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Contribution of Interfacility Patient Movement to Overall Methicillin-Resistant *Staphylococcus aureus* Prevalence Levels

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Abstract

Objectives—The effect of patient movement between hospitals and long-term care facilities (LTCFs) on methicillin-resistant *Staphylococcus aureus* (MRSA) prevalence levels is unknown. We investigated these effects to identify scenarios that may lead to increased prevalence in either facility type.

Methods—We used a hybrid simulation model to simulate MRSA transmission among hospitals and LTCFs. Transmission within each facility was determined by mathematical model equations. The model predicted the long-term prevalence of each facility and was used to assess the effects of facility size, patient turnover, and decolonization.

Results—Analyses of various healthcare networks suggest that the effect of patients moving from a LTCF to a hospital is negligible unless the patients are consistently admitted to the same unit. In such cases, MRSA prevalence can increase significantly regardless of the endemic level. Hospitals can cause sustained increases in prevalence when transferring patients to LTCFs, where the population size is smaller and patient turnover is less frequent. For 1 particular scenario, the steady-state prevalence of a LTCF increased from 6.9% to 9.4% to 13.8% when the transmission rate of the hospital increased from a low to a high transmission rate.

Conclusions—These results suggest that the relative facility size and the patient discharge rate are 2 key factors that can lead to sustained increases in MRSA prevalence. Consequently, small facilities or those with low turnover rates are especially susceptible to sustaining increased prevalence levels, and they become more so when receiving patients from larger, high-prevalence facilities. Decolonization is an infection-control strategy that can mitigate these effects.

We investigated the effects of patient movement between hospitals and long-term care facilities (LTCFs) on the long-term prevalence of methicillin-resistant *Staphylococcus aureus* (MRSA). Hospitals typically contain many interconnected units, and the length of stay for patients is usually short. Prevalence of MRSA varies widely between hospital units, but there are a number of infection-control measures, such as promoting hand hygiene

among healthcare workers, active surveillance, and contact precautions, that can be implemented to minimize transmission.¹ LTCFs house older patients who are typically more susceptible to acquiring MRSA and are more likely to remain colonized due to both internal and external factors.² In addition, there is an objective to preserve the quality of life for residents in the facility, thus options for infection control are limited.³

Patients are frequently transferred between these 2 types of facilities. Therefore, it is important for infection control practitioners to recognize the impact of this movement on MRSA prevalence in both types of facilities.⁴ Lesosky et al. implemented a Monte Carlo simulation model of a healthcare facility network to explore the effects of patient transfers on MRSA prevalence levels.⁵ However, our results focus on the effects on individual facilities, whereas the Lesosky model examines the effects of patient transfers at the system level. Smith et al. examined a similar problem using a mathematical model, but they focused mostly on transmission dynamics between healthcare facilities and the community.⁶ This work did not compare how a change in the transmission level of one facility can affect the long-term prevalence of other healthcare facilities.

The objectives for this article were to address the following 3 questions: (1) Can patient movement from a hospital affect the prevalence of a LTCF? (2) Can patients from a LTCF increase the prevalence of a hospital if they are sent to various units? (3) Can patients from a LTCF cause an increase in the prevalence level of a particular hospital unit?

Methods

We developed a hybrid model of a healthcare system using NetLogo (ver. 4.1.1), an open-source, agent-based modeling tool that employs a mathematical model to simulate patient movement between hospitals and LTCFs. Transmission within each facility is modeled using a modified version of the susceptible-infected-recovered (SIR) equations (see Figure 1).⁷ We use these equations to simulate proportions of uncolonized patients (U), persistently colonized patients (P), and transiently colonized patients (T) in each facility. The uncolonized patients in our model correspond to the susceptible patient state in the original model, whereas the persistently and transiently colonized patients represent variations of the infected state. Infected patients are included within the colonized-patient compartments because there are limited data that suggest they are more likely than colonized patients to spread MRSA to others. There is no recovered state in this model, as patients who clear colonization become immediately susceptible to recolonization.

The modified equations consist of the admission and discharge (μ), transmission (β), and recovery (γ) rate terms. Positive terms imply an increase in the proportion of patients for the corresponding patient state, while negative terms represent a decrease. Patients can be admitted in any 1 of the 3 patient states. The proportions of patients admitted into each state are represented by the terms u , p , and r , respectively. The transmission term (β) represents the rate at which uncolonized (ie, susceptible) patients enter a colonized state. The terms p and r also represent the proportions of newly colonized patients that enter each respective state. Recovery rates for persistently and transiently colonized patients are represented by γ_1 and γ_s , respectively, with $\gamma_1 \ll \gamma_s$.

Each facility is modeled as an agent in a network of healthcare facilities and has a unique state that consists of proportions of the 3 patient types. This agent-based formulation allows us to analyze various network configurations to determine the effect of patient movement on MRSA prevalence rates in each facility. Each scenario is configured as a network of facilities with directed links that represent patient movement from one facility to another (see Figure 2). The links have associated weights (m_{ij}), which in conjunction with the

facility size (N) determine the number of patients who move from one facility to another in each time step. When patients are transferred from one facility to another, the number of patients in each state is representative of the relative proportions in the source facility. For example, if proportions of patients in the source facility are $U = 0.80$, $P = 0.05$, and $T = 0.15$, and 20 patients are transferred, then 16 patients will be uncolonized, 1 patient will be persistently colonized, and 3 patients will be transiently colonized.

The agent-based modeling framework enables the comparison of infection-control strategies at 1 or more facilities that may be at risk of increased prevalence levels due to an influx of received colonized patients. One option for healthcare facilities is to start these patients on a decolonization regimen to reduce the number of colonized patients who will ultimately interact with susceptible patients. The regimen would likely consist of an application of mupirocin to the nasal cavity, chlorhexidine bathing, or both.^{8,9} This control measure could be implemented in 1 of 3 ways. The first approach is to start all patients on the decolonization regimen immediately upon their arrival to the facility. These patients would not be isolated from the general population and the benefits of decolonization would not be realized until the patients complete the process successfully, which on average takes 2 cycles of 5-day treatments.¹⁰ This approach, although simple to implement, would put a significant number of uncolonized patients through the decolonization process unnecessarily and could lead to increased resistance to the decolonization process.

The other 2 approaches screen arriving patients to determine their colonization statuses, so that only colonized patients undergo the decolonization process. Culture-based screening can take up to 3 days for results, whereas polymerase chain reaction (PCR) testing can return results within 1 day. Culture-based screening is less expensive, but there may be an increased risk of secondary transmission if the patient continues to interact with other patients or healthcare workers without control measures in place. PCR tests are more accurate and allow for control measures to be implemented sooner, but they are more expensive.¹¹

For the first approach, all patients returning to the LTCF from the hospital immediately began a decolonization regimen, which returned them to the uncolonized state in 10 days. For the second approach, patients who arrived at the LTCF underwent a basic culture screening. If a positive test result was produced 3 days later, the patient started a decolonization regimen and recovered in an additional 10 days. Uncolonized patients remained in their susceptible state. Finally, for the PCR approach, all patients received their test results in 1 day and the colonized patients then started the decolonization process.

Results

Simulation experiments were conducted to address the 3 questions posed above. Parameters for the generic hospital, LTCF, and hospital units are summarized in Table 1; these apply to each agent facility in the model. These parameters were not based on specific healthcare facilities but were chosen to represent relative sizes, admission and discharge rates, and transmission levels for typical hospitals and LTCFs in the United States.^{12–14} Facilities are initialized with an entirely susceptible population, and recovery rates for persistently and transiently colonized patients were held constant at 0.02 (γ_I) and 0.2 (γ_S), respectively. Prevalence is measured as the sum of proportions of transiently and persistently colonized patients, which implicitly includes infected patients. As a baseline, hospitals and LTCFs exchange 9 patients each time step, whereas hospital units and LTCFs exchange 2 patients, so that the size of each facility remains constant throughout the simulation period. Relaxing this assumption of equal exchange rates increased the variability of the transient prevalence

(ie, at each time step), but even large net patient flows had little effect on the steady-state prevalences in either facility type.

Can Patient Movement from a Hospital Affect the Prevalence Level of a LTCF?

The first set of experiments paired 1 hospital with 1 LTCF. All parameters were held constant except for the transmission rate parameter (β), which was varied for both facilities until all unique transmission-level pairs were simulated. The results are summarized in Figure 3, which shows MRSA prevalence for both facility types for 9 hospital-LTCF transmission level combinations. The transmission level of the hospital and LTCF specify each configuration. For example, the +/0 configuration means that a hospital with a high transmission rate was exchanging patients with a LTCF that had a medium transmission rate. The -/+ configuration means that a hospital with a low transmission rate was paired with a LTCF that had a high transmission rate. Transmission rate parameters differed for hospitals and LTCFs because each facility type had a different rate of patient turnover, which affected the steady-state prevalence level.

Figure 3 shows that the steady-state prevalence of both facilities is strongly correlated to the transmission rate in the hospital. As a baseline, consider the first 3 cases (-/-, 0/-, +/-) where a LTCF with a low transmission rate is receiving patients from a hospital with increasingly higher transmission rates. There is an increase in the steady-state prevalence of the LTCF from 3.4% to 4.7% to 6.9% as the transmission level of the hospital increases within the series. At higher LTCF prevalence levels, the increase in steady-state prevalence grows at a faster rate (eg, transmission for the high-prevalence LTCF increases from 6.9% to 9.4% to 13.8%). This trend suggests that LTCFs with higher transmission rates are more susceptible to outbreaks when receiving patients from high-prevalence hospitals.

There are 2 key factors that explain how hospitals can cause increased prevalence levels in LTCFs. The first factor is the relative size difference between the 2 facility types. Hospitals are typically larger than LTCFs. Therefore, when patients are exchanged, the number of colonized patients sent from the hospital to the smaller LTCF represents a larger proportion than they did in the hospital, which creates an increased level of colonization pressure. The second key factor is the turnover rate. Patients in LTCFs are likely to reside in the facility for longer periods of time. Consequently, when a hospital sends patients to a LTCF, those patients are ultimately more susceptible to colonization because they spend more time in the facility. In addition, transmission continues to build momentum because the population is relatively stable.

LTCFs have some ability to protect themselves from colonized patients that are either newly admitted or returning from an acute-care hospital. We compared 3 LTCF decolonization strategies for the same 9 cases to determine their effect on steady-state prevalence of both facility types. The results of these experiments are also given in Figure 3. The outcomes for all 3 decolonization strategies were approximately the same; therefore, the results are summarized as a single data set. The similarity between these results is mostly attributable to the regularity with which patients move between facilities and start the decolonization process. Once the first group of arriving patients successfully completes the decolonization process, a new group of patients will complete the process the next day, and so on, regardless of the screening test return time or the recovery period, which are both held constant for all patients. As a result, the long-term LTCF prevalences are approximately equal, because each scenario differs only in the initial time frame before patients start to become decolonized.

The key result from these experiments is that any decolonization strategy can significantly decrease the risk of increased prevalence levels for LTCFs receiving patients from hospitals.

Under decolonization, the LTCF can identify patients who acquired MRSA in a hospital or returning patients who were already colonized. Hospital prevalence levels also showed marginal improvement under the LTCF decolonization program. Our model does not account for the cost of the various approaches in terms of the numbers of screening tests and decolonization supplies or the effect of each approach on a resident's quality of life. Decolonizing all patients has no cost with respect to screening but requires more supplies for the regimen and may reduce the quality of care for patients who have adverse reactions to the process. The screening strategies reduce the number of patients who undergo decolonization, which improves quality, but both have associated costs due to the testing procedures.

Can Patients from a LTCF Increase the Prevalence of a Hospital If They Are Sent to Various Units?

The answer to this question is also derived from the results in Figure 3. It is clear from this figure that the steady-state prevalence of the hospital changes significantly only with its own transmission level. For example, a comparison of the first (−/−), fourth (−/0), and seventh (−/+) cases shows a negligible change in the prevalence of the hospital as the transmission level of the LTCF increases. Even changes at higher transmission levels (cases 2, 5, and 8; cases 3, 6, and 9) lead to only small changes in steady-state prevalence. Therefore, changes in the transmission level of the LTCF have little to no effect on MRSA prevalence in the hospital when the patients are sent to multiple units.

Facility size and patient turnover also explain why LTCFs have little effect on the prevalence level of hospitals as a whole. Hospitals are typically large in size, so a few additional colonized patients in the population will have little effect on the relative proportions of patient states and colonization pressure will essentially remain unchanged. In addition, hospitals typically admit and discharge patients more frequently than LTCFs. Therefore, the hospital population is changing rapidly and the transmission process is continually interrupted.

Can Patients from a LTCF Cause an Increase in the Prevalence Level of a Particular Hospital Unit?

In some cases, patients from a LTCF are consistently sent to the same unit within a hospital. This situation can occur in intensive care units or on geriatric floors, which usually receive patients who reside in LTCFs. For these cases, the population size is the unit size, which is much smaller than the hospital and typically smaller than the LTCF. The turnover rates in these types of units can vary, and so we conducted experiments using a high turnover rate and a low turnover rate (see Table 1). These experiments were conducted simultaneously, with a single LTCF exchanging patients with 1 low-, 1 medium-, and 1 high-prevalence hospital unit. The results are summarized in Figure 4.

The data from the high-turnover case in Figure 4 shows that admissions from a LTCF can have a noticeable effect on the prevalence within a specific hospital unit. In these types of units, the addition of 1 or 2 colonized patients may be sufficient to cause a significant outbreak. The low-turnover case in Figure 4 presents a different outcome, as patients remain in the hospital unit for longer lengths of stay and, therefore, have an increased exposure to colonization. In all 3 cases of hospital transmission levels there is a significant increase in the unit prevalence. In addition, there is a reciprocal effect that increases the LTCF prevalence to higher levels than in the high-turnover case.

Discussion

Our results suggest there are 2 primary drivers that lead to sustained increases in MRSA prevalence when healthcare facilities are exchanging patients. The patient departure rate, which incorporates the discharge and transfer of patients, plays the most significant role in whether a facility is susceptible to external influence. When patients have longer lengths of stay, they are visited more by healthcare workers who may have become transiently colonized. Thus, the risk to the facility is minimized when patients are discharged sooner. The facility size is also critical, because colonized patients represent larger proportions in smaller facilities and, therefore, contribute more to colonization pressure per capita. Consequently, small populations or facilities with low turnover rates are especially susceptible to increased prevalence levels, and they become more at risk when they receive patients from larger, high-prevalence facilities. These types of facilities can protect themselves by implementing control measures, such as bundling active surveillance with decolonization, that ultimately limit the interactions between susceptible and colonized individuals.

There are several limitations to our model and the simulation experiments we performed. The mathematical model is sensitive to the admission and discharge, transmission, and movement terms. The effect of the transmission parameter depends on the values of the other 2 parameters, because when patients leave the facility at a high rate, transmission is less likely to occur than if the patient population was more stable. A more extensive study would explore wider ranges of these parameters to assess their relative effects on long-term prevalence levels. In addition, patient admissions and transfers occurred on a regular, periodic schedule in blocks of fixed sizes. In practice, these patient flows are less regular and probably impact the long-term effects of facility interactions and control measures.

Aside from the limitations, our model provides a unique perspective on exploring the effects of patient movement on long-term MRSA prevalence in hospitals and LTCFs. Combining agent-based and mathematical modeling techniques allowed us to adequately represent transmission dynamics and analyze the interconnectivity of multiple healthcare facilities that exchange patients. Future work may focus on developing an agent-based model for the transmission dynamics within each facility, which would not be limited by the restrictions of mathematical models and could begin to explore the effects of individual contact networks. In addition, we could explore empirical networks of healthcare facilities that regularly exchange patients.

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Figure 1.
Susceptible-infected-recovered (SIR) and modified SIR model equations.

Figure 2.
Example of an interfacility model.

Figure 3.

Comparison of steady-state prevalence levels for a hospital and a long-term care facility (LTCF). Hospital-D and LTCF-D represent the scenario in which the LTCF has implemented a decolonization policy. The labels on the X-axis are expressed in pairs of hospital or LTCF transmission levels.

Figure 4. Comparison of steady-state prevalence levels for 3 hospital units with low, medium, and high transmission levels that exchange patients with a long-term care facility (LTCF) with a low, a medium, and a high transmission level. High (*top*) and low (*bottom*) turnover rates were investigated.

Table 1

Model Parameters

Parameter	Hospital	LTCF	Hospital unit
N	300	100	20
μ	0.2	0.002	0.2 (high), 0.05 (low)
β			
Low	0.15	0.05	0.15
Medium	0.25	0.075	0.25
High	0.35	0.1	0.35
u	0.9	0.9	0.9
p	0	0.6	0
r	1.0	0.4	1.0

Note. LTCF, long-term care facility; N , facility size; μ , admission and discharge rate; β , transmission rate; u , uncolonized admitted patients; p , persistently colonized admitted patients; r , transiently colonized admitted patients.