Practice of Epidemiology

How Long-Term Acute Care Hospitals Can Play an Important Role in Controlling Carbapenem-Resistant Enterobacteriaceae in a Region: A Simulation Modeling Study

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Typically, long-term acute care hospitals (LTACHs) have less experience in and incentives to implementing aggressive infection control for drug-resistant organisms such as carbapenem-resistant Enterobacteriaceae (CRE) than acute care hospitals. Decision makers need to understand how implementing control measures in LTACHs can impact CRE spread regionwide. Using our Chicago metropolitan region agent-based model to simulate CRE spread and control, we estimated that a prevention bundle in only LTACHs decreased prevalence by a relative 4.6%–17.1%, averted 1,090–2,795 new carriers, 273–722 infections and 37–87 deaths over 3 years and saved \$30.5–\$69.1 million, compared with no CRE control measures. When LTACHs and intensive care units intervened, prevalence decreased by a relative 21.2%. Adding LTACHs averted an additional 1,995 carriers, 513 infections, and 62 deaths, and saved \$47.6 million beyond implementation in intensive care units alone. Thus, LTACHs may be more important than other acute care settings for controlling CRE, and regional efforts to control drug-resistant organisms should start with LTACHs as a centerpiece.

Carbapenem-resistant Enterobacteriaceae; hospitals; long-term acute care hospitals; prevention and control

Abbreviations: CMS, Center for Medicare and Medicaid Services; CRE, carbapenem-resistant Enterobacteriaceae; ICU, intensive care unit; LOS, length of stay; LTACH, long-term acute care hospital; QALY, quality-adjusted life year; SNF, skilled nursing facility; vSNF, skilled nursing facility caring for patients requiring mechanical ventilatory support.

Long-term acute care hospitals (LTACHs) may play important roles in the spread and potential control of multidrug-resistant and extensively drug-resistant organisms such as carbapenem-resistant Enterobacteriaceae (CRE) in a region. Such facilities can have higher prevalence of CRE carriage compared with other health-care facilities (1–4). Patients tend to stay in LTACHs for extended periods, resulting in prolonged exposure to CRE and opportunity for CRE transmission. Our previous studies have shown that LTACHs are highly interconnected with short-term acute care hospitals and nursing homes in a region via direct and indirect patient sharing (5–7).

Typically, LTACHs have less experience in infection surveillance and prevention than do short-term acute care hospitals. For example, the requirements for LTACHs to re-

port a limited number of quality measures to the Centers for Medicare and Medicaid Services (CMS) began in fiscal year 2013, and public reporting by LTACHs of infections such as catheter-associated urinary tract infections and central-line associated bloodstream infection began only in fiscal year 2016 (8). In addition, most LTACHs are for-profit and members of large chains. Such facilities may need strong economic justification or incentives to implement infection-control measures. Like many preventive measures, infection-control efforts often require upfront investment, and the resulting economic benefits may not be immediately obvious or may take time to manifest. This is especially true of health-care facilities that form a highly interconnected system in a region, making it difficult to view the far-reaching impact of an infection-control measure (9–17).

The nature of this system raises another issue: what LTACHs do may affect many other facilities. Therefore, it is important for payers like CMS to structure reimbursements that will incentivize LTACH policies and measures that will then benefit the overall system and society. Such payers could benefit from a better understanding of the impact of CRE-control measures in LTACHs. In health-care networks, LTACHs represent a small fraction of facilities yet may care for a disproportionately large number of patients with CRE infection. Thus, LTACHs represent a potential high-yield target for infection-prevention efforts. To better understand the role of LTACHs in CRE spread and the potential broader impact of CRE prevention and control in these facilities, we used our Regional Healthcare Ecosystem Analyst-generated, agent-based model of the Chicago metropolitan region to simulate a range of scenarios.

METHODS

Chicago metropolitan region

The Chicago metropolitan area, the third largest population in the United States with 9.9 million people, covers 10,800 square miles, and includes 462 health-care facilities: 90 short-term acute care hospitals, 9 LTACHs, 351 skilled nursing facilities (SNFs), and 12 vSNFs (SNFs caring for patients requiring mechanical ventilatory support (4)) across 3 states: Illinois ($n = 402$ facilities), Wisconsin ($n = 11$ facilities), and Indiana ($n = 49$ facilities).

Regional Healthcare Ecosystem Analyst: Chicago model

Using our previously described software platform, Regional Healthcare Ecosystem Analyst (18), we generated an agent-based model of all 462 health-care facilities serving adult inpatients in the Chicago metropolitan region and the patients moving among these facilities and surrounding communities to simulate CRE spread (10, 19). Web Appendix 1 provides model details as well as all model inputs (Web Table 1, available at <https://academic.oup.com/aje>) and data sources; Web Figure 1 shows the flow of patients through the model.

Briefly, the model represents each patient as a computational agent, which, on a given day, can either carry (i.e., agent is infected or colonized) or not carry CRE. Each simulated day, patients move to and from the community and other health-care facilities to various health-care facilities in Chicago. Each virtual facility has a total number of beds (based on actual bed counts) and a number of units based on facility type: acute care hospitals consist of general units and intensive care units (ICUs); LTACHs consist of long-term units; vSNFs consist of skilled and other units with ventilatory support capability; and SNFs consist of 1 large unit to represent the high degree of social interactions among residents. Upon admission to a facility, a probability draw occurs to determine the patient's admission unit and the patient's length of stay (LOS), which is facility and unit specific. Within each unit, patients mix homogeneously and CRE carriers can transmit to noncarriers using a facility- and

unit-specific transmission coefficient (β): $\beta \times$ susceptible patients $\times$ infectious patients. After the LOS elapses, the patient leaves the facility, transfers to a different facility, or returns to the community before potentially returning to a facility (same or different). CRE carriers have an additional LOS, staying 3.75 and 9.0 days longer in hospitals and LTACHs, respectively. Compared with noncarriers, CRE carriers discharged from a facility have a 2-fold increased risk of readmission within 1 year.

In the absence of CRE-specific interventions, only a fraction of CRE carriers would be detected, based on the fraction of carriers identified by clinical cultures (12%). Known CRE-positive patients are placed on contact precautions (i.e., a private room and providers don gloves and gowns upon room entry) for their entire LOS in hospitals, LTACHs, and vSNFs. In SNFs, known CRE-positive patients remain on contact precautions for 10 days (representing symptom-based contact precautions). Patients on contact precautions have a probability of remaining so upon transfer to other facilities (based on the likelihood of interfacility communication) and when readmitted to the same facility (Web Table 1). A fraction of patients (regardless of CRE status) could also be placed on contact precautions for non-CRE reasons (e.g., methicillin-resistant *Staphylococcus aureus* colonization) and varied by facility type. Regardless of facility type, contact precautions attenuate CRE transmission by 40%, which accounts for both intervention efficacy and health-care worker compliance, based on existing studies (20–24).

We modeled the use of a CRE prevention bundle, consisting of admission screening, daily chlorhexidine bathing, a hand-hygiene campaign, and either placing CRE carriers in the same room or in private rooms. This prevention bundle has shown a significant reduction in CRE colonization and infection in LTACHs, decreasing the incidence of colonization from 4 to 2 acquisitions per 100 patient-weeks (50% reduction) (25).

We applied the CRE prevention bundle to patients on admission to hospital ICUs and/or LTACHs, depending on the scenario (described later in this section). On admission, patients underwent rectal screening with an associated sensitivity and specificity. Patients testing positive (i.e., true and false positives) were immediately placed under contact precautions with an associated effectiveness (40% at the patient level). The CRE prevention bundle reduced transmission overall by 50% (25); therefore, we calibrated the effectiveness of the remaining bundle portions (i.e., daily chlorhexidine bathing, a hand-hygiene campaign, and geographic separation) to achieve this 50% overall reduction. Considering that screening is not perfect (i.e., not all true-positive cases are identified), screening plus contact precautions have a combined effectiveness of <40%; thus, calibration resulted in 40% patient-level effectiveness for the nonsurveillance portion of the bundle. Patients receiving the CRE prevention bundle incurred costs for swabs, chromogenic agar materials, technician wages for time to process the sample, and chlorhexidine-wipe costs per bath for the LOS duration; those on contact precautions incurred the cost of gowns plus time to don and doff for each room entry and gloves for the LOS duration.

Each carrier had a probability of CRE infection development (26, 27) and a probability of that infection being bacteremia, intra-abdominal, pneumonia, or complicated urinary tract infection, with each infection type having an associated attributable LOS (Web Table 1). Patients with pneumonia had a probability of ventilator-associated pneumonia. Additional tests and procedures were infection specific. All patients infected with CRE were placed on contact precautions (i.e., health-care providers use disposable gloves and gowns) for their attributable LOS, following the standard of care. Regardless of the infection type, all patients had probabilities of receiving monotherapy, carbapenem-containing combination therapy, or non-carbapenem-con-

taining combination therapy. Depending on the infection type, treatment received, and CRE-attributable death (28), each patient had a probability of death.

We estimated costs (in 2018 USD) from the hospital, third-party payer, and societal perspectives, on the basis of our previous publications (29, 30). Following a method described by Graves (31), the hospital perspective measured illness costs in lost bed days (i.e., additional CRE-attributable LOS) based on the infection-specific attributable LOS and cost per bed day plus intervention costs. The third-party payer perspective included direct medical costs (e.g., intervention, hospitalization, drug treatments). The societal perspective included direct and indirect (i.e., productivity

Figure 1. Carbapenem-resistant Enterobacteriaceae (CRE) prevalence in health-care facilities regionwide over time after implementation of a CRE prevention bundle in A) hospital intensive care units (ICUs) alone or together with long-term acute care hospitals (LTACHs), and B) LTACHs alone.

Figure 2. Impact of implementing the carbapenem-resistant Enterobacteriaceae (CRE) bundle in an increasing number of long-term acute care hospitals (LTACHs) and hospital intensive care units (ICUs) on the total number of new CRE carriers regionwide (transmission events) over 3 simulated years. Boxes represent the interquartile range (25th and 75th percentiles), the central line in each box is the median, whiskers are the minimum and maximum. ICU, intensive care unit.

losses due to absenteeism and death) costs. Productivity losses for death resulted in the net present value of missed lifetime earnings derived from the yearly annual wage and years of life lost based on that patient's life expectancy. We measured health effects in quality-adjusted life years (QALYs). We calculated the QALYs lost due to CRE infection by accounting for reductions in health effects due to illness and/or death. Each CRE infection accrued QALY values on the basis of the patient's age-dependent, healthy QALY value attenuated by the infection-specific utility weight for the duration of the patient's infection. Death resulted in the loss of a patient's discounted lifetime QALY value for the remainder of their life expectancy.

For each scenario, we calculated the incremental cost-effectiveness ratio (ICER) as follows:

$$\text{ICER} = \frac{(\text{Cost}_{\text{CRE Prevention Bundle}} - \text{Cost}_{\text{No Specific Control}})}{(\text{Health Effects}_{\text{No Specific Control}} - \text{Health Effects}_{\text{CRE Prevention Bundle}})}$$

The impact of intervening in LTACHs on CRE transmission and prevalence was the difference between scenarios with and without an intervention in LTACHs. The intervention was considered cost-effective when ICERs were $\leq \$50,000/\text{QALY}$ saved and economically dominant if the intervention scenario saved costs and provided health

benefits compared with the scenario of no specific CRE control measures.

Experiments and sensitivity analyses

Our baseline scenario assumed no specific CRE intervention in any facility. The first set of experimental scenarios evaluated the impact of using a CRE prevention bundle in only hospital ICUs. The second set of experimental scenarios evaluated the impact of using a CRE prevention bundle in a varying number of LTACHs (1 to 9), ordered and intervened in by decreasing CRE prevalence, and assumed no specific CRE interventions were implemented in hospitals, vSNFs, and SNFs. The third set of experimental scenarios implemented the prevention bundle in all hospital ICUs and LTACHs to evaluate the added impact of also intervening in LTACHs. Each simulation consisted of running the model 50 times for 3 simulated years.

RESULTS

No specific CRE control measures

Figure 1 shows the CRE prevalence in health-care facilities regionwide over time. In the absence of specific CRE control measures, prevalence reached 1.5% regionwide by year 3 (Figure 1). Figure 2 shows the total number of new carriers in health-care facilities regionwide. Over the 3-year

period, there were 12,740 new CRE carriers with no specific intervention. Of these, 47.2% ($n = 6,030$) occurred in hospitals (with 1,609 (12.6%) in hospital ICUs), 30.1% in LTACHs, and 10.1% in vSNFs. These new carriers resulted in 3,183 infections and 382 deaths, costing \$325.1 million (societal perspective; Table 1).

Impact of intervening in only hospital ICUs

When all regionwide hospital ICUs implemented the CRE prevention bundle, CRE prevalence decreased by a relative 5.1% compared with no specific intervention after 3 years (Figure 1A). There were 11,540 new CRE carriers in health-care facilities regionwide (Figure 2), which was more than when at least 2 of the LTACHs in the region implemented the bundle. Hospital ICUs that implemented the bundle had a 16.0% relative reduction in new carriers ($n = 1,217$ fewer), but nonparticipating facilities experienced little to no gain ($n = 19$ fewer) compared with no specific control measures (Table 2). As Table 1 shows, intervening in only hospital ICUs resulted in a similar number of infections and deaths as intervening in LTACH A; however, it cost substantially more. Figure 3 shows the relative reduction in CRE prevalence at year 3 (Figure 3A) and in total new carriers (Figure 3B) by facility type, with other facilities having very little indirect impact.

Impact of intervening in only LTACHs

Figure 1B shows the CRE prevalence in health-care facilities regionwide over the 3-year period when increasing the number of LTACHs implementing the CRE prevention bundle. Progressively adding LTACHs resulted in a 4.6%–17.1% relative decrease in CRE prevalence compared with no intervention after 3 years. For example, when LTACHs A–H used the prevention bundle, prevalence decreased to 1.3%. Figure 2 shows the gains in progressively implementing the prevention bundle in a greater number of LTACHs. Even when only LTACH A implemented control measures, the prevention bundle averted 1,090 new carriers regionwide compared with no specific intervention. In some cases, only small gains were achieved by intervening in more LTACHs (e.g., intervening in LTACHs A–D compared with LTACHs A–G resulted in a similar number of total new carriers). There was no additional gain when adding LTACHs outside of Illinois (i.e., LTACHs A–I compared with LTACHs A–H).

Table 2 shows the direct impact (i.e., in facilities implementing the intervention) and indirect impact (i.e., on nonparticipating facilities) of the CRE prevention bundle on the total number of new carriers over the 3 years. Reductions in new carriers started to occur within 6 months. Over the 3 years, LTACHs implementing the bundle had a 40.7%–52.6% relative decrease in the total number of new carriers compared with when no specific control measures were implemented. Even facilities that did not implement the CRE bundle garnered benefits, with a 2.3%–8.3% relative reduction in new carriers (Table 2). However, although gains took longer to manifest, they appeared faster as more LTACHs implemented the prevention bundle. Overall, ICUs garnered

the largest indirect benefits, with a 13.1%–35.6% relative decrease in CRE prevalence at year 3 (Figure 3A and 3B).

When only LTACHs implemented the CRE prevention bundle, there were 273–722 fewer CRE infections and 37–87 fewer deaths (varying with the number of LTACHs that participated), which garnered cost savings (Table 1). Table 1 can be used to determine the savings for any scenario; for example, compared with no specific intervention, when LTACHs A–D implemented a bundle (which cost \$2.5 million), \$8.2 million was saved from the third-party payer perspective and \$54.0 million from the societal perspective.

Impact of intervening in hospital ICUs and LTACHs

When all regionwide hospital ICUs and LTACHs implemented the prevention bundle, CRE prevalence decreased by a relative 21.2% regionwide at year 3 (Figure 1B). There were 9,545 new CRE carriers, resulting in 2,354 infections and 283 deaths (Table 1). Participating facilities had a 28.5% relative reduction in new carriers, whereas those nonparticipating had an 8.9% relative reduction in new carriers (Table 2). Compared with implementing no specific control measures, intervening in all regionwide ICUs and LTACHs saved \$21.9 million and \$77.4 million from the hospital and societal perspectives, respectively (Table 1).

Figure 2 shows the additional gains that can be achieved when LTACHs implement control measures in addition to hospital ICUs, and Table 1 can be used to determine the additional clinical and economic gains. For example, when all LTACHs implement the bundle, compared with only ICUs, there were 1,995 fewer new carriers, 513 fewer infections, and 61 fewer deaths (Figure 2; Table 1). Using the CRE prevention bundle in LTACHs in addition to ICUs resulted in a 17.0% relative reduction in CRE prevalence compared with using the bundle only in ICUs. Figure 3 shows the substantial gains achieved in vSNFs and SNFs when LTACHs intervene in addition to hospital ICUs.

DISCUSSION

Our results show that although applying CRE control measures in all hospital ICUs and LTACHs can provide the largest reductions in CRE burden in health-care facilities regionwide, even implementing the measures in a single LTACH (i.e., the one with the highest prevalence) can decrease the CRE transmission and prevalence regionwide. Our results also show that in some cases, increasing the number of LTACHs implementing the CRE prevention bundle does not provide substantial additional regional gains. Nonparticipating facilities had reductions in their CRE burden, with ICUs garnering the largest indirect benefits ($\leq 22\%$ reduction in new carriers). Even when hospital ICUs are already intervening, implementing the CRE bundle in LTACHs can provide substantial additional benefits, further reducing the number of new carriers by 17.3%.

Our study shows that in a region with high LTACH use, LTACHs are important more so than other acute care hospital types for controlling CRE spread. This is consistent with findings of previous studies (32, 33). For example, our

Table 1. Clinical and Economic Outcomes of Implementing a Carbapenem-Resistant Enterobacteriaceae Prevention Bundle in Varying Numbers of Long-Term Acute Care Hospitals and Hospital Intensive Care Units

Facility Implementing CRE Prevention Bundle	Mean No. of CRE Infections	Mean No. of CRE-Attributable Deaths	Mean QALYs Lost	Total Cost (millions, \$US) ^a					
				CRE Prevention Bundle Costs		Hospital Perspective		Third-Party Payer Perspective	
				Mean	95% CI	Mean	95% CI	Mean	95% CI
No specific CRE control measures	3,183	382	4,044.5			111.3	111.0, 111.6	61.3	61.2, 61.5
All hospital ICUs	2,867	344	3,643.4	2.4	2.4, 2.4	102.5	102.3, 102.8	57.6	57.5, 57.8
LTACH A	2,910	345	3,654.6	0.9	0.9, 0.9	101.3	101.0, 101.7	56.2	56.1, 56.4
LTACHs A and B	2,732	328	3,472.3	1.4	1.4, 1.4	96.9	96.5, 97.2	54.0	53.8, 54.2
LTACHs A-C	2,686	323	3,413.1	1.8	1.8, 1.9	95.8	95.5, 96.1	53.6	53.4, 53.8
LTACHs A-D	2,629	316	3,339.8	2.5	2.5, 2.5	94.4	94.1, 94.6	53.2	53.0, 53.3
LTACHs A-G	2,546	306	3,235.7	3.1	3.1, 3.1	92.1	91.9, 92.4	52.2	52.0, 52.3
LTACHs A-H	2,461	296	3,126.7	4.5	4.5, 4.5	90.5	90.2, 90.8	51.9	51.7, 52.1
LTACHs A-I	2,596	312	3,298.3	4.8	4.7, 4.8	95.5	95.1, 95.8	54.7	54.6, 54.9
All hospital ICUs and LTACHs A-I	2,354	283	2,992.0	7.1	7.1, 7.1	89.4	89.1, 89.7	52.5	52.3, 52.6
								Mean	95% CI
								325.1	324.2, 326.0
								295.3	294.5, 296.1
								294.6	293.7, 295.6
								280.5	279.4, 281.5
								276.3	275.4, 277.1
								271.1	270.3, 271.9
								263.3	262.6, 264.1
								256.0	255.1, 256.8
								269.9	269.0, 270.9
								247.7	246.9, 248.4

Abbreviations: CI, confidence interval; CRE, carbapenem-resistant Enterobacteriaceae; ICU, intensive care unit; LTACH, long-term acute care hospital; QALY, quality-adjusted life years.
^a Costs are in net present value in 2018 United States dollars.

Table 2. Total Number of New CRE Carriers in Participating and Nonparticipating Health-Care Facilities Over 3 Years When Implementing the CRE Prevention Bundle

Facility Implementing CRE Prevention Bundle	Total No. of New CRE Carriers With No Specific CRE Control Measures		Total No. of New CRE Carriers With the CRE Prevention Bundle Implemented in Participating Facilities		Median New Carriers Averted
	Median	95% CI	Median	95% CI	Median
<i>In Participating Facilities That Implement the CRE Prevention Bundle</i>					
All hospital ICUs	7,624	5,519, 9,833	6,407	5,084, 8,772	1,217
LTACH A	1,890	1,721, 2,014	1,121	954, 1,228	769
LTACHs A and B	2,624	2,440, 2,886	1,428	1,217, 1,602	1,196
LTACHs A–C	3,013	2,749, 3,302	1,622	1,353, 1,792	1,391
LTACHs A–D	3,675	3,359, 4,039	1,806	1,582, 2,114	1,869
LTACHs A–G	3,776	3,458, 4,173	1,849	1,585, 2,074	1,927
LTACHs A–H	3,843	3,533, 4,263	1,822	658, 2,053	2,022
LTACHs A–I	3,843	3,533, 4,263	1,911	1,557, 2,267	1,932
All hospital ICUs and LTACHs A–I	11,513	9,371, 13,932	8,237	6,283, 10,142	3,276
<i>In Nonparticipating Facilities That Do Not Implement the CRE Prevention Bundle</i>					
When all hospital ICUs implement the CRE prevention bundle	5,080	4,745, 5,736	5,061	4,612, 5,432	19
When LTACH A implements the CRE prevention bundle	10,898	8,709, 13,218	10,646	7,256, 12,424	252
When LTACHs A and B implement the CRE prevention bundle	10,051	7,899, 12,420	9,611	7,079, 11,826	441
When LTACHs A–C implement the CRE prevention bundle	9,638	7,489, 12,059	9,217	6,752, 10,863	421
When LTACHs A–D implement the CRE prevention bundle	9,069	6,924, 11,426	8,509	6,918, 10,691	561
When LTACHs A–G implement the CRE prevention bundle	9,011	6,862, 11,351	8,498	6,179, 10,073	513
When LTACHs A–H implement the CRE prevention bundle	8,893	6,790, 11,231	8,155	2,767, 9,921	738
When LTACHs A–I implement the CRE prevention bundle	8,893	6,790, 11,231	8,533	6,134, 10,776	360
When all hospital ICUs and LTACHs A–I implement the CRE prevention bundle	1,257	1,034, 1,516	1,145	882, 1,380	112

Abbreviations: CI, confidence interval; CRE, carbapenem-resistant Enterobacteriaceae; ICU, intensive care unit; LTACH, long-term acute care hospital.

previous work showed that implementing a CRE prevention bundle in 4 LTACHs in Chicago resulted in significant reductions in the incidence and prevalence of CRE colonization and infection at participating facilities (i.e., the intervention resulted in direct beneficial effects to LTACHs) (25). The current study furthers this work and quantifies the benefits to nonparticipating facilities (i.e., the indirect effects), highlighting their importance to reduce CRE spread regionwide. In addition, we previously demonstrated through social network analysis that a single LTACH was at the center of a

regional, multifacility outbreak in Northwest Indiana (near Chicago) (34). Epidemiologic studies in the Chicago region have demonstrated that the prevalence of CRE in LTACHs outnumbers that in short-term acute care hospital ICUs by 10:1 (approximately 30% vs. 3%) (3). Because transmission, in large part, is driven by colonization pressure, (35) it follows that the incidence of CRE transmission is also proportionately higher in LTACHs compared with hospital ICUs. Our static and dynamic modeling has demonstrated that LTACHs play a central role in patient movement and sharing

Figure 3. Percent relative reduction in A) prevalence of carbapenem-resistant Enterobacteriaceae (CRE) at year 3, and B) the total number of new CRE carriers over 3 simulated years, by facility and unit type, when implementing a CRE prevention bundle in long-term acute care hospitals (LTACHs) and hospital intensive care units (ICUs). Note: Skilled nursing facilities (SNFs) did not see an effect on the number of new carriers. vSNF, skilled nursing facility caring for patients requiring mechanical ventilatory support.

in health-care facilities, and that LTACHs are highly influential in the regional prevalence of CRE infection. Thus, our results, in combination with previous work, provide evidence that may motivate more large-scale intervention studies for CRE targeting LTACHs.

Because LTACHs typically represent a small proportion of total health-care facilities in a region (8), targeting LTACHs for intervention may be an efficient regional control

strategy. Often, infection control programs in LTACHs are underdeveloped; in fact, CMS requirements for reporting of quality measures (e.g., rates of health-care-associated infections) are relatively new. As our results show, major health-care benefits (i.e., infections averted, lives saved, and costs reduced) are achievable by including LTACHs in regional infection-control strategies. This provides evidence for public health authorities and infection control

practitioners to help prioritize such facilities, motivate funding for these programs, and justify reporting. For these programs to be successful, the challenges to implementing interventions in LTACHs must be recognized and mitigated. In addition, concerns about the quality and cost of LTACH care prompted recent changes in the federal payment-rate structure that, in turn, resulted in decreased Medicare admissions and revenue for some for-profit LTACH chains (36). Lower revenue may result in less enthusiasm for investment in infection prevention in the short term. As the federal government and CMS struggle with approaches to controlling antibiotic resistance, our findings could inform payers and owners of largely for-profit LTACH chains to cover these programs and determine reimbursements and subsidies. Also, infection-control practitioners can use our results to help justify infection-control programs and limits on the number of patient beds per room, preferably single-bed rooms. However, implementing interventions in LTACHs may require additional resources (e.g., funding and infrastructure for admission testing, chlorhexidine gluconate bathing supplies, adequate personnel to enable placing patients in cohorts) and could take time for some facilities to adopt.

Limitations

By definition, models represent simplifications of real life and may not fully capture all events or outcomes (37). Although our model is populated with data specific to 1 region, we do include several different types of health-care facilities across a diverse population and wide geographic area. Results may be quite different in other parts of the country if patient sharing is uncommon because of geographic distances or insurance restrictions. In addition, CRE prevalence is higher in Chicago compared with other US regions, and LTACHs and vSNFs are uncommon in some states (8, 38). We were limited to patient data from CMS, which may not represent the transfer patterns of all patients because CMS patients tend to be older and have more comorbidities. CRE transmission in non-health-care settings (i.e., the community) is relatively uncommon in the United States (>90% of patients with CRE have prior documented health-care exposure (39, 40)); therefore, we assumed in our model minimal community CRE transmission, and the model did not explicitly represent potential transmission in the community or environment. Including community transmission may increase the prevention bundle's value, which included admission screening, in health-care facilities, but it would have a limited impact on CRE in the community. We also assumed compliance with contact precautions was consistent over time, but research has shown that compliance could decline when more patients are placed on precautions (41). Although changes in parameters such as contact-precaution effectiveness and transmission coefficients would influence CRE spread, the assumption was that changes in these parameters would be similar across our modeled scenarios and would not substantially affect the resulting differences between them. For example, we previously showed that when we changed contact-precaution effectiveness (12, 14, 32, 42, 43), results were robust and

outcomes were similar when compared across scenarios; in fact, decreases in effectiveness can further increase the value of other interventions (12). We have also shown that increasing transmission coefficients, while increasing overall pathogen prevalence, resulted in similar outcomes when comparing between scenarios (18, 32).

Conclusion

Although implementing a CRE prevention bundle in all hospital ICUs and LTACHs in the Chicago metropolitan area provided the largest reductions in CRE regionwide, even intervening in a single LTACH could reduce CRE spread in a region. Thus, LTACHs may actually be more important than other acute care hospital settings for controlling CRE, and regional efforts to control drug-resistant organisms should start with LTACHs as a centerpiece.

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