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Review

# Exposure to infected/colonized roommates and prior room occupants increases the risks of healthcare-associated infections with the same organism

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SUMMARY

***Background:*** The survival of pathogenic organisms in the healthcare environment plays a major role in acquiring healthcare-associated infections (HAIs).

***Aim:*** This meta-analysis was conducted to investigate whether pathogenic organisms can be transmitted from roommates and prior room occupants to other inpatients and thus increase the risks of HAIs.

***Methods:*** PubMed (from January 1966) and Embase (from January 1974) were searched to identify studies up to March 2018. The quality of the studies was assessed using the Newcastle–Ottawa Scale. Heterogeneity was assessed using the *I*-squared statistic. The random-effects model was applied which provides more conservative estimates. Subgroup analyses, cumulative meta-analysis, publication bias diagnosis, and sensitivity analysis were conducted. All the statistical analyses were performed using Stata statistical software version 9.0.

***Results:*** Twelve studies including 33,153 subjects reported risk from exposure to infected/colonized roommates and nine studies including 49,839 subjects reported risk from infected/colonized prior room occupants. Exposure to infected/colonized roommates and prior room occupants were associated with the increased risks of HAIs with the same organism (odds ratio (OR) = 2.69, 95% confidence interval (CI) = 1.61–4.49; OR = 1.96, 95% CI = 1.36–2.68; respectively). Sensitivity analyses results did not show major changes in the overall findings. No publication bias was detected.

***Conclusions:*** This meta-analysis showed exposure to infected/colonized roommates and prior room occupants significantly increased the risks of HAIs with the same organism. Health authorities and hospitals should attach higher importance to the fact that current standards or practices for disinfection and isolation are often not sufficient to block

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transmission of pathogens in the healthcare settings, which may warrant enhanced terminal and intermittent disinfection and strict isolation for reducing HAIs.



## Introduction

Despite rapid advances in medical science and implementation of infection-prevention strategies in healthcare facilities, healthcare-associated infections (HAIs) still represent a serious worldwide public health problem and result in increased healthcare costs [1]. Evidence based on a multistate point-prevalence survey indicated that 4.0% of inpatients had at least one HAI in the USA [2], and HAIs annually caused around 99,000 attributable deaths and financial losses of about US$6.5 billion [1]. The European Centre for Disease Prevention and Control (ECDC) proposed that the prevalence of HAIs was approximately 7.1% in Europe [3], which annually caused 37,000 attributable deaths and financial losses of about US$7 billion [1]. The burden of HAIs in low- and middle-income countries is even higher [4].

Many studies have revealed that pathogenic organisms can cause widespread contamination of various environment surfaces in healthcare settings [5,6]. The survival of pathogenic organisms in the healthcare environment plays a major role in acquiring HAIs [7,8]. Furthermore, studies have shown that even when hospital surfaces are cleaned and disinfected according to recommended standards and practices, contamination can persist or return [9,10]. Therefore, inpatients may be infected with the same pathogenic organisms through direct or indirect contact with surrounding environments contaminated by infected/colonized roommates and prior room occupants. On the basis of this assumption, many studies have been performed to explore the association between infected/colonized roommates or prior room occupants and the risk of HAIs [11—15]. A population-based cohort indicated that *Clostridium difficile* infections were significantly higher in patients sharing a room with an asymptomatic carrier than in unexposed patients [11]. Another cohort study revealed that subsequent room occupants admitted to a room previously occupied by a patient with multi-drug-resistant (MDR) *Pseudomonas aeruginosa* or *Acinetobacter baumannii* were at the increased risk of acquiring the same bacteria [12]. One recent large case—control study showed that both exposure to roommates and prior bed occupants with a positive culture increased the risk of HAIs with the same organism [13]. By contrast, some other studies demonstrated non-significant and even protective effects [14,15]. Ford *et al*. found that colonized prior room occupants did not increase the vancomycin-resistant enterococcus (VRE) colonization risk of subsequent occupants, whereas patient and treatment factors were more significant determinants [14]. Another study suggested that being in the room of previous patients colonized or infected with VRE was protective after strictly performed effective infection control and isolation procedures [15]. However, a single study is insufficient to demonstrate the relationship. The extent of the contribution of infected/colonized roommates or prior room occupants to HAI rates among inpatients remains unclear.

Given these inconsistent findings, it is important to understand the risks of HAIs from infected/colonized roommates and/or prior room occupants, which can help to establish appropriate prevention and control strategies. This meta-analysis was therefore conducted to investigate whether pathogenic organisms can be transmitted from roommates and prior room occupants to other inpatients and thus increase the risks of HAIs.

## Methods

### *Search strategy and studies selection*

This meta-analysis adhered to the standard methodological guidelines of Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA) [16]. PubMed (from January 1966) and Embase (from January 1974) were searched to identify studies up to March 2018. The terms 'hospital room', 'patients room', 'roommate', 'prior bed occupant', 'previous bed occupant', 'previous room occupant' or 'prior room occupant' AND 'transmission', 'outbreak' or 'infection' were used to search for articles. In addition, the reference list of a previous review article [17] was manually screened.

Eligible publications were included which met all of the following inclusion criteria: (i) original studies; (ii) human studies; (iii) provide an estimate (i.e. risk ratio, odds ratio (OR)) or sufficient data can compare HAIs and/or colonization rates between patients exposed to infected/colonized roommates or prior room occupants and non-exposed controls (the 'exposure' was defined as patients who have infected/colonized roommates or prior room occupants); (iv) were conducted in the healthcare settings; (v) outcomes were infection or colonization with the same organism. Because most of studies used 'acquiring infection' as the outcome, the few studies using the 'acquiring colonization' as the outcome were also regarded as HAIs in this meta-analysis. Publications were excluded if they were abstracts, case reports or reviews.

### *Data extraction and quality assessment*

Data extraction was performed by two independent reviewers, and disagreements were resolved by consensus. The following information was collected: first author's name, publication year, country, study design, study sample, confounders adjustment, and the association estimates with corresponding 95% confidence intervals (CIs). The estimate with the greatest maximum degree of adjustment for confounders was preferred. As HAIs are relatively rare outcomes, the distinction between odds ratios (ORs), risk ratios, and hazard ratios were ignored and interpreted as ORs. Two authors independently assessed the quality of the studies using the Newcastle—Ottawa Scale [18], which is a validated tool for assessing the quality of non-randomized studies based on the study group selection (0—4 stars), the groups comparability (0—2 stars), and the exposures and outcomes elucidation (0—3 stars). A minimum total of 7 stars was considered as a high-quality study.

### Statistical analysis

The ORs and corresponding 95% CIs were used as the risk measure. Heterogeneity was assessed using the *I*-squared ($I^2$) statistic, which reflected the proportion of the total variation of the pooled estimates that was due to the heterogeneity between studies [19]. The random-effects model was applied because most of the pooled analyses had moderate/high heterogeneities [20]. Subgroup analyses were performed by study characteristics. To examine possible publication bias, the symmetry of funnel plots was visually inspected. Begg's test and Egger's test were employed to provide further quantitative analysis [21]. Sensitivity analyses were conducted by removing each individual study and recalculating a pooled OR to determine whether some studies markedly affected the overall ORs. All of the statistical analyses were performed using Stata statistical software version 9.0 (Stata Corporation, College station, TX, USA). A two-sided *P*-value $<0.05$ was considered statistically significant.

## Results

### Study characteristics

As presented in Figure 1, a total of 2618 citations were initially identified. Of these, 2523 were removed based on the title and abstract screening, 95 were retained for full-text reviewing. After full-text evaluation, 77 were excluded because they were reviews or case reports ($N = 3$), or because they had no comparison group ($N = 15$), others exposure ($N = 26$), no target outcomes ($N = 32$), and overlap studies ($N = 1$). Finally, 18 eligible articles published between 1992 and 2018 involving 59,372 subjects met the inclusion criteria and are summarized in Table I [11–15,22–34]. Nearly three-quarters of studies were conducted in the USA [12,13,22,24–30,32–34], three in Europe [11,12,31], and the rest were carried out in other regions [15,23]. Nine articles investigated the risks of exposure to infected/colonized roommates [11,15,24,25,29–32,34], six investigated the risks of exposure to infected/colonized prior room occupants [12,14,22,26–28], and three investigated both exposures [13,23,33].

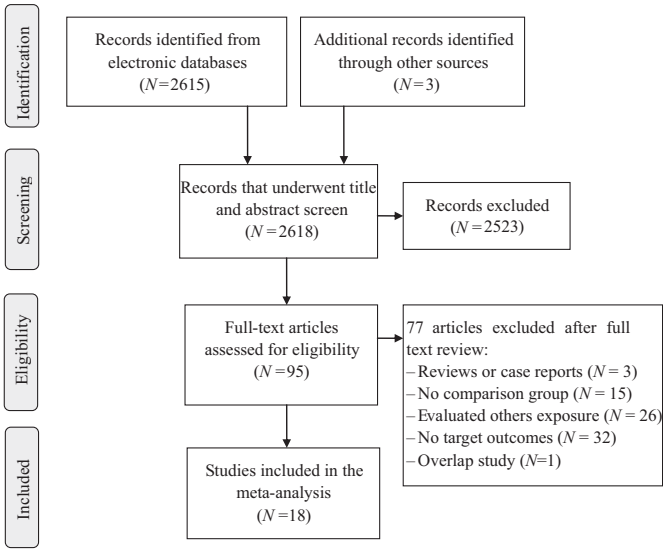


**Figure 1.** PRISMA flow diagram for inclusion of studies. PRISMA, Preferred Reporting Items for Systematic Review and Meta-analyses.

### Exposure to infected/colonized roommates and risk of HAIs with the same organism

There were 12 studies comprising 13 datasets (one study [25] contained two separate datasets) including 33,153 subjects for investigating the association between exposure to infected/colonized roommates and risk of HAIs with the same organism. Overall, exposure to infected/colonized roommates was significantly associated with the increased risk of HAIs (OR = 2.69, 95% CI = 1.61–4.49; $I^2 = 76.8\%$; Table II, Figure 2a).

Table II shows the pooled ORs from subgroup analyses. In subgroup analyses by study design, a significant association was observed in cohort studies with low heterogeneity (OR = 2.09, 95% CI = 1.51–2.90; $I^2 = 19.1\%$), but the association was not significant in case–control studies. Though a significantly higher risk was observed in an experimental study (OR = 18.80, 95% CI = 5.37–66.15), there was only one such study [23]. When stratified by geographic location, nine studies conducted in the USA showed a similar risk to the overall risk (OR = 2.73, 95% CI = 1.70–4.38), but it was not significant in two European studies. Notably, a significantly decreased risk was observed based on one study from Saudi Arabia (OR = 0.04, 95% CI = 0.004–0.40) [23]. Regarding exposure type, definitions of exposure were various across studies. The exposure type was assumed as 'exposure to colonization' if only colonized patients were included in the risk group. Studies that analysed the risk of exposure to infected or either infected or colonized patients would be defined as 'exposure to infection'. The studies were then pooled in those two exposure types, and the risk of HAIs was found to be significantly higher in patients exposed to roommates with infection (OR = 3.57, 95% CI = 2.00–6.42) than those only with colonization. Regarding pathogen type, the magnitude of the association was higher in patients exposed to roommates with viral pathogens (OR = 3.08, 95% CI = 1.91–4.98) compared with exposure to roommates with non-viral pathogens (OR = 2.41, 95% CI = 1.24–4.70). In addition, the significant association also could be observed in studies with samples numbering more than 1000, high-quality scores, and unadjusted data.

### Exposure to infected/colonized prior room occupants and risk of HAIs with the same organism

Nine studies constituting 12 datasets (two studies [12,26] contained two and three separate datasets, respectively) involving 49,839 participants indicated that exposure to infected/colonized prior room occupants significantly increased the risk of HAIs with the same organism (OR = 1.96, 95% CI = 1.36–2.68; $I^2 = 78.5\%$; Table III, Figure 2b).

In subgroup analysis by study design, the significant positive association was observed in nine cohort and one case–control studies (OR = 1.61, 95% CI = 1.30–1.99; OR = 5.83, 95% CI = 3.62–9.39, respectively), whereas no significant association was detected in two experimental studies. On stratified analysis by geographic location, the significant risk was found to be higher in studies from Europe

**Table I**
Characteristics of 18 studies included in this meta-analysis

| First author | Country | Subjects | Exposure | Study design | OR (95% CI) | | NOS score | Adjustment factors |
|---|---|---|---|---|---|---|---|---|
| | | | | | Roommates | Prior room occupants | | |
| Cohen (2018) [13] | USA | 20,322 | *Staphylococcus aureus*, *Streptococcus pneumonia*, AB, *Pseudomonas aeruginosa*, *Klebsiella pneumonia*, or Enterococci | Case–control | 4.82 (3.67–6.34) | 5.83 (3.62–9.39) | 9 | Adjusted[a] |
| Blixt (2017) [11] | Denmark | 3713 | *Clostridium difficile* | Prospective cohort | 1.79 (1.16–2.76) | — | 8 | Unadjusted |
| Ford (2015) [14] | USA | 214 | VRE colonization | Retrospective cohort | — | 1.22 (0.75–1.20) | 7 | Unadjusted |
| Shorman (2013) [15] | Saudi Arabia | 90 | VRE | Case–control | 0.04 (0.004–0.40) | | 6 | Adjusted[b] |
| Ajao (2013) [22] | USA | 7651 | ESBL-producing organism | Retrospective cohort | — | 1.39 (0.94–2.08) | 8 | Adjusted[c] |
| Bass (2013) [23] | Australia | 439 | VRE | Interventional | 18.80 (5.37–66.15) | 0.37 (0.11–1.22) | 7 | Adjusted[d] |
| Deutscher (2011) [24] | USA | 50 | Group A streptococcus | Case–control | 15.30 (2.50–110.90) | — | 6 | Adjusted[e] |
| Furuno (2011) [25] | USA | 443 | MRSA colonization | Prospective cohort | Residential care: 1.4 (0.5–3.9); rehabilitation care: 0.5 (0.1–2.2) | — | 8 | Adjusted[f] |
| Datta (2011) [26] | USA | 15,435 | MRSA or VRE | Retrospective cohort | — | MRSA: 1.4 (1.0–1.8); VRE: 1.4 (1.0–1.9) | 9 | Adjusted[g] |
| Nseir (2011) [12] | France | 511 | MDR PA, AB, or ESBL-producing GNB | Prospective cohort | — | MDR PA: 2.3 (1.2–4.3); AB: 4.2 (2.0–8.8); ESBL-producing GNB: 1.5 (0.6–3.5) | 8 | Adjusted[h] |
| Shaughnessy (2011) [27] | USA | 1770 | *C. difficile* | Retrospective cohort | — | 2.35 (1.21–4.54) | 8 | Adjusted[i] |
| Drees (2008) [28] | USA | 638 | VRE colonization | Prospective interventional | — | 3.82 (1.99–7.35) | 8 | Adjusted[j] |
| Drinka (2005) [29] | USA | 489 | Influenza B | Retrospective cohort | 2.60 (1.20–5.60) | — | 6 | Unadjusted |
| Greene (2005) [30] | USA | 125 | Group A streptococcus | Retrospective cohort | 2.00 (1.10–5.10) | — | 7 | Adjusted[k] |
| Forns (2005) [31] | Spain | 1301 | Hepatitis C | Prospective cohort | 12.00 (1.39–103.00) | — | 7 | Unadjusted |
| Drinka (2003) [32] | USA | 3294 | Influenza A | Retrospective cohort | 3.07 (1.61–5.78) | — | 6 | Unadjusted |
| Chang (2000) [33] | USA | 2859 | *C. difficile* | Retrospective cohort | 2.37 (0.63–6.95) | 1.21 (0.32–3.39) | 7 | Unadjusted |
| Pegues (1994) [34] | USA | 28 | *P. aeruginosa* | Case–control | 12.50 (0.60–607.00) | — | 6 | Unadjusted |

AB, *Acinetobacter baumannii*; CI, confidence interval; ESBL, extended-spectrum beta-lactamase; GNB, Gram-negative bacilli; MDR PA, multidrug-resistant *Pseudomonas aeruginosa*; MRSA, meticillin-resistant *Staphylococcus aureus*; NOS, Newcastle–Ottawa Scale; OR, odds ratio; VRE, vancomycin-resistant enterococci.

[a] Adjusted for age, sex, Charlson Comorbidity Index, malignancies, renal failure, diabetes, and controlling for each exposure to prior occupant or roommate.

[b] Adjusted for colonization pressure, renal disease, anti-MRSA, and anti-pseudomonal betalactam therapies.

[c] Adjusted for prior bed occupants VRE status and intervention phase.

[d] Adjusted for age and sex.

[e] Adjusted for age, sex, body mass index, death, special care unit admission, length of stay >4 weeks, admission from home, CD, diabetes, congestive heart failure, hypertension, peripheral vascular disease, chronic renal failure/dialysis, malignancies, ventilator, cellulitis, nonsurgical wound, neg pressure.

[f] Adjusted for antibiotic therapy, bedbound status, and limited mobility status.

[g] Adjusted for age, sex, comorbidities, pre-intensive medical care (ICU) length of stay, prior occupant length of stay, duration of room vacancy, and clustering by ICU ward.

[h] MDR PA model adjusted for age, simplified acute physiology score, logistic organ dysfunction, transfer from other wards, duration of hospitalization before ICU admission, prior antibiotics, room occupancy rate, central venous, arterial, and urinary catheters, tracheostomy, sedation, percentage of days in the ICU with several specified antibiotics use, mechanical ventilation, and length of ICU stay; MDR AB model adjusted for simplified acute physiology score, logistic organ dysfunction admission type, prior antibiotics, colonization pressure, central venous, arterial and, urinary catheters, sedation, percentage of days in ICU with several specified antibiotics use; ESBL model's adjusted results not reported.

[i] Adjusted for age, Acute Physiology and Chronic Health Evaluation, proton pump inhibitor, and antibiotics exposure.

[j] Adjusted for average colonization pressure and mean antibiotics per day.

[k] Adjusted variables not described.

**Table II**
Summary of the association between the risk of healthcare-associated infections and exposure to infected/colonized roommates

| Analysis | No. of datasets | OR (95% CI) | Significant | | Heterogeneity | |
|---|---|---|---|---|---|---|
| | | | Z | *P* | *P* | $I^2$ (%) |
| All studies | 13 | 2.69 (1.61–4.49) | 3.79 | <0.001 | <0.001 | 76.8 |
| Design | | | | | | |
| Cohort | 8 | 2.09 (1.51–2.90) | 0.82 | 0.412 | 0.279 | 19.1 |
| Case–control | 4 | 2.47 (0.29–21.35) | 4.43 | <0.001 | <0.001 | 83.6 |
| Experiment | 1 | 18.80 (5.37–66.15) | 4.58 | <0.001 | — | — |
| Geographic location | | | | | | |
| USA | 9 | 2.73 (1.70–4.38) | 4.17 | <0.001 | 0.009 | 60.5 |
| European countries | 2 | 3.42 (0.58–20.01) | 1.36 | 0.173 | 0.089 | 65.3 |
| Saudi Arabia | 1 | 0.04 (0.004–0.40) | 2.74 | 0.006 | — | — |
| Australia | 1 | 18.80 (5.37–66.15) | 4.58 | <0.001 | — | — |
| Number of samples | | | | | | |
| <1000 | 8 | 2.20 (0.82–5.91) | 1.57 | 0.117 | <0.001 | 78.3 |
| ≥1000 | 5 | 3.17 (1.80–5.60) | 3.98 | <0.001 | 0.003 | 75.4 |
| Exposure type | | | | | | |
| Colonization | 3 | 1.48 (0.88–2.51) | 1.48 | 0.140 | 0.287 | 19.9 |
| Infection | 10 | 3.57 (2.00–6.42) | 4.25 | <0.001 | <0.001 | 71.9 |
| Exposure species | | | | | | |
| Virus | 3 | 3.08 (1.91–4.98) | 4.60 | <0.001 | 0.423 | 0.0 |
| Non-virus | 10 | 2.41 (1.24–4.70) | 2.59 | 0.010 | <0.001 | 82.0 |
| NOS | | | | | | |
| <7 | 5 | 2.32 (0.68–7.88) | 1.34 | 0.179 | 0.002 | 76.4 |
| ≥7 | 8 | 2.81 (1.53–5.17) | 3.32 | 0.001 | <0.001 | 79.5 |
| Confounders adjustment | | | | | | |
| Yes | 7 | 2.27 (0.88–5.89) | 1.69 | 0.092 | <0.001 | 84.6 |
| No | 6 | 2.37 (1.70–3.32) | 5.50 | <0.001 | 0.003 | 6.5 |

CI, confidence interval; NOS, Newcastle–Ottawa Scale; OR, odds ratio.

**Table III**
Summary of the association between the risk of healthcare-associated infections and exposure to infected/colonized prior room occupants

| Analysis | No. of datasets | OR (95% CI) | Significant | | Heterogeneity | |
|---|---|---|---|---|---|---|
| | | | Z | *P* | *P* | $I^2$ (%) |
| All studies | 12 | 1.91 (1.36–2.68) | 3.70 | <0.001 | <0.001 | 78.5 |
| Design | | | | | | |
| Cohort | 9 | 1.61 (1.30–1.99) | 4.38 | <0.001 | 0.143 | 34.3 |
| Case–control | 1 | 5.83 (3.62–9.39) | 7.25 | <0.001 | — | — |
| Experiment | 2 | 1.26 (0.13–12.37) | 0.20 | 0.844 | 0.001 | 91.0 |
| Geographic location | | | | | | |
| USA | 8 | 1.96 (1.32–2.89) | 3.35 | 0.001 | <0.001 | 81.9 |
| European countries | 3 | 2.51 (1.45–4.34) | 3.30 | 0.001 | 0.199 | 38.2 |
| Australia | 1 | 0.37 (0.11–1.23) | 1.62 | 0.105 | — | — |
| Number of samples | | | | | | |
| <1000 | 7 | 1.86 (1.04–3.33) | 2.09 | 0.036 | 0.001 | 74.6 |
| ≥1000 | 5 | 1.92 (1.21–3.04) | 2.77 | 0.006 | <0.001 | 83.9 |
| Exposure type | | | | | | |
| Colonization | 1 | 3.82 (1.99–7.35) | 4.02 | <0.001 | — | — |
| Infection | 11 | 1.79 (1.26–2.54) | 3.27 | 0.001 | <0.001 | 78.5 |
| Confounders adjustment | | | | | | |
| Yes | 9 | 2.11 (1.40–3.18) | 3.55 | <0.001 | <0.001 | 83.3 |
| No | 3 | 1.27 (0.85–1.90) | 1.18 | 0.239 | 0.919 | 0.0 |

CI, confidence interval; OR, odds ratio.

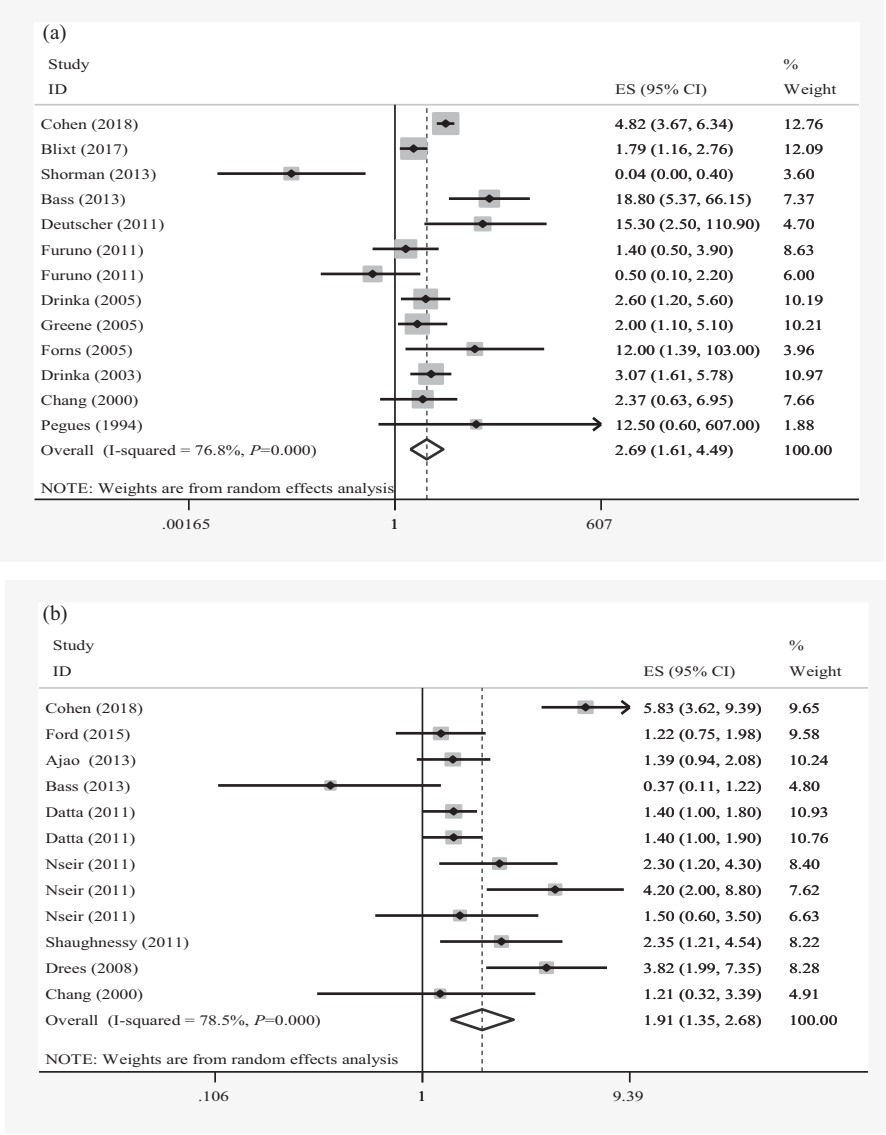


**Figure 2.** Forest plots for the random effect meta-analysis of the association between the risk of healthcare-associated infections and exposure to infected/colonized roommates (a) and prior room occupants (b). ES, effect size (odds ratio).

(OR = 2.51, 95% CI = 1.45–4.34) than from the USA (OR = 1.96, 95% CI = 1.32–2.89). With regard to exposure type, only one study [28] analysed exposure to the colonized prior room occupants, and reported a statistically significant association (OR = 3.82, 95% CI = 1.99–7.35). The remaining studies that analysed exposure to infected prior room occupants and also indicated the significant association (OR = 1.79, 95% CI = 1.26–2.54) were pooled. There was no difference between studies stratified by samples number. When the subgroup stratified by confounders was adjusted, the subgroup of studies that was adjusted for any confounders showed the significant association (OR = 2.11, 95% CI = 1.40–3.18), but the association was insignificant in studies that did not adjust for confounders.

### *Cumulative meta-analysis*

Cumulative meta-analysis showed that an increased risk of HAIs associated with exposure to infected/colonized roommates became evident in 2003, when three studies were conducted (OR = 3.01; 95% CI = 1.73–5.25). Subsequent studies increased the number of patients, and the OR remained very similar from 2005 onwards (Supplementary Figure S1a). With regard to exposure to infected/colonized prior room occupants, the increased risk of HAIs became statistically significant in 2011 (OR = 2.55; 95% CI = 1.47–4.44), when three studies were conducted. The OR remained significant and slightly decreased after six studies were subsequently conducted (Supplementary Figure S1b).

### *Sensitivity analyses and bias diagnostics*

After excluding a single study at a time, results did not show major change in the overall findings, which suggested a high stability of results. Visual inspection of funnel plots did not reveal obvious evidence of asymmetry (Figure 3). In addition, no publication bias was detected by quantitative analysis for association between risk of HAIs and exposure to infected/

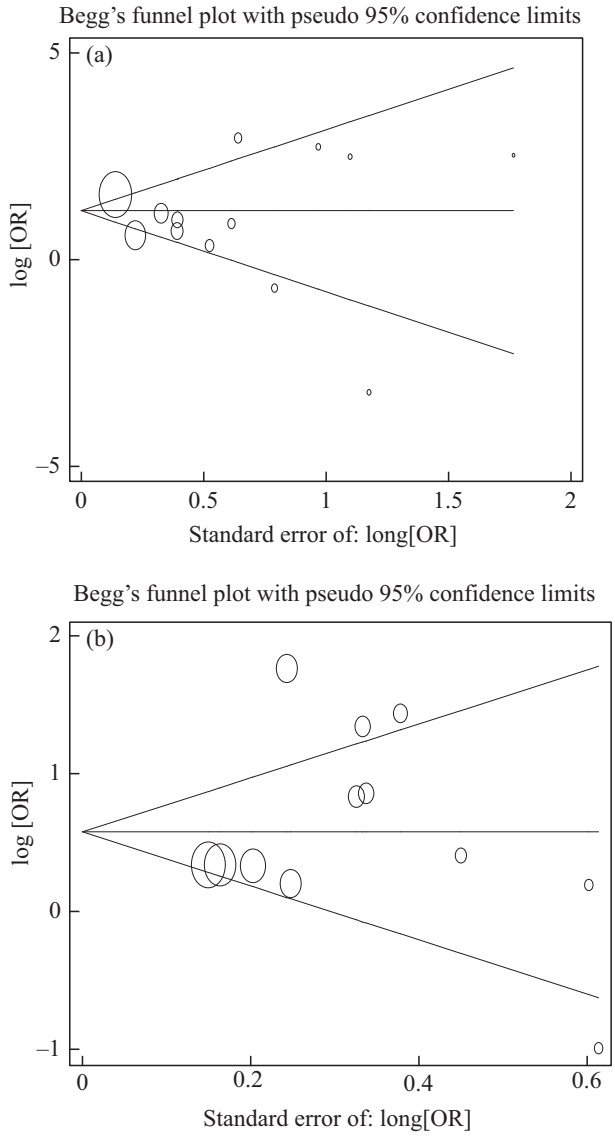


**Figure 3.** Funnel plots for the random effect meta-analysis of the association of risk of healthcare-associated infections and exposure to infected/colonized roommates (a) and prior room occupants (b).

colonized roommates (Begg's test: $Z = 0.06$, $P = 0.951$ and Egger's test: $t = -0.84$, $P = 0.421$) and prior room occupants (Begg's test: $Z = 0.24$, $P = 0.806$ and Egger's test: $t = 0.53$, $P = 0.634$).

## Discussion

This meta-analysis provides coherent evidence that pathogenic organisms can be transmitted from infected/colonized roommates and prior room occupants to other inpatients and significantly increases the risks of HAIs. Our results strengthen the importance of infection prevention and control measures to protect patients who have infected/colonized roommates or prior room occupants. Compared with a previous qualitative review [17], this comprehensive meta-analysis could quantify both the overall and subgroups risks of HAIs from infected/colonized roommates and prior room occupants. Furthermore, some new studies [20,22,23] were included in this meta-analysis, which increased the sample size and made the conclusion more powerful. Associations between increased risk of HAIs and exposure to infected/colonized roommates and prior room occupants are biologically plausible. One study investigated VRE colonization in an intensive care unit (ICU), and revealed that despite aggressive double-terminal cleaning, 10% of rooms still showed residual VRE [35]. Vickery *et al*. found that the presence of multi-resistant organisms was being protected within these biofilms, which made them persist on clinical surfaces despite terminal cleaning [36]. Furthermore, many intervention studies have indicated that increased intensity or regulating methods of terminal cleaning were the main means of significantly reducing the microorganisms [37,38]. All these findings implicate inadequate healthcare room cleaning practices as contributing to transmission of organisms.

Exposure to infected/colonized roommates made the development of HAIs with the same organism 2.69-times more likely. The risks of HAIs from infected/colonized roommates were highly variable across studies, which gave the expected heterogeneity among studies in terms of different characteristics such as study design, exposures and pathogen type, endemic pathogens, colonization/infection rates, room size and occupancy, and confounders adjustment. One study showed a very high risk (hazard ratio = 18.8) of acquiring VRE in patients who had a roommate with VRE [23]. Most of the cohort studies showed an obvious association [11,29–32], and a significant association with low heterogeneity was observed by pooling cohort studies, which suggested a higher homogeneity of results among cohort studies. Only one case–control study identified a statistically significant protective effect of admission with a roommate colonized or infected with VRE, and researchers concluded that it might be explained by the strict isolation precautions [15]. However, there was no significant association of pooled case–control results, though this might be due to insufficient statistical power. When stratified by geographic location, more than two-thirds of studies were conducted in the USA and showed a similar risk to the overall risk, and other four studies from Europe, Saudi Arabia and Australia showed higher or lower risks compared with the overall risk [11,15,23,31]. In other words, studies from USA represent an important component of the overall result. Regrettably, eligible studies from other regions where HAIs also represent a serious public health problem could not be screened [4]. Results also indicated that the risk of HAIs was higher in patients exposed to roommates with infection than roommates with colonization only. Patients with asymptomatic colonization may have a limited role in transmission compared with patients with symptomatic infection who may shed greater amounts of infectious body fluid [17,39]. Larger studies are required to confirm the differences in infectiousness between patients with colonization and those with infection. Only three studies assessed the risk of exposure to infected roommates with viral pathogens [29,31,32]. Two studies [29,32] of droplet-transmitted respiratory viral infection at the same long-term care setting were pooled and one study [31] of blood-borne viral infection found slightly higher magnitude of risk of HAIs than exposure to non-viral pathogens. Nevertheless, the conclusion should be made with caution for limited species of virus and sample size. In order to minimize the risk of

confounding, the subgroups were stratified by adjusted estimates. The most frequently adjusted factor included age [12,13,23,24,26,27], sex [13,23,24,26], and antibiotics [12,15,25,27,28]. Nevertheless, the residual confounding in pooled adjusted findings could not be totally eliminated because the extent of confounders adjustment was often not uniform among studies. Differences in confounders adjustment across studies could also be reflected by the high heterogeneity ($I^2 = 84.6\%$) in the pooled adjusted finding.

Similar to exposure to infected/colonized roommates, exposure to infected/colonized prior room occupants could also increase the risk of HAIs, although it was of slightly lower magnitude at 1.96-times increased risk. The reasonable explanation for lower magnitude of risk from exposure to infected/colonized prior room occupants may be due to the partial effectiveness of terminal cleaning, although the subsequent risk could not be totally eliminated. Also, the higher risk of roommate-to-roommate transmission may be partially attributable to healthcare workers serving as a medium. In addition, differences in environmental survival time of diverse pathogens may mitigate the risk. Most of the studies adopted a cohort design [12,14,22,26,27,33] and half of them showed a significant association [12,26,27]. In pooled analysis, the significant positive association was observed in cohort and case–control studies. However, no significant association was detected when the inconsistent findings from two experimental studies of VRE acquisition were pooled [23,28]. Drees *et al*. showed that prior VRE-colonized room occupancy was highly predictive of VRE acquisition (OR: 1.99–7.35) [28]. However, Bass *et al*. indicated that patients admitted to a bed that was previously occupied by a VRE-colonized patient were not at increased risk of VRE acquisition [23]. As authors concluded, this might be due to the differences in effectiveness of terminal cleaning or the type of cleaning agents used in different healthcare settings [23]. Regarding geographic location, most studies were found to be from the USA and Europe, and pooled findings revealed a significant association. Only one study in another country [23] limited the further subgroup analysis of geographic area. Contrary to exposure to infected/colonized roommates, significant association in the subgroups of studies adjusting for confounders was found. Although the unadjusted results in three studies were not statistically significant, increased risks of different magnitudes were detected in all studies [12,14,33].

This meta-analysis has several inherent limitations. First, although the same pathogens were cultured among the patients and their infected/colonized roommates or prior room occupants, but it could not be determined whether the pathogens were genetically identical because molecular typing was unavailable for most of the studies. Second, most studies were conducted in the USA and Europe, and the eligible studies from other regions where HAIs also represent a serious public health problem could not be included, which might limit the generalizability to populations in other areas, given potential differences in geographic and medical conditions, and other factors. Third, because of small sample sizes in some subgroups, conclusions of some subgroups were made based on limited information. Additionally, results are limited for this meta-analysis did not include more types of pathogens that can cause HAIs.

This meta-analysis showed that exposure to infected/colonized roommates and prior room occupants significantly increased the risks of HAIs with the same organism. Health authorities and hospitals should attach higher importance to the fact that current standards or practices for disinfection and isolation are often not sufficient to block transmission of pathogens in healthcare settings [13,40], which may warrant enhanced terminal and intermittent disinfection and strict isolation for reduction of HAIs. Further well-designed epidemiological studies performed in different countries and full adjustment for confounders to test the specific risks of diverse pathogens types are recommended, which could provide the precise prevention and control measures.

**Conflict of interest statement**
None declared.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhin.2018.10.014.

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