_{10Lv}, CRR_{Lv} and ACE_{Lv}) was significantly higher for the UDAF-2_{Lv} system compared with the other ventilation systems (Figure 3). For comparison, results of our previous study are presented in Table I.

Discussion

The goal of this study was to provide insight into what the effect is on the VE when the air change rate in an ultra-clean OR is reduced from an average of 69/h to approximately 20/h. The air volume of a class 1+ air-handling installation and air-supply system, according to the Dutch Federation of Medical Specialists (FMS) [4], was lowered to achieve the required ACH (≥20) as required for a FMS class 1 OR.

When reducing the number of air changes to approximately 20/h the CV, cDV, TcAF and UDAF-2 measured in the current study comply to an OR Class I as described in the FMS [4]. These systems also comply with other international standards and guidelines such as the Swedish SIS TS 39, other surgery [10], the English HTM 03-01, conventional surgery [11], the German DIN1946-4, OR Class 1b [12] and the French NF S 90 351, class zone 3 [13]. The UDAF-1 system in this study did not comply with an OR Class 1 as it was, without major modifications, not possible to increase the number of air changes to ≥20/h. The OR air-handling installation and CV, cDV, TcAF and UDAF-2 air-supply systems in the current study can, when not used for major (orthopaedic) implants, large joints procedures or other infection prone surgeries, be switched to a lower ACH. Reducing the ACH will reduce the energy consumption of the air-handling installation [16,17]. Further study should be conducted to determine the extent to which reducing the air volume of UCV air-supply systems translates into the reduction of energy consumption and the resulting level of cfu when reducing the air volume of UCV air-supply systems.

In this study, no major technical modifications were executed to reduce the ACH or air volumes of the air-handling installation and air-supply system, to allow for an equal VE comparison of the results out of our previous study [19]. When comparing the VE_{Lv} with the VE of our previous study, lower RDs and CRRs were seen in the current study (Tables I and II). Compared with our previous study, the 10-min RD in area AB was 1000 times lower for the cDV and UDAF when the number of air changes was reduced to 20/h. However, when reducing the ACH to 20, the RD of the TcAF and UDAF-2 was only 100 times lower compared with the original design conditions. The local air change rate (CRR) was, compared with our previous study, decreased by 72% for the cDV and 81% for the UDAF-1, whereas the decrease in the local air change rate was lower for the TcAF and the UDAF-2 by 52% and 42%, respectively. In Area AB, the results of the ACE were comparable to the ACE of the previous study, with the exception of the UDAF-2 and TcAF. The ACE of the UDAF-2 and TcAF were higher than the ACE in the previous study. In this study, the UDAF-2 and the TcAF performed best regarding VE when air change rates were reduced from an ultra-clean OR to a generic OR.

Reducing the air change rate in the OR from an ultra-clean OR to a generic OR will reduce the RD_{10} by a factor 10–100. The local air change rate (CRR) will be reduced between 42% and 81%. The effect of lowering the air change rate possibly reduces contaminant removal effectiveness [26]. Because the examined ultra-clean ventilation systems show a mixing character when reducing the ACH, no ultra-clean area or protected area [11] was created in the OR as intended according to international standards and guidelines [4,10,12].

The VE_{Lv} of an UDAF is not self-explanatory. A uni-directional air flow is designed to introduce the air directly above the ultra-clean area with a discharge velocity of 0.25–0.3 m/s [13,27]. The aim of the UDAF is to displace the body convection (thermal plume) generated by the surgical staff [27] and to reduce the microbiological concentration in the ultra-clean area [3,28]. When reducing the air volume of an existing UDAF system as executed in this study, it is important to know how the air-handling system and air-supply system is constructed. The VE_{Lv} of an UDAF depends on whether it is possible to create an

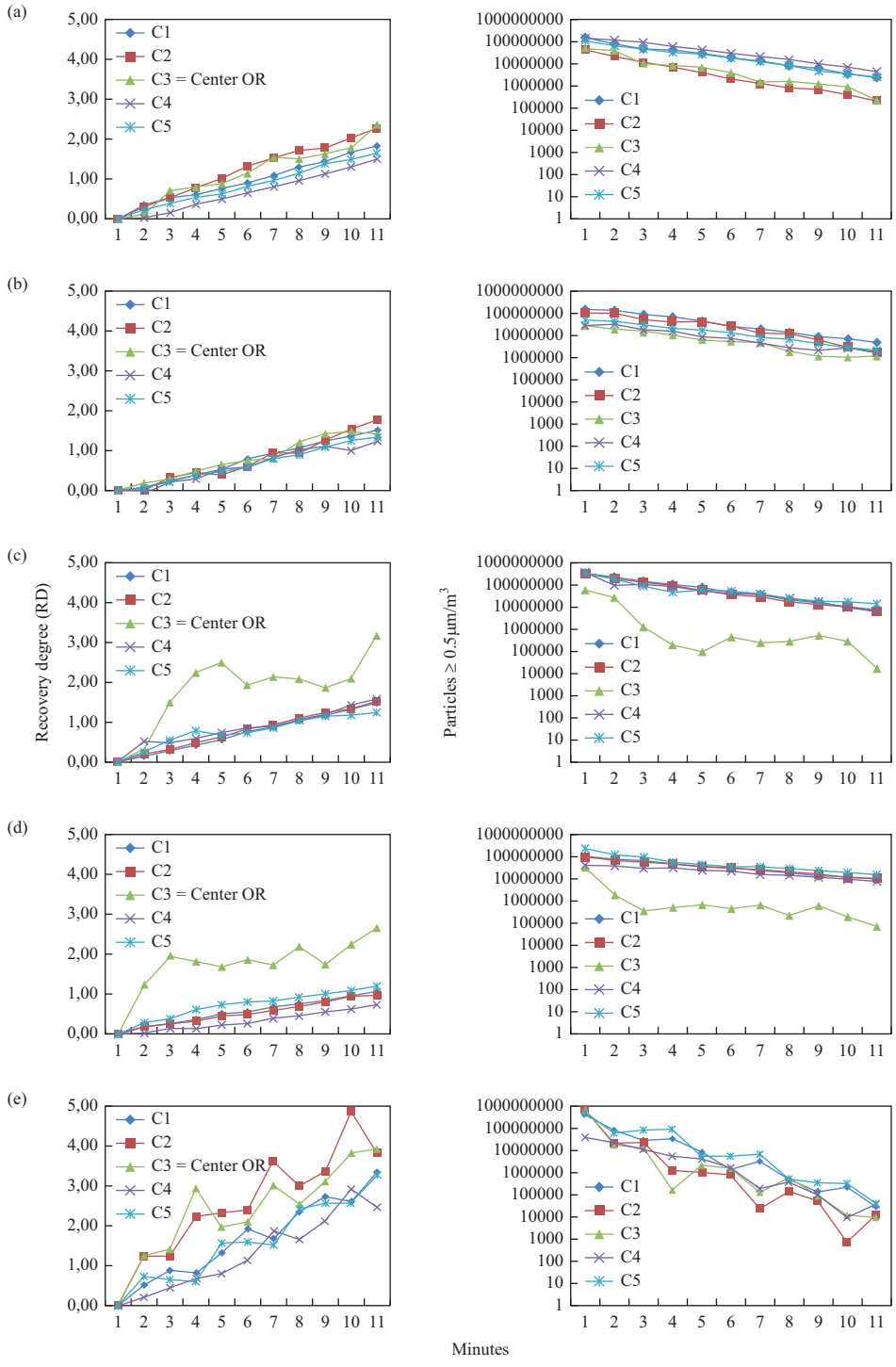

Figure 2. (a). The RD_{10Lv} (left), recovery degree within 10 min low volume, and decay of airborne particles concentration CRR_{Lv} (right), cleanliness recovery rate per min low volume at row C1 -C5 of the CV_{Lv}, conventional ventilation system low volume. (b) The RD_{10Lv} (left), recovery degree within 10 min low volume, and decay of airborne particles concentration CRR_{Lv} (right), cleanliness recovery rate per min low volume at row C1 -C5 of the cDV_{Lv}, controlled dilution ventilation system low volume. (c) The RD_{10Lv} (left), recovery degree within 10 min low volume, and decay of airborne particles concentration CRR_{Lv} (right), cleanliness recovery rate per min low volume at row C1 -C5 of the $TcAF_{Lv}$, temperature-controlled airflow system low volume. (d) The RD_{10Lv} (left), recovery degree within 10 min low volume, and decay of airborne particles concentration CRR_{Lv} (right), cleanliness recovery rate per min low volume at row C1 -C5 of the $UDAF_{Lv\text{-}1}$, uni directional airflow-1 system low volume. (e) The RD_{10Lv} (left), recovery degree within 10 min low volume, and decay of airborne particles concentration CRR_{Lv} (right), cleanliness recovery rate per min low volume at row C1 -C5 of the $UDAF_{Lv\text{-}2}$, uni directional airflow-1 system low volume.

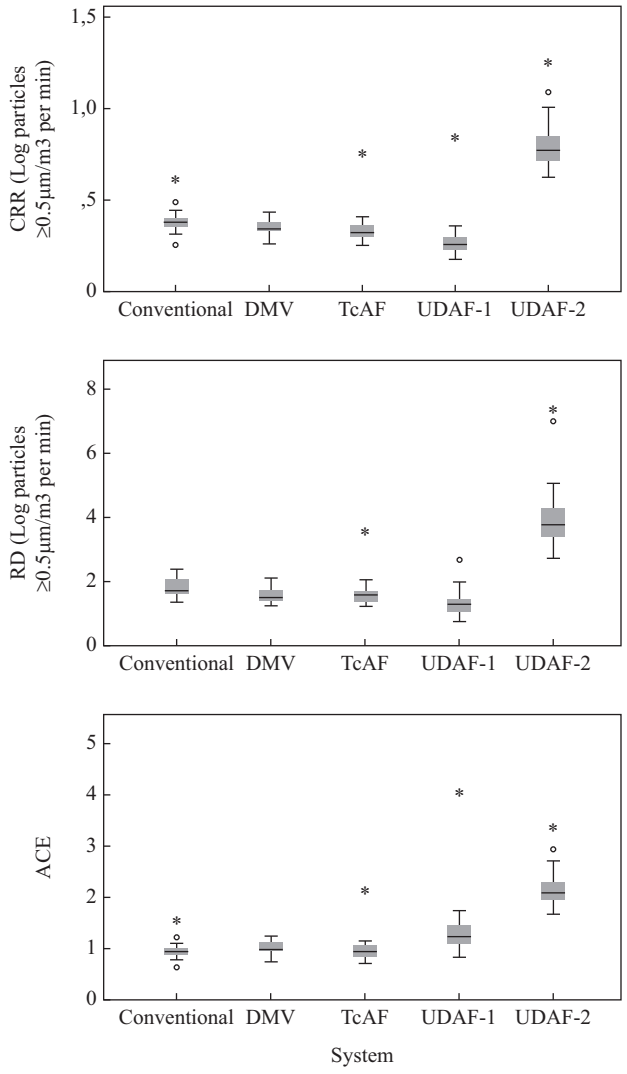

Figure 3. Boxplots of Area AB to compare the ventilation effectiveness low volume (VE_{Lv}) of the different ventilation air-supply systems. CRR_{Lv} (top) cleanliness recovery rate low volume, RD_{Lv} (middle) recovery degree within 10 min low volume, ACE_{Lv} (bottom), air change effectiveness low volume.

equal velocity under the entire surface of the UDAF. Without first making a comparable measurement corresponding to this study, it is not advisable to adjust the air volume of a UDAF. A study on how the differently designed UDAF systems behave when reducing the air volume is recommended.

One limitation of the current study is that it was executed in an 'at-rest' situation. We therefore did not take the dispersion and contamination dynamics in the OR into consideration. We did not measure the level of cfu/m^3 in the OR when the air change rate was lowered. A further study should investigate what the effect is on the level of cfu/m^3 in the surgical field when reducing the number of air changes per hour in the OR, taking into account the discipline of the surgical staff, number of door openings during surgery [29—31], the quality of the clothing [28,32,33] used, etc. The methodology used in this study offers a technical evaluation of the installed air-handling installation and air-supply system when reducing the air change rate.

Second, the number of ACH and total introduced air volume was not exactly the same per system. In case of the UDAF-1_{Lv} it was technically not possible to adjust the air volume without major technical changes. This resulted in a lower number (12, see Table II) of air changes at the UDAF-1_{Lv}. Another UDAF-2_{Lv} system, at a different clinic, was selected and assessed for comparison with the CV system and other UCV systems.

Third, the CV system in this study was designed as a mixing system Class 1 [4] according to the FMS and not as an ultra-clean ventilation air-supply system. The effect of reducing the air volume or number of air changes for this system was not assessed in this study.

In conclusion, the VE decreases when an ultra-clean OR with an ultra-clean ventilation air-supply system is switched, from on average 69/h [15], to an air change rate of 20/h. Reducing the air change rate in the OR from an ultra-clean OR to a generic OR will reduce the RD_{10} by a factor of 10—100 and the local air change rate (CRR) by between 42% and 81%. The low-volume ventilation effectiveness (VE_{Lv}) was higher for the UDAF-2_{Lv} system compared with the other ventilation systems. In this study, the UDAF-2 and the TcAF performed best regarding the VE, as defined in this study, when air change rates were reduced from an ultra-clean OR to a generic OR.

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Conflict of interest statement

J.L.A.L. is CEO of Medexs BV, a company that supplies and installs OR ventilation systems. All other authors report no conflict of interest relevant to this article.

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