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Preventing the transmission of multidrug-resistant organisms (MDROs): Modeling the relative importance of hand hygiene and environmental cleaning interventions

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Abstract

OBJECTIVES—Hand hygiene and environmental cleaning are essential infection prevention strategies, but the relative impact of each is unknown. This information is important in assessing resource allocation.

METHODS—We developed an agent-based model of patient-to-patient transmission—via the hands of transiently colonized healthcare workers (HCW) and incompletely terminally cleaned rooms—in a 20-patient intensive care unit. Nurses and physicians were modeled and had distinct hand-hygiene compliance levels on entry and exit to patient rooms. We simulated the transmission of *Acinetobacter baumannii*, methicillin-resistant *Staphylococcus aureus* and vancomycin-resistant Enterococci for one year using data from the literature and observed data to inform model input parameters.

RESULTS—We simulated 175 parameter-based scenarios and compared the effects of hand hygiene and environmental cleaning on rates of MDRO acquisition. For all organisms, increases in hand-hygiene compliance outperformed equal increases in thoroughness of terminal cleaning. From the baseline, a 2:1 improvement in terminal cleaning compared to hand hygiene was required to match an equal reduction in acquisition rates (e.g., a 20% improvement in terminal cleaning was required to match the reduction in acquisition due to a 10% improvement in hand hygiene compliance).

CONCLUSIONS—Hand hygiene should remain a priority for infection control programs, but environmental cleaning can have significant benefit for hospitals or individual hospital units that have either high hand hygiene compliance levels or low terminal cleaning thoroughness.

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Potential Conflicts of Interest:

D.J.M. has served as a consultant for Sanofi and Welch-Allyn.

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Introduction

Multidrug-resistant organisms (MDROs) are prevalent in most healthcare settings and are responsible for infections resulting in increased morbidity, mortality and healthcare costs.¹ Hospitalized patients are at risk for acquiring MDROs primarily from the hands of transiently colonized healthcare workers or indirectly from contaminated environmental surfaces. Hand hygiene has long been considered the central tenet of infection prevention aimed at limiting the spread of MDROs, as well as susceptible-pathogens.² More recently, potential pathogens, have been found to contaminate the near-patient environment³ and environmental contamination has been linked to transmission from one patient to another.^{4–7} Infection prevention strategies to improve hand hygiene compliance and environmental cleaning in the healthcare setting are aimed at reducing this risk of transmission.

However, despite knowledge of the importance of these strategies, compliance is notoriously poor. Historically, compliance with hand hygiene has been reported to be less than 40% on average (ranging from 30–60% depending on healthcare worker type and unit)⁸ and while more recent studies are reporting higher rates of compliance (up to 77%), additional work in this area is needed.^{9,10} Similar findings exist for appropriate terminal cleaning with 30–60% (Average 38%) of near patient surfaces being cleaned according to policy.¹¹ Significant efforts and resources are required to improve compliance in either of these areas as they both rely on sustained change of behaviors among healthcare personnel. When healthcare facilities are investing limited resources in infection prevention strategies, it would be useful to know which strategy is likely to have the greater impact on preventing transmission; however, the relative impact of each of these strategies is unknown. A randomized trial comparing improvements in hand hygiene and environmental cleaning would be unethical and infeasible. Therefore, we employ a mathematical model to investigate the relative impact of each factor to provide valuable insights into this area.

In this study, we use agent-based modeling to explore the relative impact of hand hygiene and environmental cleaning on acquisition of multidrug-resistant (MDR) bacteria including MDR-*Acinetobacter baumannii*, methicillin-resistant *Staphylococcus aureus* (MRSA) and vancomycin-resistant enterococci (VRE), because greater understanding of the relative impact of these two strategies could be very useful in optimizing resource allocation for infection prevention interventions.

Methods

We developed a detailed agent-based model of patient-to-patient transmission in a 20-patient ICU using NetLogo (v5.0.3), an open-source modeling tool.¹² We use agent-based modeling to explicitly simulate the interactions between patients, healthcare workers, and the healthcare environment. Transmission among patients in the model occurs via the hands of transiently colonized healthcare workers. We model nurses and physicians explicitly, and each healthcare worker type (i.e., nurse or physician) has distinct hand hygiene compliance levels on entry and exit to patient rooms. We modeled hand hygiene efficacy to be 83% based on prior studies.^{13,14}

Prior studies have shown that patients residing in a room previously occupied by a colonized patient have a higher risk of acquisition. We modeled this higher risk of acquisition using odds ratios reported in these studies for the various MDROs^{5,6,15}; *A. baumannii*, OR 4.2, 95% Confidence Interval (CI) 2 to 8.8 and MRSA/VRE, OR 1.4, 95% CI 1.0 to 1.8; of note, the lower bound OR = 1 was not modeled as we would anticipate this scenario would have no impact on transmission. Adequate environmental cleaning mitigates the additional risk of acquisition due to prior-room occupancy, which is modeled as an experimental probabilistic variable. For example, thoroughness of cleaning of 40% implies that, given a single cleaning opportunity, there is a 40% probability that the room will be cleaned sufficiently well as to remove all additional risk for the next admitted patient. For this analysis, we focus on terminal cleaning only (i.e., cleaning a room after discharge of a patient) because there is more available data to support its use in practice and its effectiveness in reducing MDRO transmission.

Table 1 summarizes the model inputs used for our simulation experiments. Three categories of model inputs are presented in Table 1: selected parameters, parameters fit by observed data, and experimental parameters. The selected parameters are model inputs that we chose, to model a generic hospital ICU. The parameters fit by data were either fit using data from the research literature or observed data from a large, academic medical center. Selected parameters and parameters fit by data were held constant for all of our simulation experiments. Hand hygiene compliance and thoroughness of terminal cleaning are the experimental variables. The baseline levels for hand hygiene compliance depend on the healthcare worker type and whether the hand hygiene opportunity was on entry to the patient room or on exit. We set the baseline rates for the hand hygiene compliance of nurses at 70% and 85% on entry and exit, respectively, and at 57% and 67% on entry and exit for physicians, respectively, based on observed data from a single facility in the mid-Atlantic region. The baseline level for thoroughness of terminal cleaning (i.e. 40% of surfaces being appropriately cleaned) was set at 40%.¹¹ We varied these experimental variables in increments of 10% relative to their respective baseline levels.

The general dynamics of the model are described as follows:

1. *Admission prevalence*: We used an admission prevalence parameter to reflect the proportion of patients colonized or infected with a given MDRO at admission to the unit.
2. *Length of stay*: Each patient is assigned a predetermined length of stay, drawn from a probability distribution fit to observed data.
3. *Healthcare worker and patient interactions*: During each time step, one healthcare worker is chosen to visit one of his or her assigned patients. The healthcare worker type is determined probabilistically, based on a parameter that reflects the proportion of patient visits performed by nurses (vs. physicians). Once the healthcare worker type is chosen, each specific healthcare worker is equally likely to be chosen, as is the patient belonging to the chosen healthcare worker. Each time step represents one visit to a patient; therefore, real time in the model is determined by the number of visits per patient per hour.

4. *Transmission dynamics*: During each patient visit, there may be an opportunity for transmission to occur, depending on the colonization status of the patient and healthcare worker. Transmission is probabilistic in the model and is determined by a transmission probability parameter, which is calibrated to generate acquisition rates of 5–40 per 1000 patient days as found in the research literature.^{16,17}
5. *Hand hygiene compliance and efficacy*: On entry to the patient room and on exit, the healthcare worker has independent opportunities to wash his or her hands. Each hand hygiene event has a probability of successfully cleaning the healthcare worker's hands, which is determined by a hand hygiene efficacy parameter that is constant across all healthcare worker types. A healthcare worker with clean hands poses no risk to patients.
6. *Prior-room occupant risk*: If a patient becomes colonized, the status of the room is changed to reflect this change in patient status. Subsequent patients that occupy the same room may have a higher risk of acquiring the MDRO from a transiently colonized healthcare worker, unless the room has been cleaned sufficiently well.
7. *Patient discharge and terminal room cleaning*: When the patient's length of stay has ended, the patient is discharged and the room is turned over prior to the next patient admission. The terminal cleaning parameter determines the likelihood that the room is sufficiently cleaned (i.e., thoroughness of cleaning) during turnover and is estimated based on the percent of surfaces appropriately cleaned. Rooms remain in a colonized status until they are successfully cleaned (i.e., rooms can remain contaminated for multiple patient stays). Rooms that are clean remain clean until a colonized patient occupies the room.

Results

We simulated the transmission of MDR-*A. baumannii*, *MRSA* and VRE for one year using the model inputs specified in Table 1. We performed 100 replications each for 175 parameter-based scenarios and compared the effects of the two experimental factors (i.e., hand hygiene and terminal cleaning) on acquisition rates. We first discuss the results of the MDR-*A. baumannii* scenarios, and then compare these results to the scenarios representative of *MRSA* and VRE transmission.

Figure 1 summarizes the results in which acquisition of MDR-*A. baumannii* is modeled as a function of hand hygiene compliance and thoroughness of terminal cleaning. Hand hygiene compliance was varied from the baseline to reflect 10% and 20% improvements and 10% and 20% decreases in compliance. Thoroughness of terminal cleaning was varied from 30% to 90% in ten percent increments. In the top of Figure 1, we plot the percent reduction in mean acquisition rates for MDR-*A. baumannii* and show that increases in hand hygiene compliance (equally across nurses and physicians, entry and exit) outperform equal improvements in terminal cleaning. From the baseline, a 2:1 improvement in terminal cleaning is required to match an equal reduction in acquisition rates (e.g., a 20% increase in thoroughness of terminal cleaning is required to match the reduction in acquisition rates due to a 10% improvement in hand hygiene compliance). These results also show that

acquisition rates would increase substantially more if hand hygiene compliance fell 10% or 20% than it would if cleaning thoroughness fell from its baseline level. We found that the relative reduction in acquisitions would be even larger from lower baseline levels of hand hygiene compliance, whereas the effect of cleaning thoroughness is generally linear and constant.

In the bottom of Figure 1, we compare the individual strategies of improving hand hygiene or terminal cleaning with mixed strategies that improve some combination of each; and show that the strategy of improving only hand hygiene compliance outperforms any mixed strategies as long as the total percent improvements are equal (e.g., comparing a 20% improvement in hand hygiene compliance to a mixed strategy of +10% hand hygiene compliance and +10% terminal cleaning). In addition, the strategy of improving hand hygiene compliance by 20% actually outperforms the mixed strategy of improving hand hygiene compliance by 10% and terminal cleaning thoroughness by 20%.

We performed sensitivity analyses modifying the risk of acquisition of *A. baumannii* from the prior-room occupant based on the relative risks reported in the literature (e.g. where relative risk ranges from 2 to 8.8; see Table 1). The results (not shown) continue to demonstrate the 2:1 advantage for hand hygiene over terminal cleaning; however, the acquisition rates vary significantly. In the high-risk case (prior-room occupant risk = 8.8), acquisition rates are substantial (~15–50 per 1000 patient days) for scenarios with hand hygiene compliance and thoroughness of terminal cleaning below the baseline levels.

The results for the MRSA/VRE scenario are shown in Figure 2 for the experimental level of prior-room occupant risk (OR 1.8). The low risk case (OR 1.4) demonstrates similar trends, with approximately 25% lower acquisition rates (not shown). On average, the same 2:1 ratio held when we compared the effects of these two factors on reducing acquisition rates. Hand hygiene compliance outperformed terminal cleaning by more than two-fold at the less thorough cleaning levels but less than that at higher levels. As in the first scenario, the strategy of improving hand hygiene compliance by 20% outperformed the mixed strategy of improving hand hygiene compliance by 10% and terminal cleaning by 10%.

However, the mixed strategies in this scenario perform significantly better than for *A. baumannii*, where there was little benefit of improving hand hygiene once cleaning thoroughness reached levels of +20% or higher. This trend suggests that, for organisms with low environmental risk, some effort to improve hand hygiene compliance should accompany any strategy to improve terminal cleaning. The only exception to this trend in mixed strategies is the case where terminal cleaning is improved by approximately 50% or higher. In this case, the acquisition rate reduction is better than that of any mixed strategy, and substantially better than the maximum hand hygiene improvement of +20%.

Discussion

Environmental disinfection and hand hygiene are two pillars of infection prevention, however, the relative importance of each in the healthcare setting is unknown. We explored the relative impact of hand hygiene and environmental cleaning on acquisition of MDROs

including MDR-*A. baumannii*, MRSA and VRE by using an agent-based model. According to our model, hand hygiene is a more efficient strategy for preventing transmission of MDROs and in general a 2:1 improvement in thoroughness of terminal cleaning compared to hand hygiene compliance is required to achieve an equal reduction in acquisition rates for all MDROs tested. Furthermore, strategies of solely hand hygiene improvement outperformed terminal cleaning alone or mixed strategies. The importance of hand hygiene is emphasized in the scenarios that involved an MDRO of low environmental impact, that is, those in which the risk of acquisition from the prior-room occupant is lower (e.g., MRSA, VRE, or the low-risk MDR-*A. baumannii* scenarios). In these situations, strategies that included hand hygiene improvements, either alone or in combination with improvements in environmental cleaning, performed significantly better than for the high-risk *A. baumannii* scenarios, where there was little benefit at total percent improvement levels of 30% or higher. This trend suggests that, for organisms with low environmental impact, some effort to improve hand hygiene compliance should accompany any strategy to improve terminal cleaning.

It is unclear if these findings suggest favoring investment in hand hygiene compliance over improving environmental cleaning. For each of the organisms modeled, a benefit was seen for each increment of improvement in terminal cleaning, consistent with the clinical studies on which our modeling was based, that environmental hygiene has an important role in the prevention of MDRO acquisition and possible infection. This effect may be most pronounced in scenarios that include an MDRO with a significant environmental risk (e.g., the high-risk MDR-*A. baumannii*), which suggest that if improvements in terminal cleaning thoroughness above 30% can be achieved, a strategy focusing solely on environmental cleaning may be of greater benefit. The literature suggests that thoroughness of terminal cleaning is 40% on average and studies have shown that specific interventions may enhance cleaning to 78–88%.¹¹

For facilities with low baseline levels of compliance of both hand hygiene and environmental cleaning, the question may then be, which strategy is easiest to employ? This is dependent on facility characteristics, personnel and whether improvements in terminal cleaning are easier to achieve than improvements in hand hygiene compliance. If terminal cleaning is more easily improved (as may be the case in many settings), then improving thoroughness may be the more effective strategy.

There are several limitations to this study. The model parameters used in this study were taken from the literature when available, otherwise we used unpublished data from a single-center to inform our parameter selection. We acknowledge that our results would likely change if we used different parameters, as some parameters vary widely across different facilities. In particular, the admission prevalence of MDROs and baseline values for hand hygiene and thoroughness of terminal cleaning are also likely to vary. We varied these parameters in the sensitivity analyses so that our results would be applicable to most facilities, and we have offered some considerations for facilities that may be operating outside of our parameter ranges. In addition, facilities could adapt and individualize our model by incorporating their own parameters. Another limitation is that this model focused only on terminal cleaning after patient discharge and not daily cleaning when the room is

occupied. A greater relative impact of environmental cleaning on MDRO transmission (compared to hand hygiene) might be seen if hospitals were to improve the thoroughness of both terminal and daily cleaning.

In the setting of unlimited time and resources, healthcare facilities may choose to invest heavily in multiple strategies aimed at reducing transmission. However, resources are often limited and efforts must be invested in one strategy over another. In addition to available resources, institutions need to consider MDRO prevalence, baseline compliance rates with infection prevention strategies, and personnel buy-in. Our model may assist facility leadership in determining the best strategy for their site. In general, a strategy that includes improvements in hand hygiene is likely to be beneficial, however, environmental cleaning also plays an important role in the prevention of transmission. In our modeling, improvements in hand hygiene were more efficient than comparable improvements in terminal cleaning, however a strategy of improving some combination of both factors predicted the greatest reduction of MDRO acquisition and may be the most effective approach to minimizing transmission.

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Figure 1.

Panel A: Percent reduction (from the baseline) in mean *Acinetobacter baumannii* acquisition rates as a function of hand hygiene compliance and thoroughness of terminal cleaning. Baseline hand-hygiene compliance rates were 70% and 85% for nurses on entry and exit, respectively, and 57% and 67% for physicians on entry and exit, respectively. Baseline terminal cleaning thoroughness was 40%. Baseline prior-room occupant risk was set at 4.2. These simulation conditions produced a mean acquisition rate of 2.90 per 1000 patient days. Panel B shows mixed strategies combining hand hygiene and thoroughness of cleaning.

Figure 2.

Percent reduction (from the baseline) in mean Methicillin-resistant *Staphylococcus aureus* and Vancomycin-resistant *enterococci* acquisition rates as a function of hand-hygiene compliance and thoroughness of terminal cleaning, shown with mixed strategies. Baseline hand hygiene compliance rates were 70% and 85% for nurses on entry and exit, respectively, and 57% and 67% for physicians on entry and exit, respectively. Baseline terminal cleaning thoroughness was 40%. Prior-room occupant risk was set at the experimental level of 1.8. These simulation conditions produced a mean acquisition rate of 3.88 per 1000 patient days.

Table 1

Agent-based model input parameters

Parameter	Baseline Value	Experimental Values	Source
Number of patients	20		Selected
Number of nurses	10		Selected
Number of physicians	2		Selected
Cleaning frequency	Discharge only		Selected
Admission prevalence	0.032 (AB) 0.10 (MRSA) 0.20 (VRE)		Observed data ^a , Climo (2009) ¹⁶ , Huskins (2011) ¹⁷ , Harris (2013) ⁹
Length of stay, in days (median)	2		Observed data
Proportion of visits to patients by nurses versus physicians	0.7		Observed data
Patient visits per hour	3 ^{9,18}		Observed data
Transmission probability ^b	0.05		Calibrated to fit observed acquisition rate data, Hornbeck (2012) ¹⁴
Hand hygiene compliance	70% (nurse on entry) 85% (nurse on exit) 57% (physician on entry) 67% (physician on exit)	-20%, -10%, +10%, +20%	Observed data
Hand hygiene efficacy	0.83		Girou (2002) ¹³ , Hornbeck (2012) ¹⁴
Prior-room occupant risk	4.2 (AB) 1.4 (MRSA/VRE)	2, 8.8 (AB) 1.8 (MRSA/VRE)	AB: Nseir (2010) ⁶ MRSA/VRE: Datta (2011) ¹⁵ , Huang (2006) ⁵
Thoroughness of terminal cleaning	40%	-10%, +10%, +20%, +30%, +40%, +50%	Hayden (2006) ¹⁹ , Carling (2006) ²⁰ , Goodman (2008) ²¹

^a In the absence of data from the research literature, we used unpublished data from a single site to inform our parameter selections

^b The probability of transmission given an interaction between a susceptible agent and a colonized agent