Journal of Hospital Infection 105 (2020) 216–224

Available online at www.sciencedirect.com

Journal of Hospital Infection

journal homepage: www.elsevier.com/locate/jhin

Operating room ventilation and the risk of revision due to infection after total hip arthroplasty: assessment of validated data in the Norwegian Arthroplasty Register

H. Langvatn [a,b,c,*], J.C. Schrama [a], G. Cao [d], G. Hallan [a,c], O. Furnes [a,c], E. Lingaas [e], G. Walenkamp [f], L.B. Engesæter [a,c], H. Dale [a,c]

[a] Norwegian Arthroplasty Register, Department of Orthopedic Surgery, Haukeland University Hospital, Bergen, Norway
[b] Department of Orthopedic Surgery, St Olav's University Hospital, Trondheim, Norway
[c] Department of Clinical Medicine, University of Bergen, Bergen, Norway
[d] Department of Energy and Process Engineering, Norwegian University of Science and Technology, Trondheim, Norway
[e] Department of Infection Prevention, Oslo University Hospital, Oslo, Norway
[f] Department of Orthopedic Surgery, Maastricht University Hospital, Maastricht, the Netherlands

ARTICLE INFO

Article history:
Received 9 March 2020
Accepted 6 April 2020
Available online 11 April 2020

Keywords:
Total hip arthroplasty
Periprosthetic joint infection
Operating room ventilation
Laminar airflow
Unidirectional airflow
Norwegian Arthroplasty Register

SUMMARY

Background: The air in the operating room is considered a risk factor for surgical site infection (SSI) due to airborne bacteria shed from the surgical staff or from patients themselves.

Aim: To assess the influence of validated operating room (OR) ventilation data on the risk of revision surgery due to deep infection after primary total hip arthroplasty (THA) reported to the Norwegian Arthroplasty Register (NAR).

Methods: Forty orthopaedic units reporting THAs to the NAR during the period 2005–2015 were included. The true type of OR ventilation in all hospitals at the time of primary THA was confirmed in a previous study. Unidirectional airflow (UDF) systems were subdivided into: small, low-volume, unidirectional vertical flow (lvUDVF) systems; large, high-volume, unidirectional vertical flow (hvUDVF) systems; and unidirectional horizontal flow (UDHF) systems. These three ventilation groups were compared with conventional, turbulent, mixing ventilation (CV). The association between the end-point, time to revision due to infection, and OR ventilation was estimated by calculating relative risks (RRs) in a multivariate Cox regression model, with adjustments for several patient- and surgery-related covariates.

Findings: A total of 51,292 primary THAs were eligible for assessment. Of these, 575 had been revised due to infection. A similar risk of revision due to infection after THA performed was found in ORs with lvUDVF and UDHF compared to CV. THAs performed in ORs with hvUDVF had lower risk of revision due to infection compared to CV (RR = 0.8; 95% CI: 0.6–0.9; $P = 0.01$).

* Corresponding author. Address: Department of Orthopedic Surgery, St Olav's University Hospital, Prinsesse Kristinas Gate 3, 7035, Trondheim, Norway. Tel.: +47 72 55 32 15.
E-mail address: hakon.langvatn@helse-bergen.no (H. Langvatn).

https://doi.org/10.1016/j.jhin.2020.04.010

Conclusion: THAs performed in ORs with hvUDVF systems had lower risk of revision due to infection compared to THAs performed in ORs with CV systems. The perception that all UDF systems are similar and possibly harmful seems erroneous.

Introduction

Infection after total hip arthroplasty (THA) is devastating for the patients and generates high public costs [1]. The air in the operating room (OR) is considered a potential source of contamination and subsequently a risk factor for surgical site infection (SSI) due to airborne bacteria and other viable microorganisms (colony-forming units (cfu)) shed from the surgical staff or from patients [2–7]. The number of cfu in the OR may be altered by staff behaviour such as the number of personnel, door openings, and physical movement, and by the use of other preventive measures such as impermeable gowns and space helmets [8–10]. Previous studies have postulated that the density of cfu is correlated with the rate of postoperative infection, but the findings are controversial as the isolated effect of air cleanliness is hard to assess [6,11–15]. Other studies show that air contamination is not directly associated with wound contamination and periprosthetic joint infection [16,17].

Unidirectional airflow (UDF or UDAF) systems (formerly known as laminar airflow (LAF) systems) have been used during ultraclean surgery since the late 1960s, as they were thought to reduce the incidence of SSI by reducing the cfu density [13]. UDF systems work by sending parallel, filtered air streams with constant velocity directly on to the surgical field to intentionally displace and reduce the flow of less clean air from the rest of the OR to the surgical field. This is in contrast to the conventional ventilation (CV) systems, which use the dilution principle. CV systems supply turbulent air in order to dilute airborne contamination, mixing polluted air with clean air, and are often termed turbulent and/or mixing ventilation systems [18].

Unidirectional airflow as a prophylactic measure against SSI has been supported ever since Lidwell and colleagues published their randomized, clinical trial in the 1980s [19]. For THA and total knee arthroplasty (TKA), they found lower risk of 'deep joint sepsis' after arthroplasty performed in ultra-clean air (UCA; cfu $<10/m^3$) with a relative risk (RR) of 0.4 compared to a control group with non-ultra-clean air. The study has been criticized for having methodological weaknesses, but both historic and recent re-evaluations of the study confirm the validity of the findings [15,20–23]. Subsequent observational studies from the same decade, controlled for antibiotic prophylaxis, found no convincing influence of OR ventilation on the rate of SSI [24,25]. More recently, studies from surveillance registries have suggested that LAF actually may increase the risk of infection after arthroplasty [26–28]. Two recent systematic reviews, based partly on these registry studies, conclude that UDF systems should not be installed in new ORs [20,29]. One of the reviews includes an observational study from the Norwegian Arthroplasty register (NAR), not studying the effect of UDF specifically, using ventilation only as an adjustment variable in the study of infection trend [30]. In a previous validation study, we found 12% misreporting of ventilation data to the NAR, questioning the validity of studies based exclusively on ventilation data reported from surgeons or surgical departments [31]. In addition, there are numerous different configurations of UDF systems, and when studying their effect on the rate of postoperative infections it is important to know the dissimilarities between the different UDF systems and that these have evolved over the decades.

Our aim in the present study was to assess the association between validated, factual OR ventilation systems and the risk of revision due to deep infection after primary THA.

Methods

Since its inception in 1987, the NAR has registered data on primary and revision THAs in Norway. The register form is filled in by the surgeon immediately after surgery, containing information on patient identity, date of operation, indication for surgery and other surgery-related factors. In addition, certain patient-related factors such as sex, age, and comorbidity are registered. Primary THA and any subsequent revisions are linked through a unique person identity number that follows each citizen from birth to death. Revision is defined as removal or exchange of prosthesis parts, whereas revision cause, i.e. deep infection, is determined by the surgeon based on perioperative assessments and clinical evaluation. Cases of revision due to infection are thus reported to the NAR before the culturing of peroperative tissue samples is ready. The data is validated, with 97% completeness of reporting of primary THAs, 93% reporting of revisions, and 100% coverage of Norwegian hospitals [32].

The factual OR ventilation on each hospital was validated and either confirmed or corrected in a previous study [31]. To be included as a UDF system, it had to be verified that the system had been installed with a multistage high-efficiency particulate air (HEPA)-filtered, unidirectional diffuser array. Based on technical data collected, the following classification of ventilation systems was established for further analyses: small, low-volume, unidirectional, vertical flow systems (lvUDVF: volume flow rate (VFR; m^3/h) $<10{,}000$ and canopy size (m^2) <10); large, high-volume, unidirectional, vertical flow systems (hvUDVF: VFR $\geq 10{,}000$ and canopy size ≥ 10); and unidirectional horizontal flow (UDHF). We did not have complete data on the volume of each OR, so we were unable to calculate the exact air changes per hour (ACH). As the ACH also might be dependent on other factors, we did not include ACH in the definition of the different UDF systems. The CV systems included in this study were verified to fulfil the requirement of multi-stage HEPA-filtered air with 20 ACH and positive pressurization [33].

The period of inclusion was 2005–2015, primarily due to the fact that the patients' American Society of Anesthesiologists (ASA) class, a risk factor associated with infection, was only

reported to the NAR from 2005 and onwards [34]. All patients during this period received systemic, antibiotic prophylaxis.

A separate survey confirmed negligible use of space suits and/or helmets. Three of the hospitals used space suits in very short periods of time, but discontinued the use due to loss of spatial awareness.

Validated ventilation data were obtained for 40 out of 62 public hospitals reporting THAs to the NAR in the inclusion period [31]. Out of 60,298 THAs performed in these 40 hospitals, 2046 were performed in a period of ventilation system exchange or update, and were excluded. A total of 4313 THAs performed in UDVF ventilation were excluded due to lack of detailed information on certain ventilation covariates from parts of the inclusion period, essential for our main analyses, or due to the current UDVF system not fulfilling the defined criteria for lvUDVF or hvUDVF. In addition, 2647 THAs were excluded due to missing patient or procedure covariates. Hence, 51,292 THAs were eligible for analyses.

Statistics

The association between OR ventilation and revision due to infection was estimated by Cox regression analyses. Relative risk (RR), as a measure of hazard rate ratios, was calculated with 95% confidence intervals (CIs). End-point was date of revision due to deep infection. Further, adjusted four-year survival rates were calculated, as well as Kaplan–Meier four-year survival rates, and cumulative survival curves with OR ventilation as strata. In the multivariate analyses, we adjusted for sex, age at primary surgery, indication for primary THA, ASA class, method of fixation, modularity of the prosthesis, and duration of surgery. Year of primary THA was included as an adjustment variable to account for unknown time dependent confounding. Additional analyses were made with one- and two-year follow-up. Further, additional assessments were performed to adjust for spatial orientation of the wound in the OR, whether the wound was oriented upwards or to the side, based on an evaluation of patient positioning and surgical approach as potential risk factors. The analyses were performed in concordance with the guidelines for statistical analyses of arthroplasty register data [35]. $P < 0.05$ and non-overlapping 95% CIs were considered statistically significant.

Statistical analyses were performed using SPSS version 24 (SPSS Inc., 2004) and R (R Foundation for Statistical Computing, 2014). The study was performed in accordance with the RECORD and STROBE statements.

Ethics

The registration of data and further assessment were performed confidentially following patient consent and according to Norwegian and EU data protection rules.

Results

Among the 51,292 eligible THAs, 575 (1.1%) had been revised due to infection. Demographics and distribution of risk factors in the different ventilation groups are presented in Table I. All patients received systemic antibiotic prophylaxis and all cemented THAs had antibiotic loaded bone cement. The distribution of the risk factors was similar for the four ventilation groups, except for more uncemented THAs in the two hospitals using UDHF (one rural and one regional hospital). In the remaining three ventilation groups, rural, regional, university, and specialized elective hospitals were evenly represented. During the study period, four hospitals converted from CV to hvUDVF and one hospital converted from lvUDVF to hvUDVF between 2006 and 2009. From 2009, 16 hospitals used CV, nine used lvUDVF, and 13 used hvUDVF systems. The annual distribution of THAs within the different groups of ventilation system is presented in Figure 1. The risk factors and confounders in the adjusted analyses are presented in Table II. Sex, age, ASA class, and duration of surgery were associated with risk of revision due to infection.

Table I
Baseline characteristics for the total hip arthroplasties performed in the different ventilation systems

Characteristic	Type of operating room ventilation			
	Conventional	lvUDVF	hvUDVF	UDHF
No. of THAs	17,297	12,639	17,960	3396
Sex				
Male	34%	33%	34%	33%
Female	66%	67%	67%	67%
Age group (years)				
<45	2%	3%	3%	3%
45–54	6%	7%	8%	7%
55–64	22%	23%	23%	22%
65–74	36%	36%	36%	35%
75–84	28%	27%	25%	28%
>85	5%	5%	5%	5%
Indication for primary THA				
Osteoarthritis	82%	75%	77%	83%
Inflammatory disease	3%	3%	2%	2%
Hip fracture	3%	2%	3%	1%
Complication after hip fracture	6%	6%	6%	5%
Complication after childhood hip disease	5%	12%	10%	6%
Necrosis of the femoral head	2%	2%	3%	3%
ASA class				
1	22%	18%	19%	19%
2	57%	63%	61%	62%
≥3	21%	19%	20%	19%
Method of fixation				
Uncemented	20%	9%	29%	64%
Cemented	80%	91%	71%	36%
Modularity of the prosthesis				
Monoblock	5%	5%	4%	0
Modular	95%	95%	96%	100%
Duration of surgery (min)				
<70	20%	20%	27%	18%
70–99	51%	41%	36%	48%
100–129	21%	28%	27%	27%
>130	8%	11%	10%	7%

lvUDVF, small, low-volume, unidirectional vertical flow systems; hvUDVF, large, high-volume, unidirectional vertical flow systems; UDHF, unidirectional horizontal flow systems; THA, total hip arthroplasty; ASA, American Association of Anesthesiologists.

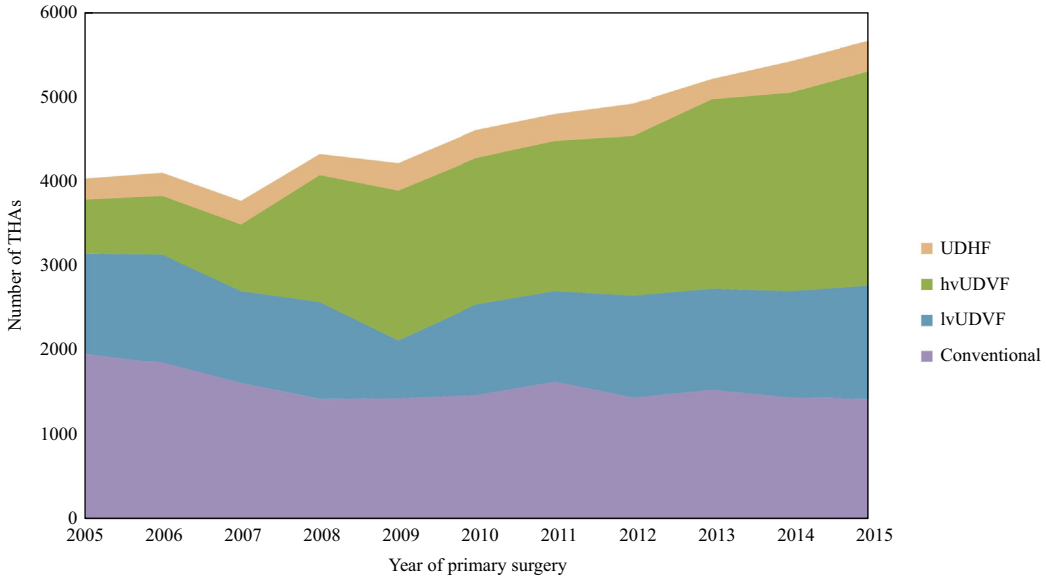

Figure 1. Annual number of primary THAs in the four different ventilation groups during 2005–2015. UDHF, unidirectional horizontal flow systems; hvUDVF, large, high-volume, unidirectional vertical flow systems; lvUDVF, small, low-volume, unidirectional vertical flow systems.

Assessing the UDF group as one encompassing entity, primary THAs performed in ORs with such unclassified UDF had a risk of revision due to infection similar to that of CV (RR: 0.9; 95% CI: 0.7–1.2). The risk of revision due to infection after THAs performed in ORs with lvUDVF and UDHF was similar to those performed in CV (Table III, Figure 2). THAs performed in ORs with hvUDVF had a lower risk of revision due to infection than those performed in CV (Table III, Figure 2). No UDF system was associated with higher risk of revision due to infection after THA compared to CV.

Adjusting for wound spatial orientation and reducing follow-up time to one year and two years had only minor influences on the results. We did not have complete data on the spatial volume of all ORs in order to calculate the exact ACH, but adjusting for operating room volume in analyses of the available ORs had negligible impact on the results.

Discussion

The risk of revision due to infection after primary THA performed in ORs with hvUDVF was 20% lower than after THA performed in CV, whereas THA performed in ORs with lvUDVF or UDHF had a risk of revision due to infection similar to that of THA performed in CV. No UDF system was associated with higher risk of revision due to infection after THA compared to CV.

Recent registry studies as well as systematic reviews and meta-analyses are questioning the effect of LAF/UDF as a prophylactic measure against postoperative infection, as they suggest for arthroplasty an increased risk of SSI and revision due to infection [20,26–30]. This is in contrast to the results from our study on validated ventilation data. Recent World Health Organization (WHO) guidelines, though conditional, recommend not to use UDF systems to reduce the risk of SSI in arthroplasty [36]. The WHO recommendation is based partly on a few observational studies with some methodological issues: no UDF system differentiation or definition based on technical specifications, limited documentation of validation on the UDF systems, and limited information on coverage or completeness of reporting of the end-point SSI or revision due to infection [21,22,31,37]. Some of these studies had only six months to one year follow-up, and others had no systematic post-discharge surveillance. This has been a point of debate as low-grade infections caused by airborne contaminants might be excluded as they may present at a much later stage [21,22]. Coagulase-negative staphylococci (CoNS) are the most frequent bacterial cause of revision of infected THA [38]. Since CoNS are regarded as commensal bacteria and since CoNS have also been shown to be the most frequent bacterial cause of late infection, this may suggest that direct contamination from primary surgery is the likely mechanism of THA infection, even in infection more than two years after primary THA [38]. Haematogenous seeding of CoNS is possible, but is less likely to occur as this requires substantial bacteraemia [39,40]. We studied the effect of OR ventilation with four years follow-up, comparable to the Lidwell studies [21,41].

One possible explanation for the reported contrary effect of UDF could be improper positioning and movement of personnel, theatre lamps, etc. in the airflow [18,42,43], thereby abolishing the preventive effect by creating more turbulence. This might especially be the case in the boundary areas due to insufficient size of the protected UDF zone. Studies have shown impact of canopy size on bacterial counts in the surgical area, where the minimum size of a UDF ceiling distribution system has been recommended to be at least 320×320 cm for ultra-clean surgery [44–46]. We studied the effect of canopy size on infection risk by defining cut-off for canopy size in accordance with this recommendation.

In addition, the potentially lower tissue temperature and bacterial impingement danger due to disruption of the

Table II
Relative risks of revision due to infection after primary total hip arthroplasties in the Norwegian Arthroplasty Register

Risk factor	Included	Revised due to infection	Relative risk	95% CI	*P*-value
Sex					
Male	17,144	268	1.8	1.5–2.1	<0.001
Female	34,148	307	1		
Age group (years)					
<45	1334	15	1.2	0.7–2.1	0.5
45–54	3667	27	0.8	0.5–1.3	0.4
55–64	11,584	101	0.9	0.7–1.2	0.6
65–74	18,475	180	1		
75–84	13,669	202	1.5	1.2–1.8	<0.001
>85	2563	50	1.9	1.4–2.7	<0.001
Indication for primary THA					
Osteoarthritis	40,305	448	1		
Inflammatory hip disease	1293	18	1.3	0.8–2.1	0.3
Hip fracture	1180	17	1.3	0.8–2.1	0.3
Complication after hip fracture	2963	39	1.0	0.7–1.4	0.9
Complication after childhood hip disease	4342	31	0.8	0.5–1.2	0.2
Necrosis of the femoral head	1209	22	1.5	1.0–2.3	0.08
ASA class					
1	10,178	60	0.6	0.5–0.8	<0.001
2	30,837	347	1		
≥3	10,276	168	1.3	1.1–1.5	0.02
Method of fixation					
Uncemented	11,974	127	1.0	0.8–1.2	1.0
Cemented	39,318	448			
Modularity of the prosthesis					
Monoblock	2059	11	0.5	0.3–1.0	0.04
Modular	49,233	564	1		
Duration of surgery (min)					
<70	11,405	120	1.1	0.9–1.4	0.4
70–99	22,125	225	1		
100–129	12,935	147	1.1	0.9–1.4	0.3
>130	4827	83	1.6	1.3–1.8	0.002

CI, confidence interval; THA, total hip arthroplasty; ASA, American Association of Anesthesiologists.
Adjusted for sex, age, indication for primary THA, ASA class, modularity of the prosthesis, method of fixation, and duration of surgery, in addition to operating room ventilation and year of primary THA.

wound's own protective, thermal plume, is also claimed to disturb the effectiveness of the UDF [26,47–49]. One recent study identifies the use of UDF as a significant risk factor for hypothermia, thereby being subsequently a risk factor for infection of the wound [50,51]. To counteract these issues, forced air warming (FAW) systems have been used. These are also thought to disturb the laminar airflow [52,53]. However, recent reviews conclude that the evidence for this is sparse [54–56]. A recent experimental study found that the disturbing effect of FAW is counteracted by sufficient air velocity in the UDF systems [57]. As the air velocity of different UDF systems is adjustable, we could not use it as a constant adjustment variable in our analyses. It was therefore indirectly assessed by studying the VFR, varying in the range of 1000–5000 m^3/h in older, low-volume systems and 10,000–20,000 m^3/h in newer, high-volume systems. The latter is necessary to create velocities in the desired minimum range of 0.3–0.38 m/s through large area canopies [58].

UDF systems are able to create lower cfu concentrations than CV systems both in air and close to the operation site. This is shown both in computational fluid dynamics studies and in experimental studies [44,59–66]. Studies have also shown an association between the cfu concentration and SSI, but the question remains whether other risk factors such as the patient's immunological status, bacterial virulence, antibiotic prophylaxis, surgical technique, etc., are indeed much more important [6,11–14]. The latter is supported by studies showing that SSI after elective orthopaedic surgery is more frequently caused by endogenous transmission than previously assumed [67,68]. Further indicating the patients' skin commensals as source of infection are studies on the bacteriology of infected shoulder arthroplasty and postoperative infections after spinal surgery, showing a high proportion of *Propionibacterium* (*Cutibacterium*) *acnes* [69–71]. This is a species known to be abundant in sebaceous glands of the skin in such regions, and as the bacteriology of infected total hip arthroplasties is different, dominated by staphylococci, this might indicate that the patients are their own source of infection. If the cleanliness of the air in the OR is the same during different types of prosthetic surgery and a significant source for postoperative infection, why does the bacteriological spectrum of

Table III
Relative risks of revision due to deep infection after primary total hip arthroplasty, adjusted four-year survival and Kaplan–Meier four-year survival for the four operating room ventilation systems

Operating room ventilation	THAs included	THAs revised due to infection	Relative risk	95% CI	*P*-value	Kaplan–Meier four-year survival	Adjusted four-year survival	Censored before four years	At risk at four years
Conventional	17,297	208	1			98.8 (98.6–98.9)	98.9 (98.7–99.0)	1627	12,914
lvUDVF	12,639	138	0.9	0.7–1.1	0.3	98.9 (98.7–99.0)	99.0 (98.9–99.2)	1081	9077
hvUDVF	17,960	175	0.8	0.6–0.9	0.01	99.0 (98.9–99.2)	99.1 (99.0–99.3)	1423	11,860
UDHF	3396	54	1.3	0.9–1.8	0.1	98.4 (97.9–98.8)	98.6 (98.2–99.0)	342	2366

THA, total hip arthroplasty; CI, confidence interval; lvUDVF, small, low-volume, unidirectional vertical flow systems; hvUDVF, large, high-volume, unidirectional vertical flow systems; UDHF, unidirectional horizontal flow systems.
Adjustments were made for sex, age, indication for primary THA, American Association of Anesthesiologists class, modularity of the prosthesis, method of fixation, duration of surgery, and year of primary THA.

infections vary between different regions of the body? This questions the extent of air cleanliness importance. Despite this, and with increasing antibiotic resistance taken into account, it seems logical to reduce the peroperative, bacterial load to a minimum. This will be increasingly important in an era with increasing microbial resistance to antibiotics [72,73].

Our finding of a 20% lower risk of revision due to infection after THA performed in hvUDVF compared to CV is minute, considering also that the incidence of revision due to infection is only around 1%. However, UDF systems can create cleaner air, and, taking our results into account, it seems erroneous to discontinue the use of large, high-volume, vertical UDF systems in the ORs of the future. Technological development and multidisciplinary co-operation with the focus on correct implementation and function of the ventilation systems should be encouraged [22,65,66].

Our study is based on data from the NAR with a large number of THAs, with good quality, coverage, and completeness [74–76]. This gives us a unique opportunity to study relatively rare events, such as deep infection after THA, with detailed information on surgery- and patient-related confounders.

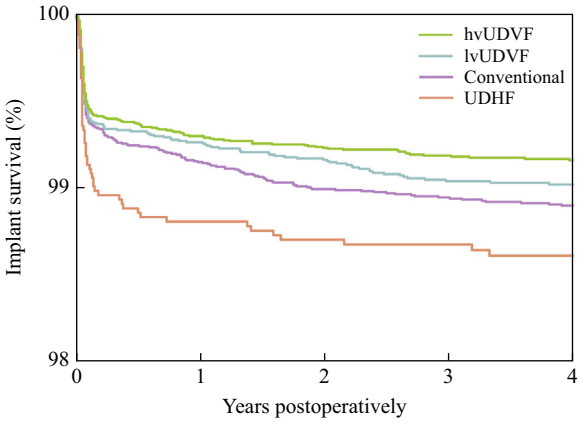

Figure 2. Survival curves for total hip arthroplasties (THAs) performed with different ventilation systems and revised due to infection. Adjusted for sex, age, indication for primary THA, American Association of Anesthesiologists class, modularity of the prosthesis, method of fixation, duration of surgery, and year of primary THA. lvUDVF, small, low-volume, unidirectional vertical flow systems; hvUDVF, large, high-volume, unidirectional vertical flow systems; UDHF, unidirectional horizontal flow systems.

Other register studies on OR ventilation have been criticized for not making a thorough adjustment of antibiotic prophylaxis, for using surgeon- or surgical department-reported data on ventilation, for not differentiating the UDF systems on technical specifications, and for having a limited follow-up time [21]. All of our cases received systemic, antibiotic prophylaxis and the multivariate analyses were conducted on the basis of validated ventilation data. Further, we did subanalyses on canopy size and VFR with four-year follow-up. All this adds strength to our study and makes it a substantial contribution to new knowledge in the field.

This study suggests merely the association between OR ventilation and revision due to deep infection after primary THA. There will be unknown confounding such as human behavioural factors in the OR, incorrect implementation and maintenance of the ventilation systems, and other factors potentially disturbing the UDF. We have no information on patient warming systems, use of surgical drapes, number of personnel in the room, number of door openings, etc., but we have no reason to believe that this would be different between the four ventilation groups in our study. In addition, revision due to infection may be underreported, but, as the underreporting of revision is similar between the hospitals, this will add minimal selection bias and subsequent impact on our results [32,77–79].

There has been an increase in the share of hvUDVF systems over the last 20 years (Figure 1). This increase is parallel to the reported, increased risk of revision due to infection after THA [80,81]. This will necessarily be a time-dependent confounder in our analyses and we have addressed this by adjusting for year of primary surgery as a continuous variable in the analysis.

Only two of the included hospitals used UDHF. In addition, these two hospitals had a higher share of uncemented THAs. This may add selection bias, but the type of fixation was adjusted for.

The modularity of the prosthesis may affect the incidence of reported revision due to infection. Non-modular/monoblock THAs (i.e. Charnley prostheses) were used by some hospitals until 2014. They do not contain modular parts, and hence, infections of such THAs treated with debridement, antibiotics, and implant retention (DAIR) were not reported to the NAR until 2011 from when all DAIRs were reported regardless of component exchange or not. This is in contrast to modular THAs, which contain removable components exchanged during a DAIR procedure. Hence, these debridements were defined as revisions throughout the study period, and were subsequently

reported to the NAR as such. This will potentially lead to an underreporting of revision due to infection after THA with monoblock prostheses, which was addressed by adjusting for modularity.

Forty of 62 public hospitals were included. Most of the excluded hospitals performed primary THAs throughout the whole study period, as did most of the included ones, and with a completeness of reporting of more than 97% [75]. Time trends of reporting are therefore not thought to affect the findings. The reporting of primary THAs was similar in the two groups (included/excluded) and the distribution of hospital types in the two groups was also similar (rural hospitals, regional/university hospitals, specialized elective hospitals). We therefore believe that the impact of selection bias is minimal.

In conclusion, UDF ventilation assessed as one encompassing entity did not influence the risk of revision due to infection after primary THA compared to CV. When differentiating the UDF systems on technical specifications, however, primary THAs performed in ORs with hvUDVF ventilation systems had a lower risk of revision due to infection compared to ORs with CV. Considering also that UDF systems can create lower particle and microbial load than CV systems, our findings support the use of hvUDVF systems for all ultraclean surgery in the future.

Acknowledgements

We would like to thank the NAR contact surgeons and engineers at the hospitals for contributing to data collection. We also thank Norwegian surgeons for persistently and thoroughly reporting primary THAs to the NAR.

Conflict of interest statement
None declared.

Funding sources
None.

References

[1] Kurtz SM, Ong KL, Schmier J, Mowat F, Saleh K, Dybvik E, et al. Future clinical and economic impact of revision total hip and knee arthroplasty. J Bone Joint Surg Am 2007;89(Suppl 3):144–51.
[2] Pedersen AB, Svendsson JE, Johnsen SP, Riis A, Overgaard S. Risk factors for revision due to infection after primary total hip arthroplasty. A population-based study of 80,756 primary procedures in the Danish Hip Arthroplasty Registry. Acta Orthop 2010;81:542–7.
[3] Namba RS, Inacio MC, Paxton EW. Risk factors associated with surgical site infection in 30,491 primary total hip replacements. J Bone Joint Surg Br 2012;94:1330–8.
[4] Berbari EF, Hanssen AD, Duffy MC, Steckelberg JM, Ilstrup DM, Harmsen WS, et al. Risk factors for prosthetic joint infection: case–control study. Clin Infect Dis 1998;27:1247–54.
[5] Whyte W, Hodgson R, Tinkler J. The importance of airborne bacterial contamination of wounds. J Hosp Infect 1982;3:123–35.
[6] Ritter MA. Operating room environment. Clin Orthop Relat Res 1999;369:103–9.
[7] Whyte W, Hambraeus A, Laurell G, Hoborn J. The relative importance of the routes and sources of wound contamination during general surgery. II. Airborne. J Hosp Infect 1992;22:41–54.
[8] Andersson AE, Bergh I, Karlsson J, Eriksson BI, Nilsson K. Traffic flow in the operating room: an explorative and descriptive study on air quality during orthopedic trauma implant surgery. Am J Infect Control 2012;40:750–5.
[9] Smith EB, Raphael IJ, Maltenfort MG, Honsawek S, Dolan K, Younkins EA. The effect of laminar air flow and door openings on operating room contamination. J Arthrop 2013;28:1482–5.
[10] Pada S, Perl TM. Operating room myths: what is the evidence for common practices. Curr Opin Infect Dis 2015;28:369–74.
[11] Gosden PE, MacGowan AP, Bannister GC. Importance of air quality and related factors in the prevention of infection in orthopaedic implant surgery. J Hosp Infect 1998;39:173–80.
[12] Whyte W, Lidwell OM, Lowbury EJ, Blowers R. Suggested bacteriological standards for air in ultraclean operating rooms. J Hosp Infect 1983;4:133–9.
[13] Charnley J, Eftekhar N. Postoperative infection in total prosthetic replacement arthroplasty of the hip-joint. With special reference to the bacterial content of the air of the operating room. Br J Surg 1969;56:641–9.
[14] Nelson JP, Glassburn Jr AR, Talbott RD, McElhinney JP. The effect of previous surgery, operating room environment, and preventive antibiotics on postoperative infection following total hip arthroplasty. Clin Orthop Relat Res 1980;147:167–9.
[15] SMM-rapport Nr. 5/2001 av operasjonsstuer Ventilasjon. Senter for medisinsk metodevurdering, SINTEF unimed 2001 [in Norwegian]. Available at: https://www.fhi.no/globalassets/dokumenterfiler/rapporter/2009-og-eldre/smm-rapporter/smm-rapport_01-05_ventilasjon_i_operasjonsstuer.pdf [last accessed February 2020].
[16] Jonsson EO, Johannesdottir H, Robertsson O, Mogensen B. Bacterial contamination of the wound during primary total hip and knee replacement. Median 13 years of follow-up of 90 replacements. Acta Orthop 2014;85:159–64.
[17] Birgand G, Toupet G, Rukly S, Antoniotti G, Deschamps MN, Lepelletier D, et al. Air contamination for predicting wound contamination in clean surgery: a large multicenter study. Am J Infect Control 2015;43:516–21.
[18] Cao G, Nilssen AM, Cheng Z, Stenstad LI, Radtke A, Skogas JG. Laminar airflow and mixing ventilation: which is better for operating room airflow distribution near an orthopedic surgical patient? Am J Infect Control 2019;47:737–43.
[19] Lidwell OM, Lowbury EJ, Whyte W, Blowers R, Stanley SJ, Lowe D. Effect of ultraclean air in operating rooms on deep sepsis in the joint after total hip or knee replacement: a randomised study. Br Med J (Clin Res Ed) 1982;285:10–4.
[20] Bischoff P, Kubilay NZ, Allegranzi B, Egger M, Gastmeier P. Effect of laminar airflow ventilation on surgical site infections: a systematic review and meta-analysis. Lancet Infect Dis 2017;17:553–61.
[21] Whyte W, Lytsy B. Ultraclean air systems and the claim that laminar airflow systems fail to prevent deep infections after total joint arthroplasty. J Hosp Infect 2019;103:e9–e15.
[22] Thomas AM, Simmons MJ. The effectiveness of ultra-clean air operating theatres in the prevention of deep infection in joint arthroplasty surgery. Bone Joint J 2018;100-b:1264–9.
[23] Lidwell OM, Lowbury EJ, Whyte W, Blowers R, Stanley SJ, Lowe D. Infection and sepsis after operations for total hip or knee-joint replacement: influence of ultraclean air, prophylactic antibiotics and other factors. J Hyg 1984;93:505–29.
[24] Marotte JH, Lord GA, Blanchard JP, Guillamon JL, Samuel P, Servant JP, et al. Infection rate in total hip arthroplasty as a function of air cleanliness and antibiotic prophylaxis. 10-year experience with 2,384 cementless Lord madreporic prostheses. J Arthropl 1987;2:77–82.
[25] Hill C, Flamant R, Mazas F, Evrard J. Prophylactic cefazolin versus placebo in total hip replacement. Report of a multicentre double-blind randomised trial. Lancet 1981;1:795–6.
[26] Brandt C, Hott U, Sohr D, Daschner F, Gastmeier P, Ruden H. Operating room ventilation with laminar airflow shows no protective effect on the surgical site infection rate in orthopedic and abdominal surgery. Ann Surg 2008;248:695–700.
[27] Hooper GJ, Rothwell AG, Frampton C, Wyatt MC. Does the use of laminar flow and space suits reduce early deep infection after

total hip and knee replacement?: the ten-year results of the New Zealand Joint Registry. J Bone Joint Surg Br 2011;93:85–90.
[28] Breier AC, Brandt C, Sohr D, Geffers C, Gastmeier P. Laminar airflow ceiling size: no impact on infection rates following hip and knee prosthesis. Infect Control Hosp Epidemiol 2011;32:1097–102.
[29] Gastmeier P, Breier AC, Brandt C. Influence of laminar airflow on prosthetic joint infections: a systematic review. J Hosp Infect 2012;81:73–8.
[30] Dale H, Hallan G, Espehaug B, Havelin LI, Engesaeter LB. Increasing risk of revision due to deep infection after hip arthroplasty. Acta Orthop 2009;80:639–45.
[31] Langvatn H, Bartz-Johannessen C, Schrama JC, Hallan G, Furnes O, Lingaas E, et al. Operating room ventilation – validation of reported data on 108 067 primary total hip arthroplasties in the Norwegian Arthroplasty Register. J Eval Clin Pract 2019. https://doi.org/10.1111/jep.13271.
[32] Norwegian Arthroplasty Register. Annual Report 2019. Available at: http://nrlweb.ihelse.net/eng/Rapporter/Report2019_english.pdf [last accessed February 2020].
[33] Health Technical Memorandum 03-01. Heating and ventilation systems. UK Department of Health; 2007. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/144029/HTM_03-01_Part_A.pdf [last accessed February 2020].
[34] Pulido L, Ghanem E, Joshi A, Purtill JJ, Parvizi J. Periprosthetic joint infection: the incidence, timing, and predisposing factors. Clin Orthop Relat Res 2008;466:1710–5.
[35] Ranstam J, Kärrholm J, Pulkkinen P, Mäkelä K, Espehaug B, Pedersen AB, et al. Statistical analysis of arthroplasty data. II. Guidelines. Acta Orthop 2011;82:258–67.
[36] WHO Guideline. Global guidelines for the prevention of surgical site infection. World Health Organization; 2016.
[37] Jutte PC, Traversari RA, Walenkamp GH. Laminar flow: the better choice in orthopaedic implants. Lancet Infect Dis 2017;17:695–6.
[38] Langvatn H, Lutro O, Dale H, Schrama JC, Hallan G, Espehaug B, et al. Bacterial and hematological findings in infected total hip arthroplasties in Norway. Open Orthopaed J 2015;9:445–9.
[39] Uckay I, Lubbeke A, Emonet S, Tovmirzaeva L, Stern R, Ferry T, et al. Low incidence of haematogenous seeding to total hip and knee prostheses in patients with remote infections. J Infect 2009;59:337–45.
[40] Honkanen M, Jamsen E, Karppelin M, Huttunen R, Eskelinen A, Syrjanen J. Periprosthetic joint infections as a consequence of bacteremia. Open Forum Infect Dis 2019;6:ofz218.
[41] Lidwell OM, Lowbury EJ, Whyte W, Blowers R, Stanley SJ, Lowe D. Airborne contamination of wounds in joint replacement operations: the relationship to sepsis rates. J Hosp Infect 1983;4:111–31.
[42] Rezapoor M, Alvand A, Jacek E, Paziuk T, Maltenfort MG, Parvizi J. Operating room traffic increases aerosolized particles and compromises the air quality: a simulated study. J Arthropl 2018;33:851–5.
[43] Aganovic A, Cao G, Stenstad L-I, Skogås JGJB. Impact of surgical lights on the velocity distribution and airborne contamination level in an operating room with laminar airflow system. Build Environ 2017;126:42–53.
[44] Diab-Elschahawi M, Berger J, Blacky A, Kimberger O, Oguz R, Kuelpmann R, et al. Impact of different-sized laminar air flow versus no laminar air flow on bacterial counts in the operating room during orthopedic surgery. Am J Infect Control 2011;39:e25–9.
[45] Traversari AAL, van Heumen SPM, van Tiem FLJ, Bottenheft C, Hinkema MJ. Design variables with significant effect on system performance of unidirectional displacement airflow systems in hospitals. J Hosp Infect 2019;103. e81–e7.
[46] DIN 1946-4:2018-09 Ventilation and air conditioning – Part 4: ventilation in buildings and rooms of health care. 2018. Available at: https://www.beuth.de/en/standard/din-1946-4/294438653 [last accessed February 2020].
[47] Memarzadeh F, Manning AP. Comparison of operating room ventilation systems in the protection of the surgical site. ASHRAE Trans 2002;108:3–15.
[48] Salvati EA, Robinson RP, Zeno SM, Koslin BL, Brause BD, Wilson Jr PD. Infection rates after 3175 total hip and total knee replacements performed with and without a horizontal unidirectional filtered airflow system. J Bone Joint Surg Am 1982;64:525–35.
[49] Taylor GJ, Bannister GC. Infection and interposition between ultraclean air source and wound. J Bone Joint Surg Br 1993;75:503–4.
[50] Yang L, Huang CY, Zhou ZB, Wen ZS, Zhang GR, Liu KX, et al. Risk factors for hypothermia in patients under general anesthesia: is there a drawback of laminar airflow operating rooms? A prospective cohort study. Int J Surg 2015;21:14–17.
[51] Kurz A, Sessler DI, Lenhardt R. Perioperative normothermia to reduce the incidence of surgical-wound infection and shorten hospitalization. Study of Wound Infection and Temperature Group. N Engl J Med 1996;334:1209–15.
[52] Wood AM, Moss C, Keenan A, Reed MR, Leaper DJ. Infection control hazards associated with the use of forced-air warming in operating theatres. J Hosp Infect 2014;88:132–40.
[53] McGovern PD, Albrecht M, Belani KG, Nachtsheim C, Partington PF, Carluke I, et al. Forced-air warming and ultraclean ventilation do not mix: an investigation of theatre ventilation, patient warming and joint replacement infection in orthopaedics. J Bone Joint Surg Br 2011;93:1537–44.
[54] Kellam MD, Dieckmann LS, Austin PN. Forced-air warming devices and the risk of surgical site infections. AORN J 2013;98:354–66. quiz 67–9.
[55] Austin PN. Forced-air warmers and surgical site infections in patients undergoing knee or hip arthroplasty. Annu Rev Nurs Res 2017;35:179–99.
[56] Ackermann W, Fan Q, Parekh AJ, Stoicea N, Ryan J, Bergese SD. Forced-air warming and resistive heating devices. Updated perspectives on safety and surgical site infections. Front Surg 2018;5:64.
[57] Shirozu K, Kai T, Setoguchi H, Ayagaki N, Hoka S. Effects of forced air warming on airflow around the operating table. Anesthesiology 2018;128:79–84.
[58] Whyte WJCA, Review C. The effect of mechanical ventilation and clothing on airborne microbes and wound sepsis in hospital operating rooms, part 1. Clean Air Contain Rev 2015;23:4–12.
[59] Chow TT, Yang XY. Ventilation performance in the operating theatre against airborne infection: numerical study on an ultraclean system. J Hosp Infect 2005;59:138–47.
[60] Erichsen Andersson A, Petzold M, Bergh I, Karlsson J, Eriksson BI, Nilsson K. Comparison between mixed and laminar airflow systems in operating rooms and the influence of human factors: experiences from a Swedish orthopedic center. Am J Infect Control 2014;42:665–9.
[61] Friberg B, Friberg S. Aerobiology in the operating room and its implications for working standards. Proceedings of the Institution of Mechanical Engineers Part H. J Engng Med 2005;219:153–60.
[62] Hansen D, Krabs C, Benner D, Brauksiepe A, Popp W. Laminar air flow provides high air quality in the operating field even during real operating conditions, but personal protection seems to be necessary in operations with tissue combustion. Int J Hyg Environ Health 2005;208:455–60.

[63] Hirsch T, Hubert H, Fischer S, Lahmer A, Lehnhardt M, Steinau HU, et al. Bacterial burden in the operating room: impact of airflow systems. Am J Infect Control 2012;40:e228–32.
[64] Talon D, Schoenleber T, Bertrand X, Vichard P. [Performances of different types of airflow system in operating theatre]. Annales de chirurgie 2006;131:316–21.
[65] Alsved M, Civilis A, Ekolind P, Tammelin A, Andersson AE, Jakobsson J, et al. Temperature-controlled airflow ventilation in operating rooms compared with laminar airflow and turbulent mixed airflow. J Hosp Infect 2018;98:181–90.
[66] Agodi A, Auxilia F, Barchitta M, Cristina ML, D'Alessandro D, Mura I, et al. Operating theatre ventilation systems and microbial air contamination in total joint replacement surgery: results of the GISIO-ISChIA study. J Hosp Infect 2015;90:213–19.
[67] Skramm I, Fossum Moen AE, Aroen A, Bukholm G. Surgical site infections in orthopaedic surgery demonstrate clones similar to those in orthopaedic *Staphylococcus aureus* nasal carriers. J Bone Joint Surg Am 2014;96:882–8.
[68] Mansson E, Hellmark B, Sundqvist M, Soderquist B. Sequence types of *Staphylococcus epidermidis* associated with prosthetic joint infections are not present in the laminar airflow during prosthetic joint surgery. APMIS 2015;123:589–95.
[69] Portillo ME, Corvec S, Borens O, Trampuz A. *Propionibacterium acnes*: an underestimated pathogen in implant-associated infections. BioMed Res Int 2013;2013:804391.
[70] Piper KE, Jacobson MJ, Cofield RH, Sperling JW, Sanchez-Sotelo J, Osmon DR, et al. Microbiologic diagnosis of prosthetic shoulder infection by use of implant sonication. J Clin Microbiol 2009;47:1878–84.
[71] Sampedro MF, Huddleston PM, Piper KE, Karau MJ, Dekutoski MB, Yaszemski MJ, et al. A biofilm approach to detect bacteria on removed spinal implants. Spine 2010;35:1218–24.
[72] Lutro O, Langvatn H, Dale H, Schrama JC, Hallan G, Espehaug B, et al. Increasing resistance of coagulase-negative Staphylococci in total hip arthroplasty infections: 278 THA-revisions due to infection reported to the Norwegian Arthroplasty Register from 1993 to 2007. Adv Orthoped 2014;2014:580359.
[73] Laxminarayan R, Duse A, Wattal C, Zaidi AK, Wertheim HF, Sumpradit N, et al. Antibiotic resistance – the need for global solutions. Lancet Infect Dis 2013;13:1057–98.
[74] Arthursson AJ, Furnes O, Espehaug B, Havelin LI, Soreide JA. Validation of data in the Norwegian Arthroplasty Register and the Norwegian Patient Register: 5,134 primary total hip arthroplasties and revisions operated at a single hospital between 1987 and 2003. Acta Orthop 2005;76:823–8.
[75] Espehaug B, Furnes O, Havelin LI, Engesaeter LB, Vollset SE, Kindseth O. Registration completeness in the Norwegian Arthroplasty Register. Acta Orthoped 2006;77:49–56.
[76] Furnes O, Hallan G, Gjertsen JE, Visnes H, Gundersen T, Fenstad AM, et al. The Norwegian Arthroplasty Register, annual report. 2019. Available at: http://nrlweb.ihelse.net/eng/Rapporter/Report2019_english.pdf [last accessed March 2020].
[77] Witso E. The rate of prosthetic joint infection is underestimated in the arthroplasty registers. Acta Orthop 2015;86:277–8.
[78] Gundtoft PH, Overgaard S, Schonheyder HC, Moller JK, Kjaersgaard-Andersen P, Pedersen AB. The "true" incidence of surgically treated deep prosthetic joint infection after 32,896 primary total hip arthroplasties: a prospective cohort study. Acta Orthoped 2015;86:326–34.
[79] Huotari K, Peltola M, Jamsen E. The incidence of late prosthetic joint infections: a registry-based study of 112,708 primary hip and knee replacements. Acta Orthoped 2015;86:321–5.
[80] Dale H, Fenstad AM, Hallan G, Havelin LI, Furnes O, Overgaard S, et al. Increasing risk of prosthetic joint infection after total hip arthroplasty. Acta Orthoped 2012;83:449–58.
[81] Kurtz SM, Lau E, Schmier J, Ong KL, Zhao K, Parvizi J. Infection burden for hip and knee arthroplasty in the United States. J Arthroplasty 2008;23:984–91.