



Design variables with significant effect on system performance of unidirectional displacement airflow systems in hospitals

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SUMMARY

Background: The effectiveness of an airflow system in preventing entrainment of particles carrying micro-organisms from the periphery of an operating room (OR) or instrument lay-up room (ILR) is affected by many variables. It is suspected that differences in the design of the systems affect the effective protection ratio (EPR): the ratio of the size of the protected area to the surface area of the supply canopy. However, no analysis has yet been done to determine which design variables have a significant effect on this ratio.

Aim: To evaluate which design variables have a significant effect on the performance of airflow systems (EPR) in ORs and ILRs.

Methods: All general and teaching hospitals in the Netherlands ($N = 77$) were asked to provide data from their standardized (at-rest measurement method) compulsory systems assessment reports for ORs and ILRs. Nineteen hospitals (25%) with a total of 22 hospital sites supplied information of sufficient completeness and homogeneity, resulting in measurement data for 101 ORs and 23 ILRs. This dataset was analysed using Statistical Package for Social Sciences.

Findings: For ORs, important predictors for the EPR were: shape of the canopy; air speed under the supply canopy; height of the canopy screen; type of system; and size of the canopy. These significant predictors ($P < 0.05$) explain 48% of the outcome in the dataset. For ILRs, significant predictors for the EPR were: the position of exhaust air terminals; height of the canopy screen; and size of the canopy. These significant predictors explain 66% of the outcome in the dataset.

Conclusion: On the basis of the dataset available for analysis, it is concluded that the ratio of the size of the protected area to the surface area of the supply canopy (EPR) improves with the presence and the height of a screen around the canopy, the surface area of the supply canopy, and the air speed of the supply air under the canopy. This information can be used as guidance for the future design of unidirectional displacement airflow systems.

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Introduction

The effectiveness of an airflow system in preventing entrainment of particles carrying micro-organisms from the periphery of an operating room (OR) or instrument lay-up room (ILR) is affected by many variables [1–4]. It is suspected that differences in the design of the systems affect the effective protection ratio (EPR): the ratio of the size of the protected area to the surface area of the supply canopy.

Studies confirm that technical variables such as size of the air supply canopy, air speed, temperature difference between the supply air and the periphery, position of the exhaust air terminals, type of operating lamps, and presence of a partial screen (glass or perspex plating) mounted around the canopy all need to be taken into consideration [1–17]. It is not automatically true that any system equipped with a supply canopy in the ceiling can be considered a proper unidirectional downflow (UDF) system [2,3,5–7,18,19]. Additional conditions have to be met. This distinction is not always made correctly either in research or practice. This may be the reason for the results of some studies indicating that the effect of UDF systems on surgical site infections (SSIs) is limited, or even adverse, regarding the number of SSIs [20–24].

In 2014 a new guideline for assessing the performance of UDF systems at rest (Guideline 7 established by the Dutch association for contamination control (VCCN)) was presented in the Netherlands [25]. Since 2017, the Dutch Health and Youth Care Inspectorate has required regular guideline compliance performance tests of UDF systems. The most important outcome variable in this guideline is the size of the protected area, defined as the area achieving a degree of protection of ≥ 2 along the perimeter relative to the periphery, with the centre of the area required to achieve a degree of protection ≥ 3 relative to the periphery 1.2 m above floor level. The surgical site and the instrument table(s) must be positioned within this area. The guideline requires measurements to be performed at least at points directly under the corner points of the air supply canopy. In addition to these mandatory measurements, for many of the ORs and ILRs in the dataset extra measurements were performed at intermediate points between corners.

In addition to the guideline compliance measurements, the present study has collected data on lay-out and technical installation parameters for the ORs and ILRs concerned. These data have been analysed to determine which lay-out and technical installation parameters have a significant effect on the EPR.

Methods

All 77 general and university hospitals in the Netherlands were invited to participate in this study and were asked to provide data from their standardized (at-rest measurement method in accordance with VCCN Guideline 7) compulsory systems assessment reports for ORs and ILRs [25,26]. Guideline 7 specifies a uniform measurement method to ensure comparability of results between measurements done by different companies. All six companies active in carrying out measurements for UDF systems in Dutch hospitals received extensive instruction on proper application of the measurement method when the guideline was originally introduced. Of the hospitals approached, 27 indicated willingness to participate in the

study. Of these, 24 provided measurement data. After screening of the data for completeness and homogeneity, data from 19 hospitals (25%) for 22 hospital sites were included. Additional information regarding the technical characteristics of the room(s) was collected through a questionnaire. The complete dataset for analysis covered 124 rooms (101 ORs and 23 ILRs) at 22 hospital sites. All data were processed in a spreadsheet for analysis with Statistical Package for Social Sciences.

The degree of protection of a protected or 'clean' area is defined as [26–29]:

$$DP_x = -\log\left(\frac{C_x}{C_{ref}}\right)$$

where DP_x is the degree of protection in the 'clean' area x , C_x is the concentration of particles in the 'clean' area x , and C_{ref} is the concentration of particles outside the 'clean' area, i.e. the background (periphery).

The degree of protection is an important variable in determining the performance of UDF systems. It is based on all particles $\geq 0.5 \mu\text{m}$ and is expressed using a logarithmic scale: a value of 2 indicates that in the protected area the concentration of particles is 100 times lower than in the periphery. According to Guideline 7 the degree of protection should be ≥ 2 along the perimeter of the protected area and ≥ 3 in the middle of the protected area 1.2 m above floor level [25,26]. The level of particles $\geq 0.5 \mu\text{m}$ in the periphery of $\sim 10^6$ particles/ m^3 is artificial, created by emitting particles.

Approaches to OR and ILR lay-out and design vary considerably from country to country. In the Netherlands, UDF systems are not limited to ORs for infection-prone clean surgery, but they are common practice in most ORs where full-scale surgical procedures are performed. For hip and knee arthroplasty procedures, UDF systems are specifically required by the Netherlands Orthopaedic Association. Separate rooms equipped with UDF systems are generally provided in Dutch operating theatre departments for laying-up of instruments. In cases where laying-up takes place in the OR, this usually takes place under the main canopy. In rare situations a separate laying-up UDF canopy is provided in the OR for this purpose.

To facilitate understanding of the set-up of the present study and the interpretation of its results, Figure 1 shows a floorplan of a typical Dutch OR lay-out and the location of the main variables included in the study. The canopy shown is of a type (irregular hexagonal shape) discussed in the study. Though there is variation in design and lay-out even within the Netherlands, the OR shown can be considered representative of the type of OR found in most Dutch general and university hospitals.

Table 1 presents the variables collected and analysed in the study. The dependent outcome variable, the effective protection ratio (EPR), is defined as the ratio of the size of the protected area to the surface area of the supply canopy [25,26]. These variables were analysed using Statistical Package for the Social Sciences version 25. The first step was to analyse all variables to check for any system missing values and the presence of extreme values, and to assess the plausibility of frequency distributions. An OR or ILR was included in the model if data for all variables (Tables I and II) were available. If data for one or more variables were missing, the OR or ILR was excluded from the model. Second, analysis was done to verify

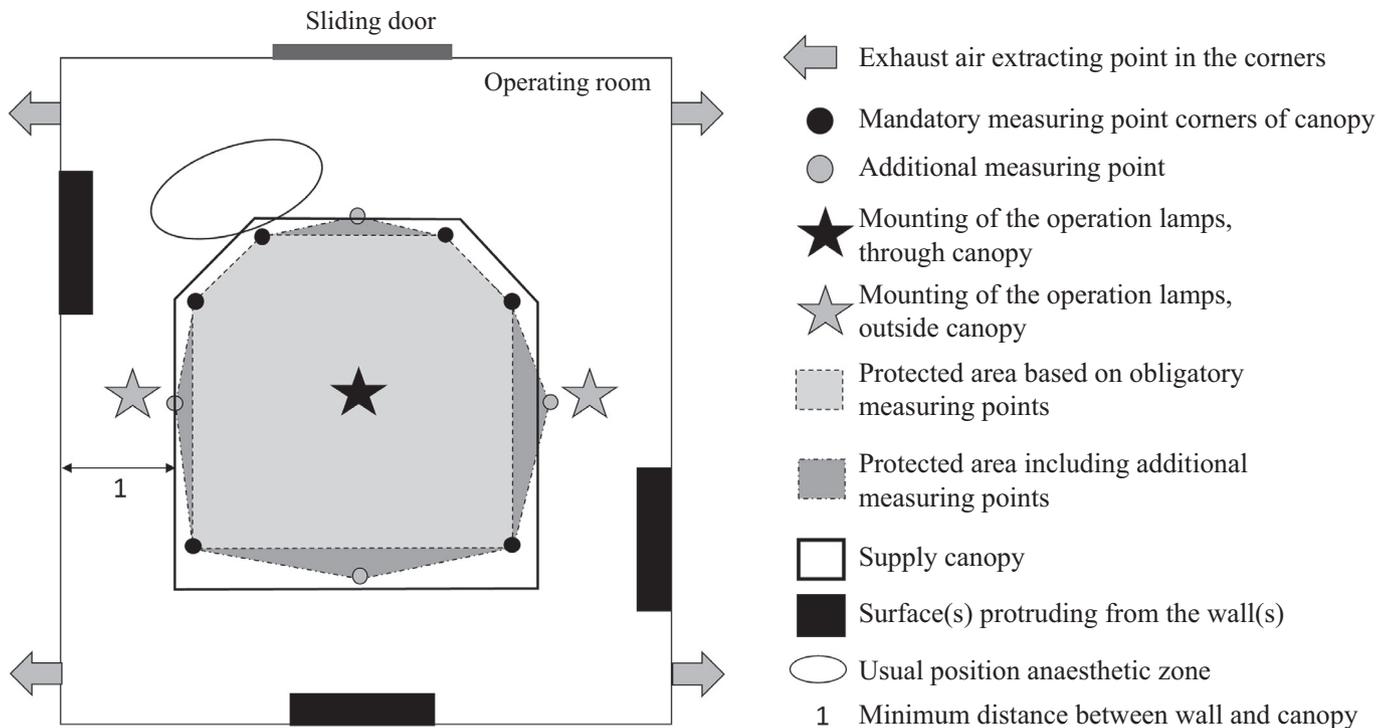


Figure 1. Spatial presentation of variables.

that the (Pearson) correlations among all variables (outcome variable and predictors) made sense. In the third step a multiple regression analysis with stepwise methods and dummy variables was performed.

Results

Tables I and II show that there were great variations in the EPR (5–128%) for the 124 rooms included in the data. An EPR of 5% means that the amount of supplied air is not used very effectively to create a protected area. Also, the design variables varied considerably, e.g. the height of the canopy screen (3–85 cm), air velocity (0.14–0.51 m/s), and temperature difference (0–3 K).

Size of the room

The mean floor area of the ORs was 45.2 m² (28.8–62.2, *N* = 94), but this variable was not provided for all ORs. The mean floor area of the hybrid ORs involved was 82.3 m² (72.7–102.3, *N* = 4) and of the ILRs 29 m² (11.6–58.2, *N* = 17). This resulted in a ratio between the surface area of the supply canopy and the floor area for the ORs of 20% (11–31%, *N* = 94), for the hybrid ORs of 15% (13–18%, *N* = 4), and for the ILRs of 22% (10–33%, *N* = 17).

Size of the supply canopy and protected area

For the ORs, the mean surface area of the supply canopy was 8.97 m² (4.32–13.50, *N* = 101). The resulting average protected area based on the mandatory measuring points (corners) was 5.76 m² (0.27–9.31, *N* = 101) in the ORs.

For 45 ORs additional measurements at intermediate points between the corners were reported. In ORs for which

additional measuring point data was provided, the average surface area of the supply canopy was 8.58 m² (4.32–13.50) and the average protected area based on only the mandatory measuring points was 5.2 m² (1.87–9.31). If the additional measuring points were also taken into account, the average size of the protected area increased from 5.2 to 6.13 m² (2.39–11.71).

For the ILRs the average surface area of the supply canopy was 8.5 m² (1.82–19.45, *N* = 23). In ILRs for which additional measuring points data was provided (*N* = 15), the average surface area of the supply canopy was 10.65 m² (3.75–19.45) and the average protected area based on only the mandatory measuring points was 7.57 m² (1.29–18.21). If the additional measuring points were also taken into account, the average size of the protected area increased from 7.57 to 9.34 m² (2.13–18.80). The relationship between the surface area of the supply canopy and size of the protected area is shown in Figure 2.

The EPR using the mandatory measuring points was 64% (5–100%) for all ORs (*N* = 101). In ORs for which additional measuring point data was provided, the EPR was 61% (32–90%) using only the mandatory measuring points, and 71% (46–128%) when also taking into account the intermediate measuring points (*N* = 45), a relative increase of 17.7%. For the ILRs, the EPR for all ILRs based on the mandatory measuring points (*N* = 23) was 76% (11–100%). In ILRs for which additional measuring point data were provided (*N* = 15), the EPR was 80% (34–98%) using only the mandatory measuring points. When taking into account the additional measuring points the average EPR rose to 88% (57–99%), a relative increase of 9.4%.

Predictors

For the ORs (*N* = 101), all variables from Table I were included in a multiple regression model.

Table I
Collected and analysed information for each operating room (OR) ($N = 101$)

Variable	Unit	Mean (range)
Effective protection ratio ^a	%	68.7 (5–128)
Size of OR (A_{OR})	m ²	46.7 (28.8–102.3, $N = 98$)
Size of the canopy (A_{canopy})	m ²	8.97 (4.32–13.5)
Ratio A_{canopy}/A_{OR}	%	20% (11–31%)
Shape of the canopy	0: rectangular 1: rectangle with two angled corners (actually hexagonal) 2: different	0: $N = 66$ 1: $N = 32$ 2: $N = 3$
Measurement with or without operating lamps	0: without operating lamps 1: with operating lamps	0: $N = 11$ 1: $N = 90$
Type of operating lamp	0: open structure 1: small lamp with closed structure 2: large lamp with closed structure	0: $N = 9$ 1: $N = 30$ 2: $N = 51$
Recovery time (according to VCCN Guideline 7)	min	1.6 (0.2–19)
Presence of furnished/equipped room	0: empty OR 1: empty OR with operating table 2: fully equipped (including OR table and medical equipment)	0: $N = 0$ 1: $N = 28$ 2: $N = 73$
Height of the canopy screen (if present)	cm	40.39 (3–85)
Temperature difference between supply and periphery air	K	1.1 (0–3.7)
Air speed direct under the supply canopy	m/s	0.27 (0.14–0.34)
Position of exhaust air terminals	0: high/low in the corners of the OR 1: only low exhaust in the corners of the OR 2: plinth exhaust 3: different	0: $N = 65$ 1: $N = 17$ 2: $N = 0$ 3: $N = 19$
Mounting of the operation lamps	0: outside canopy 1: through canopy	0: $N = 9$ 1: $N = 92$
Type of system	0: one temperature system with one speed 1: two or more temperature systems with one speed 2: two-speed system with a higher speed in the middle zone 3: two-speed system with a higher speed at the edge	0: $N = 37$ 1: $N = 58$ 2: $N = 0$ 3: $N = 6$
Minimum distance between wall and canopy	M	1.59 (0.95–2.5)
Surface(s) protruding from the wall(s)	Yes or no	No: $N = 48$ Yes: $N = 53$

^a Ratio of the size of the protected area to the surface area of the supply canopy based on the corner and intermediate points where available.

The shape of the canopy, air speed directly under the supply canopy, height of the canopy screen, type of system, and size of the canopy were significant predictors for the EPR (Table III). These predictors result in a model with an R^2 of 0.483 and an adjusted R^2 of 0.456 explaining 48% of the outcome in the dataset. All these predictors are significant ($P < 0.05$).

For the ILRs ($N = 23$) a multiple regression model was set up that included all variables shown in Table II. The position of exhaust air terminals, height of the canopy screen, and size of the canopy were found to be important predictors for the outcome. These predictors result in a model with an R^2 of 0.657 and an adjusted R^2 of 0.603 explaining 66% of the outcome in the dataset. All these predictors were significant ($P < 0.05$) (Table IV).

It follows from the multiple regression analysis that a rectangular canopy with two angled corners (more properly an irregular hexagonal shape, $N = 32$) had the largest positive

effects on the EPR in ORs. The presence of an air distribution system with two or more temperature systems with one design air speed ($N = 58$) also positively affected the EPR, as did the height of the canopy screen around the canopy (if present, $N = 69$), the surface area of the supply canopy, and the air speed directly under the diffuser cloth of the canopy. Larger canopy size and higher air speed also increased the EPR.

For ILRs, height of the canopy screen around the canopy (if present, $N = 18$) and surface area of the canopy both contributed positively to the EPR. In addition, for the ILRs the position of the exhaust air terminals was also significant. A significant positive effect was found for those ILRs ($N = 9$) where the exhaust air terminal was not in one of the pre-specified positions (0: high/low in the corners of the ILR ($N = 12$); 1: only low exhaust in the corners of the ILR ($N = 2$); and 2: plinth exhaust ($N = 0$)), but in a position marked as 'different'. In most cases 'different' referred to various positions of the exhaust air terminals on the walls between the corners of the room.

Table IICollected and analysed information for each instrument lay-up room (ILR) ($N = 23$)

Variable	Unit	Mean (range)
Effective protection ratio ^a	%	80.7 (11–100)
Size of the ILR (A_{ILR})	m ²	29.0 (11.6–58.2, $N = 17$)
Size of the canopy (A_{canopy})	m ²	8.5 (1.82–19.45)
Ratio A_{canopy}/A_{ILR}	%	22% (10–33%)
Presence of furnished/equipped room	0: empty ILR 1: empty ILR with instrument tables 2: fully equipped (including instrument tables)	0: $N = 6$ 1: $N = 6$ 2: $N = 11$
Height of the canopy screen (if present)	cm	38.89 (15–85)
Temperature difference between supply and periphery air	K	1.1 (0.2–1.5)
Air speed direct under the supply canopy	m/s	0.30 (0.19–0.51)
Position of exhaust air terminals	0: high/low in the corners of the ILR 1: only low exhaust in the corners of the ILR 2: plinth exhaust 3: different	0: $N = 12$ 1: $N = 2$ 2: $N = 0$ 3: $N = 9$
Type of system ^b	0: one temperature system with one speed 1: two or more temperature systems with one speed 2: two-speed system with a higher speed in the middle zone 3: two-speed system with a higher speed at the edge	0: $N = 6$ 1: $N = 16$ 2: $N = 0$ 3: $N = 0$
Minimum distance between wall and canopy	m	0.46 (0.00–1.32)
Surface(s) protruding from the wall(s)	Yes or no	No: $N = 21$ Yes: $N = 2$

One system with a horizontal unidirectional downflow.

^a Ratio of the size of the protected area to the surface area of the supply.^b Canopy based on the corner and intermediate points where available.

Discussion

Using additional measuring points at intermediate positions between the corners led to higher values being found both for the size of the protected area (relative increase of 17.9% for the ORs, 23.4% for the ILRs) and the EPR (relative increase of 17.7% for the ORs, 9.4% for the ILRs). This seems logical: the mandatory measuring points at the corners represent a worst-case situation; using additional measuring points helps define a more precise protected area.

Larger canopy size will result in a higher EPR in most cases. An equal absolute reduction of the protected area will have a

lower effect on the EPR with a larger canopy. This positive correlation holds for both types of room (OR and ILR).

The higher EPR of ILRs (76%/80%) compared to ORs (61%/71%) may perhaps be explained by the fact that there are usually fewer obstacles in the UDF airflow of ILRs than in ORs.

A rectangular canopy shape seemed less effective than a canopy with angled corners (irregular hexagonal shape). An angled-corner canopy not only increased the outcome but also reduced the amount of air needed. In new canopy designs elimination of all sharp corners (right angles) should be considered. In both types of room (OR and ILR) the presence of a canopy screen around the canopy had a positive effect on the

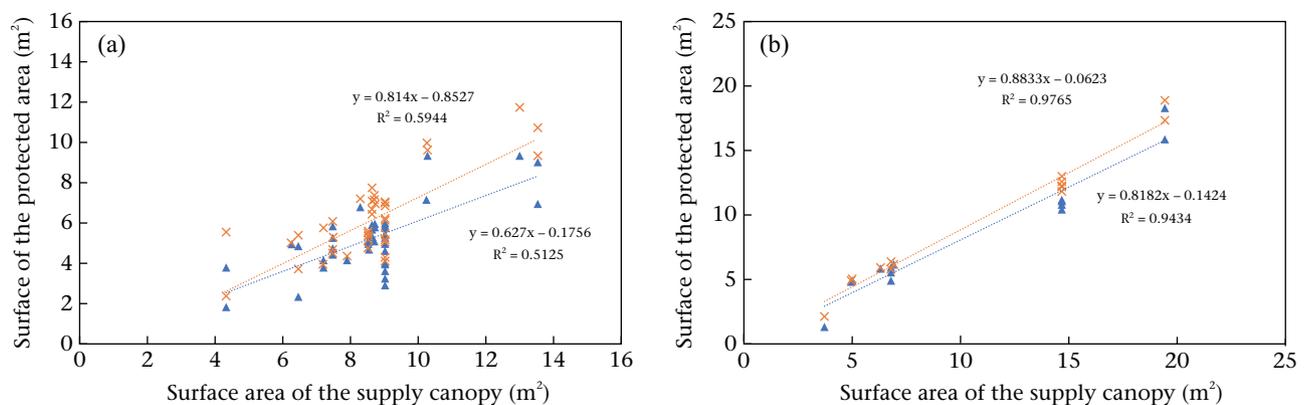


Figure 2. Relationship between the surface area of the supply canopy and size of the protected area in the operating rooms (ORs) (A; $N = 45$) and instrument lay-up rooms (ILRs) (B; $N = 15$) with mandatory and additional measurements.

Table III
Multiple regression model of the operating rooms ($N = 101$)

Variable	β	Standardized β	P-value
Constant	-18.59		0.188
Shape of the canopy = 1 (rectangle with two angled corners (i.e. hexagonal))	16.23	0.37	0.000
Air speed directly under the supply canopy	233.79	0.44	0.000
Height of the skirt	0.22	0.32	0.001
Type of system = 1 (two or more temperature systems with one speed)	-12.31	-0.30	0.002
Size of the canopy	2.10	0.18	0.030

Table IV
Multiple regression model of the instrument lay-up rooms ($N = 23$)

Variable	β	Standardized β	P-value
Constant	59.56		0.000
Position of exhaust air terminals = 3 (different)	45.40	0.93	0.000
Height of the skirt	-0.62	-0.69	0.000
Size of the canopy	2.62	0.61	0.002

outcome. Canopy screens around canopies are not currently required by most standards and guidelines giving requirements for design of air distribution systems in ORs [27–29]. This requirement is currently only found in the HTM 03 and in discussion by Whyte [1,30].

In ORs the air speed under the canopy is a significant variable even with the limited range of values found in the present study (average: 0.27 m/s; range: 0.14–0.34). Figure 3 shows the distribution of the air speed under the canopy as a box plot; the median velocity was 0.28 m/s in the OR and 0.29 m/s in the ILR.

Reasoning on the basis of physics principles, air exhausts mounted in plinth terminals should produce the best results. However, no such plinth exhausts were present in our dataset. Several studies have concluded that operating lamps have a substantial effect on the performance of air distribution systems in ORs [10,31,32]. These conclusions were not mirrored in

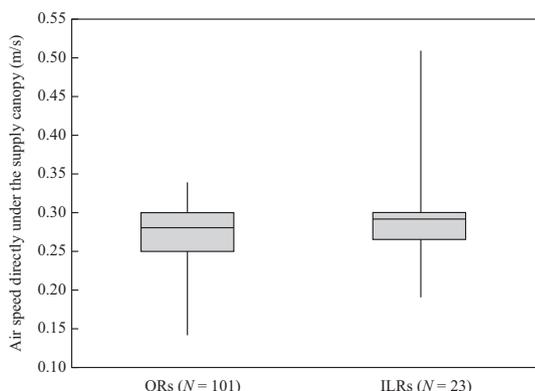


Figure 3. Distribution of the air speed under the supply canopy.

the results of the present study, which found no significant effects on the EPR from either the presence or the types of operating lamp. These findings may be influenced by the fact that Guideline 7 requires measurements with operating lamps present only for new ORs ($N = 90$). For existing ORs ($N = 11$) measurements without operating lamps present are allowed. Since in the design of new ORs the presence and characteristics of operating lamps can be taken into account, systems in new ORs can be assumed to have been designed for optimal performance with operating lamps present.

It is likely that the overall performance level of the ORs and ILRs included in the study was high compared to the average for all Dutch hospitals. This has no limiting effect on the validity of the study's findings. On the contrary, the likelihood that all systems included in the study are in good working order means that differences in outcome can be confidently attributed to design features rather than to degraded or malfunctioning system components, for example.

This study confirms that there is significant variation in the performance of UDF systems in the at-rest condition. It has been established that differences in design of UDF systems can lead to major differences in performance. Accordingly, studies that do not take design variables into account when comparing UDF systems with other system typologies cannot be said to produce accurate and balanced comparisons [20–24].

All ORs included in the study were fully equipped 'at rest'. What 'fully equipped' entails in terms of number, type, and dimensions of medical equipment, inventory items, and fixed furnishings present may vary considerably. This may have had some effect on the outcomes of the study.

The results of this study can be used as guidance for the future design of UDF systems and to improve the performance of existing systems. The study also confirms that it is not automatically true that any system equipped with a supply canopy in the ceiling can be considered an effective UDF system.

In conclusion, based on measurements according to Guideline 7 it can be concluded that on average the EPR is 66%, based on the mandatory measuring points at the corners of the canopy and an average supply surface area of 8.88 m² ($N = 124$). If additional measuring points at intermediate positions between the corners are also taken into account, the average EPR rises to 75%.

Across the 124 rooms included in the study (101 ORs and 23 ILRs) the EPR was positively affected by the presence and the height of a canopy screen around the canopy, the surface area of the supply canopy, and the air speed of the supply air under the canopy. A rectangular canopy with an irregular hexagonal shape (two angled corners) had the largest positive effects on the EPR in ORs. This information can be used as guidance for future design of UDF systems.

The availability of a standard method for measurements at rest is important as a precondition to allow consistent evaluation of the effect of measures taken, and to support the creation of a knowledge base regarding systems performance. This also applies to standard measurements of colony-forming units during ongoing surgery [33].

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with additional information regarding the technical characteristics of the rooms.

Conflict of interest statement

None declared.

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