



Management of nurse shortage and its impact on pathogen dissemination in the intensive care unit[☆]



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ABSTRACT

Introduction: Studies provide evidence that reduced nurse staffing resources are associated to an increase in health care-associated infections in intensive care units, but tools to assess the contribution of the mechanisms driving these relations are still lacking. We present an agent-based model of pathogen spread that can be used to evaluate the impact on nosocomial risk of alternative management decisions adopted to deal with transitory nurse shortage.

Materials and methods: We constructed a model simulating contact-mediated dissemination of pathogens in an intensive-care unit with explicit staffing where nurse availability could be temporarily reduced while maintaining requisites of patient care. We used the model to explore the impact of alternative management decisions adopted to deal with transitory nurse shortage under different pathogen- and institution-specific scenarios. Three alternative strategies could be adopted: increasing the workload of working nurses, hiring substitute nurses, or transferring patients to other intensive-care units. The impact of these decisions on pathogen spread was examined while varying pathogen transmissibility and severity of nurse shortage.

Results: The model-predicted changes in pathogen prevalence among patients were impacted by management decisions. Simulations showed that increasing nurse workload led to an increase in pathogen spread and that patient transfer could reduce prevalence of pathogens among patients in the intensive-care unit. The outcome of nurse substitution depended on the assumed skills of substitute nurses. Differences between predicted outcomes of each strategy became more evident with increasing transmissibility of the pathogen and with higher rates of nurse shortage.

Conclusions: Agent-based models with explicit staff management such as the model presented may prove useful to design staff management policies that mitigate the risk of healthcare-associated infections under episodes of increased nurse shortage.

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Background

In the recent decades, policies promoting higher patient throughput in hospitals have led to many wards operating near full capacity, leading to increasingly frequent staff shortage situations, which challenge hospitals to continuously provide safe, quality care to acute and critically ill patients (Clarke, 2009). In this context, efficient management of hospital staffing resources is imperative.

In particular, hospital-acquired infections are important indicators of the quality of care in the intensive-care unit (ICU), where highly-specialized healthcare-workers (HCWs) are in close contact with fragile and highly susceptible patients, and where antibiotic pressure readily favors the selection of resistant pathogens

(Fukuda et al., 2011). Several factors associated with transitory understaffing may contribute to pathogen spread in the ICU, including increased mobility of staff and patients between hospital wards, reduced levels of cohorting, and decreased compliance with infection control measures (Stone et al., 2004; Clements et al., 2008; West et al., 2009).

However, assessing the relative impact of alternative staffing policies in infection control is a complex issue (Pittet et al., 2006; Griffiths et al., 2009; Schwab et al., 2012), because significant evidence cannot be simply extracted from the analysis of administrative and surveillance data due to the abundance of confounding factors: demographic characteristics, condition, exposure to invasive life-support devices and to drug treatments of patients, as well as organizational culture, interdisciplinary collaboration, equipment facilities and documentation burden of the service (Hugonnet et al., 2007; Needleman et al., 2007). Mathematical models provide a complementary research tool that reduces the complexity of the systems under study, making them more accessible to specific questions (Grundmann and Hellriegel, 2006; van Kleef et al., 2013). Agent-based models are bottom-up computational models that describe individual behaviors and interactions in order to reproduce emergent properties of the population. They are well adapted to study the spread of pathogens in the ICU because they can capture the small size of the population, the diversity among individuals, the heterogeneity of the contact network and the stochasticity in staff-patients interactions (Hotchkiss et al., 2005; Hornbeck et al., 2012).

Using an agent-based approach, the objectives of this article were to address the following three questions regarding the management of transitory nurse shortage in the ICU: (1) How may management decisions adopted in response to a temporary nurse shortage significantly affect the prevalence of pathogens in the ICU? (2) How does the relative impact of these decisions vary with the type of pathogen transmitted? And (3), how does it vary with the severity of nurse shortage?

Methods

Data collection

A study undertaken by the French National surveillance network of ICU-acquired infections REA-RAISIN in five volunteer ICUs collected weekly data on bed occupancy, staffing conditions for registered nurses and nurse's aides and incidence of hospital-acquired infections among patients over a period of 26 weeks between January and June 2012.

The average severity of patients entering the ICU, indicated by the Simplified Acute Physiology Score (SAPSII, range 1:163), was 40 [95%CI: 15–71]. The average length of stay of patients was 12.0 days [95%CI: 2–41.7] days. The average bed occupancy rate was 0.97 [95%CI: 0.71–1.17]. It was defined as the number of patient hospital days in a week divided by the number of open bed-days in the same week, and it could adopt values greater than one because some patients remained in the ICU for less than one day. The percentage of nurse substitution was around 9.4% [95%CI: 0–21.4%] for registered nurses, and around 10.9% [95%CI: 0–32.4%] for nurse's aides. It was defined as the number of hours per week covered by substitute staff divided by the total number of weekly working hours. We used this data to define realistic scenarios in our modeling study, in which we explored nurse shortage situations with up to 40% of missing nurses. The average probability of bacterial infection per patient per week was 7% [95%CI: 0–21%] the average ratio of VRE to MRSA cases was 1.91 [95%CI: 0–3], and the average incidence of pneumonia was 7% [95%CI: 3–38%]. No significant correlations were found between incidence of infections and bed occupancy,

nor between incidence and staffing conditions, due to the lack of statistical power. Prevalence of pathogen carriage among patients or HCWs was not explicitly measured.

Modeling ICU organization

Based on the data collected, we adapted an existing agent-based model for pathogen spread in the ICU (Temime et al., 2009) to include a realistic framework for the management of patients and staff (Ferrer Savall et al., 2013). We considered a 12-bed ICU in which new patients could be admitted daily, assuming a 100% bed occupancy ratio (Barado et al., 2012). We modeled the duration of patient stay in the ICU using a long-tailed distribution with mean = 4.2 days and median = 2.1 days, in line with reported data that show 80% of patients staying for less than five days and 5% of the patients staying more than 10 days (Kramer and Zimmerman, 2010).

We established the ICU workforce, comprising two types of HCWs (physicians and nurses), in accordance with staffing practices common in the European Union and assuming in-ward staff-to-patient ratios of 1:2 for nurses and 1:6 for physicians. In a 12-bed ICU, this translated as 6 nurses and 2 physicians required round the clock, which entailed the recruitment of 20 nurses and of 14 physicians working 35 h per week in 12 h shifts. Realistic rosters for each staff member were created using the software Shift Plan Assistant©, developed by the company Ximes (Ximes GMBH). At the beginning of each work duty, patients were randomly assigned to working HCWs to model cohorted care delivery.

During the work duty, each nurse paid three 30-min visits to each assigned patient, while each physician made a single round of 25-min visits. In addition, 10-min emergency calls randomly coupling a nurse and a patient could occur at any time but during the planned visits. On average, we simulated 6 emergency calls per patient per day. Visits were scattered throughout the shift and scheduled so that only one-to-one contacts took place. Fig. 1a provides a schematic description of the modeled ICU and the network of contacts between patients and HCWs. Table 1 provides a list of model parameters and their assumed values.

Modeling pathogen spread

We described the spread of carriage of three common pathogens in the ICU: bacteria found on human skin such as methicillin-resistant *Staphylococcus aureus* (MRSA), bacteria with higher transmissibility and environmental endurance, such as vancomycin-resistant enterococci (VRE), and pathogens that can be transmitted either through droplets or via the airborne route, such as influenza. Pathogen spread was modeled exclusively via patient–HCW contagions occurring during visits and implicitly taking into account the application of hygiene measures with limited compliance.

Introduction of a pathogen in the ICU occurred at patient admission or at the arrival of HCWs. 10% of patients were assumed to be carriers at ICU admission, but this probability was varied from 5 to 20% in sensitivity analyses, in line with reported rates in the literature (Ziakas et al., 2013a, 2013b). Patients who acquired pathogen carriage usually remained carriers until their discharge from the ICU, as the average assumed carriage duration was ten days (reflecting for instance weekly screenings plus a 3-day wait for test results). In HCWs, we modeled transient contamination with the pathogen, with a duration following an exponential distribution of mean 10 h, to implicitly take into account hypothetical 80% effective hygiene measures followed by the staff with 65% compliance (Temime et al., 2009). This distribution ensured a 50% probability of pathogen removal between two consecutive nurse visits and allowed for a

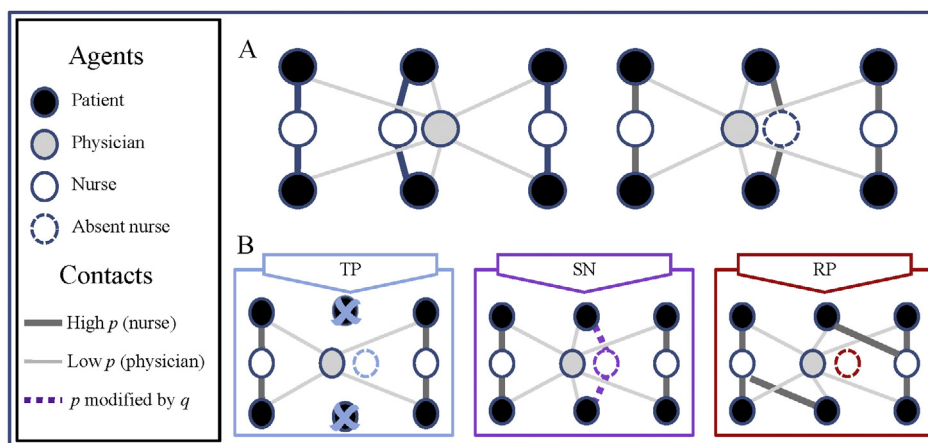


Fig. 1. Outline of the model of an ICU with 12 patients, 6 nurses and 2 doctors. (A) Network of contacts indicating an absent nurse. (B) The three prototype strategies proposed to deal with nurse shortage (TP: transfer patients; SN: substitute nurses; RP: reassign patients). Contacts between healthcare workers and patients are characterized by p : per-contact probability of pathogen transmission, and q : factor modifying the per-contact probability of pathogen transmission for substitute nurses.

10% probability of HCWs returning to work as carriers on the day following pathogen acquisition.

Cross-transmission depended on pathogen transmissibility and HCW profile, and it scaled with the duration of contact. Pathogen transmission rates were defined in line with estimates found in the literature for the three types of healthcare-associated pathogens we explored: they were set to 0.0025 per minute in contact for MRSA (Hall et al., 2012), to 0.005 per minute in contact for VRE (Austin et al., 1999), and to 0.01 per minute in contact for influenza (Oliveira et al., 2003).

These transmissibility values gave rise to probabilities of cross-transmission (p) ranging from 7.5% to 30% during a single 30-min nurse visit. In the event of nurse shortage, the probability of nurse–patient transmission was modulated by a parameter (q) that reflected altered compliance of nurses with transmission-based precautions. The probability of cross-transmission for physician–patient visits ranged from 3% to 10%. These values were smaller than those of nurses due to the shorter duration and lower frequency of physical contacts during physician–patient visits (Temime et al., 2009).

Modeling temporary nurse shortage and management strategies to deal with nurse absenteeism

Starting from a situation of normal staffing for which full work attendance was assumed (Moret et al., 2012), we analyzed the impact of suddenly increasing nurse shortage by letting the daily rate of nurse absenteeism (a_N) adopt a fixed value that could range between 10 and 40%, in line with weekly rates of nurse substitution reported in the collected data.

We analyzed three prototype strategies to cope with nurse shortage that outlined key features of alternative management decisions available in real-life hospitals:

- Transfer patients (TP):** whenever a nurse was absent, the patients that were assigned to that nurse were immediately removed from the model, simulating their transfer to other ICU facilities or hospital wards. Unoccupied beds could be re-occupied the following day if there was enough available staff. This strategy induced an effective temporary pruning of the

Table 1
List of model parameters with the range of explored values and the corresponding references.

Symbol	Description	Values (range explored)	Reference
Parameters describing ICU organization			
N_{beds}	Number of beds	12 (6–24)	
BO	Mean bed occupancy ratio	100% (50–100%)	
LoS	Patient length of stay in the ICU (gamma distribution function)	Mean = 4.2 days Median = 2.1 days	Kramer and Zimmerman (2010)
	HCW-to-patient ratio in the ICU		
	Nurses	1:2	
	Physicians	1:6	
	Number of programmed visits per patient during a work duty		
	Nurses	3	
	Physicians	1	
Parameters describing pathogen spread			
C_0	Probability of pathogen carriage at patient admission	10% (5–20%)	Ziakas et al. (2013a, 2013b)
p	Probability of pathogen transmission during a 30-min patient–nurse visit		
	MRSA-like pathogen	7.5%	Hall et al. (2012)
	VRE-like pathogen	15%	Austin et al. (1999)
	Influenza-like pathogen	30%	Oliveira et al. (2003)
	Probability of pathogen transmission during a 25-min patient–physician visit	10%	Temime et al. (2009)
t_c^P	Average duration of patient carriage	>10 days	Cooper et al. (2008)
t_c^{HCW}	Average duration of HCW contamination	10 h	Temime et al. (2009)
Parameters describing nurse shortage			
a_N	Average rate of nurse shortage during the shortage period	20% (10–40%)	
q	Performance-related relative risk of per-contact pathogen transmission	1.5 (0.7–2)	

contact network, and it increased the influx of patients while reducing their average length of stay in the ward.

- b. **Substitute nurses (SN):** whenever a nurse was absent, a substitute nurse was automatically hired in its place. In this strategy, the contact network remained unchanged, but the per-contact probability of transmission was modified by a multiplicative factor q for substitute nurses. This factor reflected several transmission-related traits that may be different for substitute nurses (skill, knowledge of the ICU setting, knowledge of the patients, fatigue level). We explored values for q ranging from 0.7 to 2, with a baseline value of 1.5. For hand-transmitted pathogens, this factor may be interpreted in terms of individual compliance with hand washing. For instance, if we assume a 65% basal compliance for nurses under normal conditions (Pittet et al., 2006), exploring values between $q=2$ and $q=0.7$ may be translated as evaluating compliances ranging from 32.5% to 93%, and our baseline value of $q=1.5$ would translate as a 43.3% compliance in substitute nurses, in accordance with hygienic compliance reported for nurses outside the ICU settings (Weber et al., 2007).
- c. **Reassign patients (RP):** whenever a nurse was absent, the patients that were originally assigned to that nurse were distributed over other working nurses. This strategy induced an effective temporary densification of the contact network.

Fig. 1b depicts a schematic representation of these 3 strategies in the modeled ICU.

Numerical simulations

We defined scenarios for different organization regimes and pathogen types. For each modeled scenario, we ran 250 simulation replicates to hold stochastic components of the model outcomes at their average value (Ferrer Savall et al., 2013). The time step to model pathogen spread was set to 5 min, while patient and staff fluxes were computed on a daily basis. We performed 500-day simulations: the baseline situation comprised the first 200 days without nurse shortage. It was followed by a 100-day period of increased nurse shortage, and back to a final 200-day period under baseline conditions.

The model was implemented using Netlogo version 4.1.3 (Wilenski, 1999), a free multi-agent modeling environment based on java. The analysis of the simulation results was carried out using R version 2.15.0 (R Development Core Team, 2012), a free software environment for statistical computing.

Results

We systematically explored pathogen dissemination under different scenarios regarding the type of pathogen circulating, the level of nurse shortage, and the adopted management strategy in case of nurse shortage. For each scenario, we compared pathogen prevalence among patients during the baseline and the shortage periods, computed as the daily prevalence averaged over a set of simulation replicates and throughout each period. We considered that the outcomes of two scenarios were significantly different if their inter-quantile ranges did not overlap with each other.

Comparison of the three management strategies

Prevalence of pathogen carriage among patients during the period of nurse shortage could significantly vary depending on the adopted management strategy. Fig. 2 shows the dynamic response of the model for a VRE-like pathogen (with a probability of transmission per 30-min nurse-patient contact $p=15\%$), during the

baseline period without absenteeism followed by a period of moderate nurse shortage (with $a_N=20\%$ absent nurses). Significant differences in pathogen prevalence could be observed as soon as after 5 consecutive days of nurse shortage.

We found that: (i) Transfer Patients reduced pathogen prevalence in the ICU (mainly because the probability of pathogen carriage at patient admission was usually lower than the steady-state baseline prevalence); (ii) *Substitute Nurse* (with the baseline assumption that the per-contact probability of transmission was increased by a factor $q=1.5$ for substitute nurses) led to a moderate increase in prevalence, and (iii) *Reassign Patients* led to the greatest increase in pathogen prevalence, because the number of daily contacts per working nurse increased.

Sensitivity analysis

In order to evaluate the impact of ICU settings and pathogen transmissibility on the model predictions, we explored different values of the severity of nurse shortage (a_N , from 10 to 40%) pathogen transmissibility (p , from 5 to 30%), nurse performance (q , from 0.7 to 2) ICU size (N_{beds} , from 6 to 24), mean bed occupancy ratio (BO, from 70 to 100%) and probability of colonization at patient admission (C_0 , from 5 to 20%). The results of this sensitivity analysis, which are provided in the Supplemental Digital Content (Fig. S1), underline the fact that significant divergences in the impact of the three management strategies we explored are driven by changes in a_N , p and q , while model outcomes are less sensitive to variations in the other parameters.

Supplementary Fig. S1 related to this article can be found, in the online version, at doi:10.1016/j.epidem.2014.07.002.

Impact of the type of pathogen

We compared the three management strategies under different scenarios regarding the type of pathogen transmitted: MRSA-like ($p=7.5\%$), VRE-like ($p=15\%$) or influenza-like ($p=30\%$). Fig. 3 depicts the predicted steady-state prevalence of pathogen carriage for a moderate shortage situation ($a_N=20\%$) under each scenario. The baseline prevalence, obtained without nurse shortage, is provided as a reference on each graph. Prevalence increased with pathogen transmissibility, leading to baseline values of $(13 \pm 2)\%$ for MRSA, $(25 \pm 4)\%$ for VRE and $(38 \pm 3)\%$ for influenza-related pneumonia which is consistent with transmission dynamics described in the literature (Austin et al., 1999; Oliveira et al., 2003; Marschall and Mühlemann, 2006).

As shown in Fig. 3, there was no significant difference between the impacts of the three strategies for low-transmissibility pathogens. For medium-transmissibility pathogens, only *Reassign Patients* led to significantly greater pathogen prevalence. For high-transmissibility pathogens, significantly greater prevalence was observed for reassignment of patients and for substitution of nurses with less prepared staff.

Impact of the level of nurse shortage

We compared the impact of the three management strategies under different scenarios regarding the severity of nurse shortage ($a_N=10\%$, 20% or 40%). Fig. 4 depicts the predicted steady-state prevalence of patient carriage of a VRE-like pathogen ($p=15\%$) under each scenario, along with the predicted values during the baseline period.

Differences in the impacts of the three management strategies became more evident as the severity of nurse shortage increased. As shown in Fig. 4, substituting absent nurses with less prepared replacements ($q=1.5$) significantly increased pathogen prevalence under severe nurse shortage only, while increasing the workload

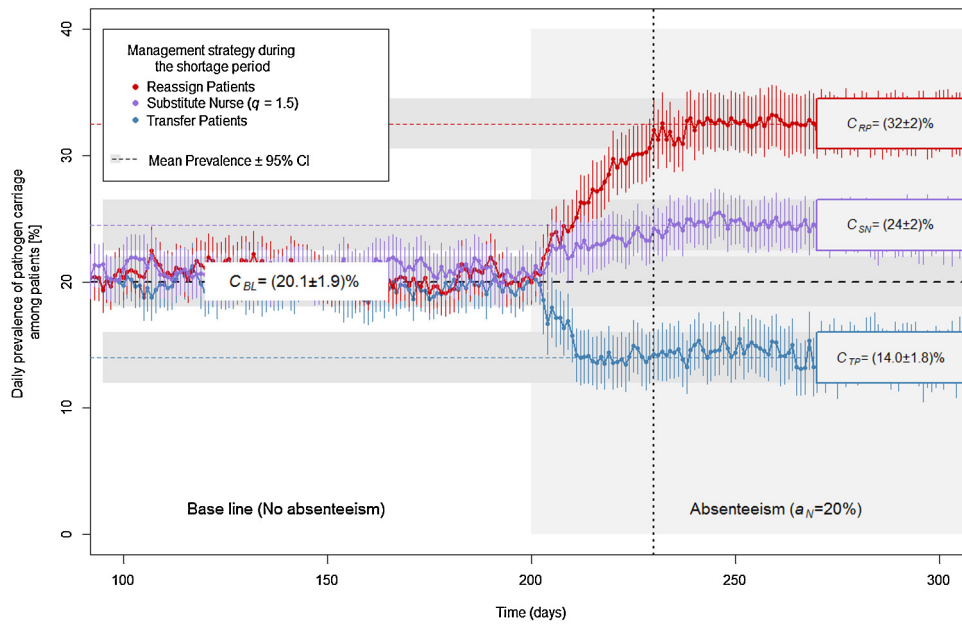


Fig. 2. Time changes in the daily prevalence of carriage of a VRE-like pathogen among patients. Initial baseline period (BL) without nurse absenteeism followed by a period of 20% nurse shortage, faced by adopting three alternative management strategies (TP: transfer the patients who were allocated to the missing nurses to other wards, SN: substitute missing nurses with agency-hired nurses for whom the transmission probability is assumed to be increased by a factor $q = 1.5$, and RP: reassign the patients who were allocated to the missing nurses to currently working nurses). The vertical dotted line indicates the burnout period until reaching the steady-state prevalence (C) in the shortage period. Sub-indices indicate each management strategy; q : factor multiplying the per-contact probability of pathogen transmission of substitute nurses; CI: confidence interval of the mean value encompassing 95% of the daily fluctuations in prevalence.

of working nurses led to important increases in prevalence when the level of nurse shortage was moderate or severe.

Impact of altered nurse performance

The results presented so far reflect the impact of the alterations of the contact network induced by each management strategy, as depicted in Fig. 1b. However, nurse shortage may also directly impact the performance of working nurses and alter the individual per-contact probability of pathogen transmission. Hence, we explored both decreased and increased transmission probabilities

during nurse shortage periods, using a multiplying factor (q) that ranged between 0.7 and 2. Fig. 5 presents the predicted steady-state prevalence of patient carriage of a VRE-like pathogen ($p = 15\%$) during a period of moderate nurse shortage ($a_N = 20\%$), obtained while varying nurse performance for each management strategy.

Varying nurse performance had a significant impact on model outputs but a limited capacity to balance network-driven effects: first, irrespective of the assumed performance of working nurses, patient transfer was never associated with significant increases in pathogen prevalence. Second, and rather intuitively, nurse substitution led to a significantly decreased prevalence when the

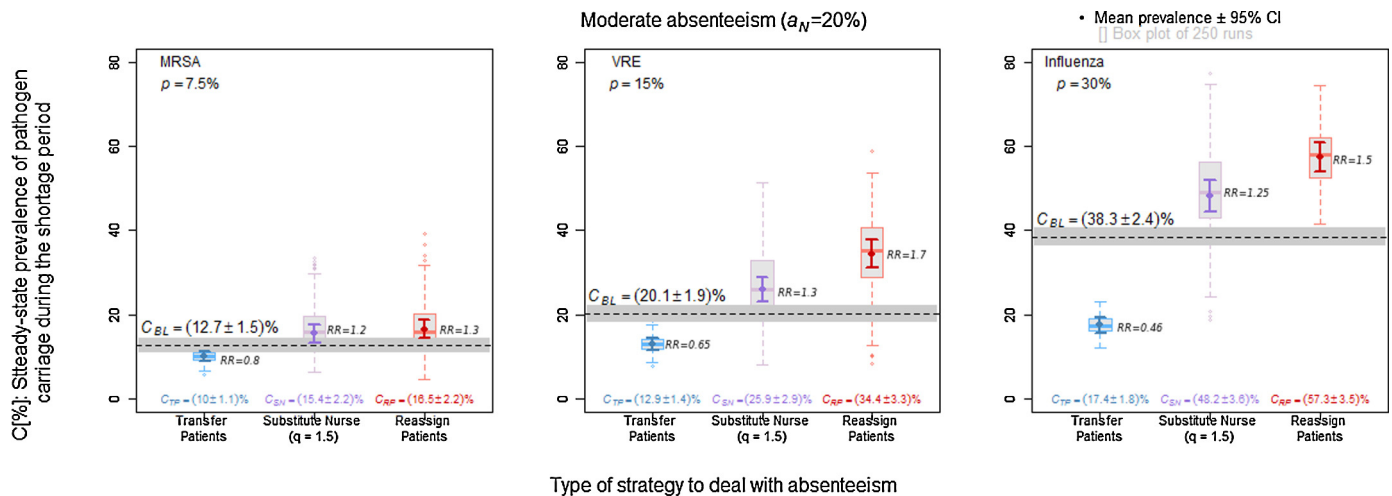


Fig. 3. Comparison of the impact of nurse shortage on the dissemination of different pathogens. Model predictions of the steady-state prevalence of pathogen carriage among patients (C) for the three explored management strategies (TP: transfer patients, SN: substitute nurse, and RP: reassign patients), under scenarios that represent the transmission of pathogens with increasing transmissibility (MRSA-like, VRE-like and Influenza-like) during a period of moderate nurse shortage ($a_N = 20\%$). For each scenario, the mean predicted prevalence is depicted along with its 95% confidence interval and with a boxplot providing the minimum, maximum, 25th and 75th percentiles of the prevalence, based on 250 simulations of the model. Baseline prevalence (BL) is provided as a visual guide for comparison. a_N : daily probability of a nurse being absent during the shortage period; p : per-contact probability of pathogen transmission; q : factor multiplying the per-contact probability of pathogen transmission in substitute nurses. RR: relative risk of the strategy, expressed as the ratio between the average prevalence during the shortage and the baseline periods.

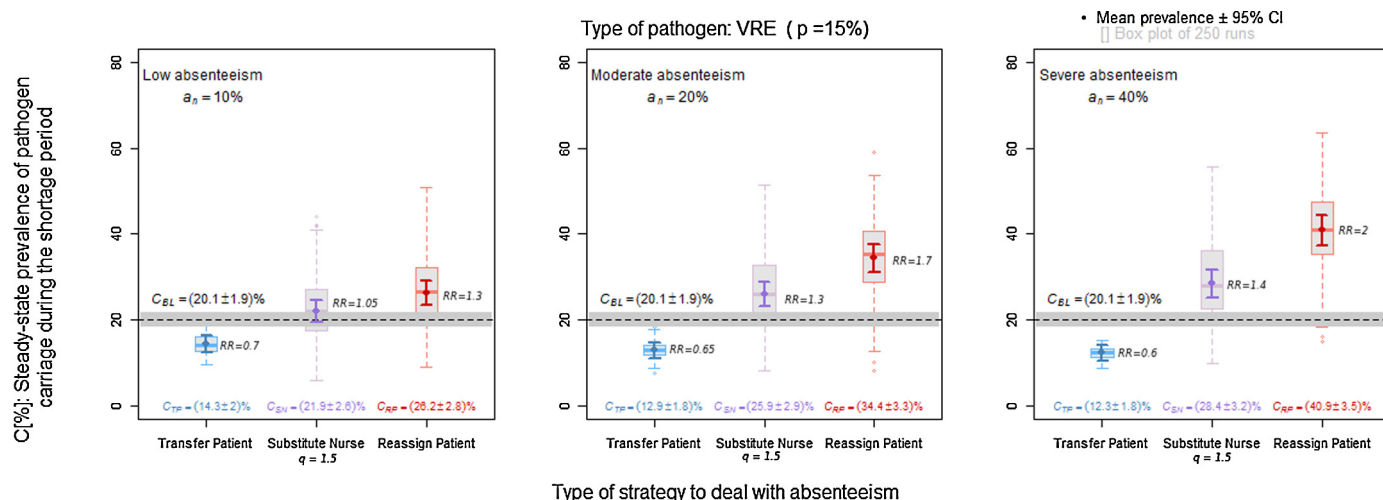


Fig. 4. Comparison of the impact of nurse shortage episodes of different severities. Model predictions of the steady-state prevalence of pathogen carriage among patients (C) for the three explored management strategies (TP: transfer patients, SN: substitute nurse $q = 1.5$, and RP: reassign patients), under scenarios that represent VRE-like transmission during periods of nurse shortage of increasing severity. For each scenario, the mean predicted prevalence is depicted along with its 95% confidence interval and with a boxplot providing the minimum, maximum, 25th and 75th percentiles of the prevalence, based on 250 simulations of the model. Baseline prevalence (BL) is provided as a visual guide for comparison. a_n : daily probability of a nurse being absent during the shortage period; p : per-contact probability of pathogen transmission; q : factor multiplying the per-contact probability of pathogen transmission of substitute nurses. RR: relative risk of the strategy, expressed as the ratio between the average prevalence during the shortage and the baseline periods.

replacement nurses were assumed to be associated with lowered transmission ($q < 1$), and to an increased prevalence otherwise ($q > 1$). Finally, the increase in pathogen spread induced by the reassignment of patients to other working nurses could never be mitigated, even if the per-contact probability of pathogen transmission of working nurses was assumed to be reduced.

Discussion

This study demonstrates how different prototype strategies to deal with temporary nurse shortage may affect the spread of pathogens in the ICU. The agent-based approach we adopted allowed us to identify determinant factors of pathogen spread

in a setting where experimental results are difficult to obtain in practice, taking into account both changes in the number of potentially harmful contacts and alterations of nurse performance. Our results, which suggest that substituting missing nurses with less prepared staff may be significantly hazardous under moderate or severe nurse shortage, and that increasing the workload of working nurses with the care of additional patients is the most unsafe decision possible, are in line with observed data (Robert et al., 2000).

The analysis of sensibility of the model suggests that management strategies dealing with nurse shortage that aim to minimize the risk of infection outbreaks should focus on the performance of working nurses and of available substitutes, and take into account

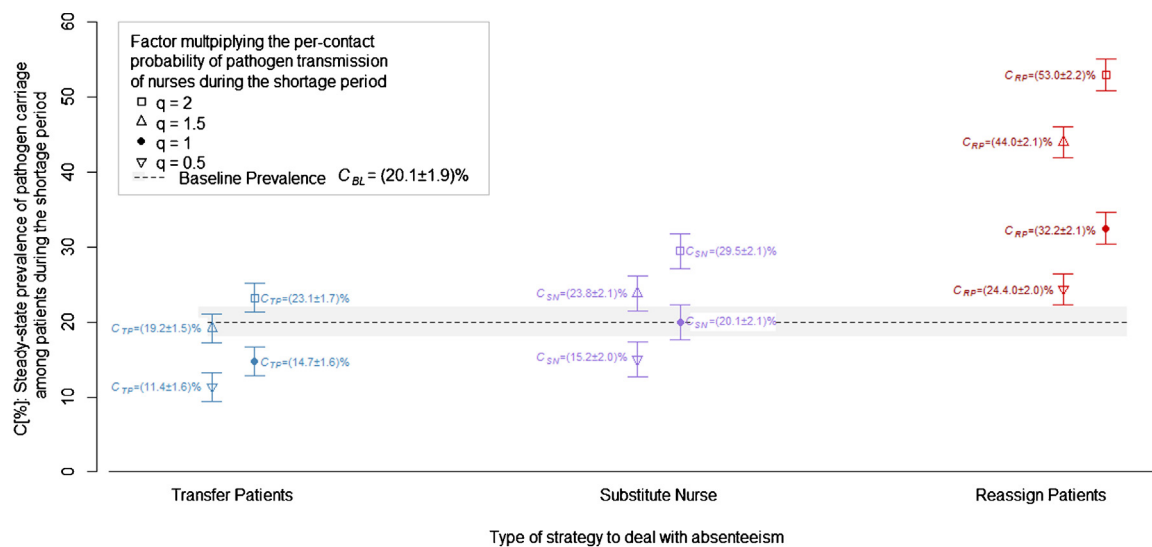


Fig. 5. Impact of changes in nurse performance during shortage episodes. Model predictions of the steady-state prevalence of pathogen carriage among patients (C) for the three explored management strategies (TP: transfer patients, SN: substitute nurse, and RP: reassign patients), under a scenario that represents VRE-like transmission during a period of moderate nurse shortage, while varying the per-contact probability of transmission for on-duty nurses by a factor q . Baseline prevalence (BL) is provided as a visual guide for comparison. CI: confidence interval encompassing 95% of the daily fluctuations in prevalence.

both the type of pathogens which circulate in the ICU and the severity of nurse shortage.

Several assumptions of the model are discussed next. First, this study used a somewhat simplified description of pathogen transmission processes in the ICU. We assumed that all pathogen transmissions occurred via nurse–patient interactions, we considered a simplified contact structure with a limited number of patient–HCW contacts, and we ignored direct HCW-to–HCW transmissions, in line with recent observations of contact patterns in ICUs (Isella et al., 2011). In the absence of detailed information, we also assumed equal HCW-to–patient and patient-to–HCW transmissibility rates and that all contacts were equally hazardous. Finally, we neglected environmental contamination, although it may be an important driver of the spread of some pathogens, including VRE for instance (Huang et al., 2006). Indeed, while accounting for environmental contamination could have a quantitative impact on our predictions, it should not significantly affect our main conclusions regarding the comparison between management strategies.

Second, we used average prevalence of pathogen carriage among patients as the main outcome, rather than infection rates, because carriage prevalence is directly related to colonization pressure, a key parameter in the epidemiology of hospital-acquired infections (Cooper et al., 2008; Bonten, 2012). Consequently, we did not attempt to simulate the repercussions of infection, such as a possible increase in the length of stay of patients, or variations in patient care-load.

Finally, our model was restricted to a single ICU, which means that we did neither attempt to model the impact of patient discharges on other hospital services, nor on the community.

The prototype strategies presented here are simplified representations of management decisions made to alleviate sudden increases in nurse shortage. As such, they are not fully realistic, and some limitations are discussed below.

First, *patient transfer* to other intensive care units is not lifelike because in real ICUs suffering from nurse shortage, beds would be closed by suspending patient admissions after a discharge, rather than by transferring patients whose safety may be compromised. Besides, the outcomes of this strategy, which indicate an effective reduction of pathogen prevalence in the ICU, mostly reflect that patients have a probability of carriage at admission smaller than the average prevalence among patients. Moreover, from the whole hospital point of view, this strategy may well be the most hazardous, as our predictions show that the prevalence of pathogen carriage then becomes larger at ICU patient discharge than it was at admission, thus increasing the global risk of pathogen spread within the hospital. Even so, this strategy has been introduced in the model for the sake of comparison, and also because patients could be actually transferred to other facilities during severe epidemic outbreaks for isolation purposes. Second, in real ICUs, *substitution of nurses* depends on the immediate availability of replacement staff, and the transmission-related performance of substitutes varies accordingly: within over-time limits, absent nurses may at first be replaced by other ICU nurses on leave, which could induce a fatigue-related decrease in nurse performance. For hired agency nurses, performance could depend on their preparation, but also on their familiarity with ICU settings. Finally, substitution can be unfeasible in situations associated to simultaneous increased nurse shortage in all healthcare settings such as during a large-scale community epidemic (e.g. influenza pandemic).

Third, in ICUs, regulations may forbid using strategies based on the *reassignment of patients* if they increase the nurse-to-patient ratio over a pre-specified value in the long term. However, from our experience and contacts with ICU managers, patient reassignment may be adopted transiently when a nurse must leave work on short notice and if no other strategy can be adopted. Moreover, this practice may be more frequent in other

types of hospital wards, where patients require less constant monitoring.

Conclusions

Real-time management of nurse shortage episodes requires ICU schedules to be adjusted on a shift-by-shift basis while considering multiple contingencies (such as local offer and demand of nursing services, costs and budget limitations). In order to achieve sufficient coverage in the ICU and among many other options (for instance, asking for voluntary overtime or negotiating for float nurses with other units), managers may resort to a combination of the three strategies explored in this study.

However, even the simplified analysis presented here may already have direct management implications. First, it demonstrates that such management decisions may significantly affect the nosocomial risk. Second, it allows estimating the maximum potential impact of alternative management decisions and it provides the means to weigh the contribution of network-related versus performance-related factors affecting pathogen spread. And third, it enables tracking how the impact of these decisions varies with the transmissibility of the pathogen to be controlled and with the severity of nurse shortage.

In order to provide a comprehensive practical guide for decision makers in hospitals, future studies based on observed data should describe transient states that better represent pathogen transmission dynamics in real-life ICUs, use alternative model outcomes, such as the number of in-ward transmissions accumulated over a fixed period, and include a cost-effectiveness approach, taking into account the costs and viability of mixed strategies as well as their impact on patient safety.

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