On Hand Hygiene Compliance and Diminishing Marginal Returns: An Empirically-Driven Agent-Based Simulation Study

Thomas Hornbeck[1], David Naylor[1], Alberto Maria Segre[1], Geb Thomas[2], Ted Herman[1], Philip M. Polgreen[3],

[1] Computer Science, [2] Industrial Engineering, [3] Carver College of Medicine
The University of Iowa, Iowa City, IA USA
{Tom-Hornbeck, David-Naylor, Alberto-Segre, Geb-Thomas, Philip-Polgreen}@uiowa.edu

Abstract. Failure of healthcare workers to perform hand hygiene is one of the leading preventable causes of healthcare-associated infections. Despite targeted interventions to improve hand-hygiene compliance, rates remain relatively low (averaging less than 50%) in many healthcare settings. Since it is much harder to raise compliance rates when rates are already high, achieving 100% compliance may ultimately be infeasible or cost prohibitive. In this paper, we use agent-level simulations empirically grounded in fine-grained healthcare-worker movement data collected by wearable sensors deployed in a working intensive care unit to explore the effect of hand-hygiene compliance on the spread of healthcare-associated infections. These simulations permit us to determine if a "law of diminishing returns" applies to hand hygiene: in other words, is achieving 100% compliance always worth the cost?

Keywords: agent-based modeling, nosocomial infections, hand hygiene, compliance.

1 Introduction

Healthcare-associated infections affect about 2 million patients in US hospitals each year, resulting in thousands of deaths [1,2]. Failure of healthcare workers to perform appropriate hand hygiene is one of the leading preventable causes of these infections [3]. Healthcare workers' hands can harbor and transmit infectious agents to patients in their care. For example, methicillin-resistant Staphylococcal aureus (MRSA) is primarily transmitted by direct contact, and there is considerable evidence that such pathogens are often spread from patient to patient via the hands of healthcare workers in hospital settings [4]. Nosocomial pathogens can also survive on objects in the environment and then spread to patients via healthcare workers' hands [5,6].

Several clinical studies have demonstrated that improving hand hygiene can decrease the rate of healthcare-associated infections [7-9] and because of its effectiveness, hand hygiene is considered one of the most important infection control interventions for preventing the spread of such infections. Hand hygiene is part of standard infection control precautions and should be practiced by healthcare workers before and after each patient contact. Many professional societies have published hand-hygiene guidelines, and many local, national, and international hand-hygiene campaigns have been launched [3,10,11]. But notwithstanding these efforts, good hand-hygiene practice remains an elusive goal [12]. Rates among healthcare workers remain low, averaging less than 50% [3,11,13].

The infection control literature identifies many barriers to proper hand-hygiene practice, such as lack of proper facilities (e.g., sinks, supplies) [3], undesirable side effects (e.g., dry skin) [14-16], lack of knowledge about the importance of hand hygiene [3], and busy clinical schedules [3,14,15]. In addition to these physical barriers, factors in an individual's social environment, such as organizational culture and leadership, also play a critical role in hand-hygiene adherence [17]. Moreover, for healthcare workers, role-model behavior also strongly influences hand-hygiene adherence in both positive and negative ways [18-20]. Despite these barriers, effective campaigns for increasing hand-hygiene rates have been well described in the literature, yet hand-hygiene rates, while improving, remain low in many healthcare settings around the world [3,11,13].

Effective hand-hygiene campaigns require resources and commitments from both healthcare workers and healthcare administrators. Since it gets much harder to raise rates when rates are already high, achieving 100% compliance may be ultimately infeasible (or simply cost prohibitive). This paper explores precisely this tradeoff: in the absence of full compliance, is there a lower rate that still yields a significant reduction in healthcare-associated infections? In other words, is there a rate beyond which the marginal benefit of increased compliance is not worth the additional cost? In settings where resources are scarce, how should interventions be targeted for maximal impact on healthcare-associated infections? Should units with lower rates be preferentially targeted? Should improving factors other than hand-hygiene compliance take precedence?

Answering these questions through observational studies would require mechanisms for consistently measuring both compliance and clinical outcomes (e.g., healthcare-associated infections). Also, demonstrating effectiveness of hand hygiene may be difficult if outcomes (e.g., infections) are rare during the study period, especially in the presence of confounding factors (e.g., patient comorbidities). As an alternative to such clinical outcome studies, agent-based simulations can be used to study the diffusion of nosocomial infections and the effectiveness of improved compliance. Of course, the results of such studies can only be as good as the underlying models: many such studies use mathematical models to derive contact patterns or contact rates [21,22]. These models assume homogeneous mixing and fail to adequately model individual behaviors (such as the peripatetic nature of some healthcare workers), which can have substantial influence on the outcome of the simulation [23]. In contrast to these studies, our simulations are empirically grounded in fine-grained healthcare-worker movement data collected by wearable sensors deployed in a working intensive care unit, allowing us to explore the effect of hand-hygiene compliance on the spread of healthcare-associated infections over a broad range of transmission parameters with great confidence. These simulations permit us to determine if a "law of diminishing returns" applies to hand hygiene: in other words, is achieving 100% compliance always worth the cost?

2 Methods

Data Acquisition. As part of a process-improvement project to measure hand-hygiene behavior, we deployed a set of wearable sensors to capture detailed location (e.g., "in patient room," "out of patient room," "nurses' station," etc.) and interaction data for 6 different classes of healthcare workers in the University of Iowa Hospital and Clinics (UIHC) Medical Intensive Care Unit (MICU). This wireless sensor network consists of small credit-card-sized wearable devices called motes: active, battery-powered, programmable devices consisting of a small processor, flash memory and an IEEE 802.15.4 compliant wireless radio. Each mote is programmed to broadcast a brief message at regular intervals 5 or 6 times a minute. When received by other motes within range, we can derive: (1) the identifier of the mote that sent the message; (2) the received signal strength (RSSI); and (3) the time the message was received. These data are recorded in the receiving mote's flash memory for later analysis. The motes communicate over unused space in the WiFi spectrum, do not interfere with medical devices, and because they do not rely on fixed infrastructure, are easily collected and quickly redeployed.

We placed fixed-location motes, or "beacons," in all 20 single patient rooms in our MICU and also outside all patient rooms in commonly shared patient-care areas (i.e., hallways and nurses' stations). By placing these motes in fixed locations throughout the unit we formed a grid of spatial reference points with which we can triangulate and therefore accurately estimate the location of other motes.

In addition to beacons, we distributed wearable motes, or "badges," to every healthcare worker present in the MICU. Technically, badges are identical to beacons in capability, but differ physically (wearable badges are packaged in recycled pager enclosures). By downloading the data stored in each badge, we can reconstruct when the healthcare worker wearing the badge, e.g., entered a particular patient room, or when the healthcare worker came within 3-6 feet of another healthcare worker.

We deployed badges and collected data from all the MICU healthcare workers over a period of seven days. Every morning at 7am (beginning of shift) we distributed badges to each healthcare worker, and collected the badges at 7pm (end of shift). New badges were distributed to night shift workers at 7pm and then collected the following morning at 7am. Once the badges were collected, their memory contents were offloaded to a server and the badges were reset for use the next day.

Each badge was assigned a unique identification number which is associated with one of three healthcare worker categories: nurses (i.e., MICU floor nurses, nursing assistants and nurse managers), doctors (i.e., staff physicians, fellows and residents) and critical support (i.e., clerks, pharmacists and respiratory therapists). Note that badges were assigned at random within categories: we did not record the association between badge identification number and the healthcare worker wearing the badge, nor were healthcare workers assigned the same badge for subsequent shifts. This badge distribution protocol ensures that (1) individual workers could not be identified, and (2) no healthcare worker could be tracked across multiple shifts. No patient identifiers or patient-specific clinical data were collected for this process-improvement project.

Once collected, data from individual badges were merged by time stamp to produce a chronological log of all messages received by any badge over the course of the each shift. From this log, we were able to reconstruct contacts between healthcare workers as well as between healthcare workers and fixed-location beacons located in patient rooms. Using the recorded RSSI and triangulation with beacons, we were able to detect hand-hygiene opportunities occurring whenever a healthcare worker enters or leaves a patient room.

Agent-Based Simulations. The spread of nosocomial pathogens was modeled using an agent-based discrete event simulation. Inputs to the model consist of the reconstructed healthcare worker/worker and healthcare worker/patient contacts as well as the hand-hygiene opportunities present as healthcare workers entered and left patient rooms; for the simulations described here, only contacts longer than 30 seconds were considered "legal" opportunities for pathogen transmission. Since healthcare workers could not be linked across shifts, each simulation was run independently on data collected over the course of a single 12-hour shift. Thus each simulation replicate represents a "month" of thirty 12-hour "days" where each day is represented by replaying the same 12-hour daytime (e.g., 7AM-7PM) shift (although day and night shifts differ in activity level, the results reported are broadly consistent across both day and night shifts).

Disease Model. Initially one patient is selected at random and infected by the pathogen at the beginning of the 30 day simulation: we assume no patients are admitted or discharged from the unit during the simulation. As the simulation replays the reconstructed "legal" contacts between healthcare workers and/or patients the pathogen will eventually spread according to preset simulation parameters. Each hand-hygiene event in the input presents an opportunity for colonized healthcare workers to quash the pathogen (i.e., move from a colonized state back to a susceptible state), and susceptible healthcare workers are at some small risk of colonization from the environment outside the patient room, again according to the simulation parameters. Infected patients will remain infected for the entire duration of the 30 day simulation.

Simulation Parameters. Each simulation is governed by a set of four simulation parameters, which, when allowed to vary, explore a large space of outcomes. Any reasonable conclusions one may draw from the simulations should reflect broad trends observed across the entirety of the simulation space.

The simulation parameters are the aggregate hand-hygiene compliance rate γ, the efficacy of hand hygiene λ, the transmission probability p, and the environmental contamination probability ε, modeling the risk that a healthcare worker is colonized from the environment outside the patient room.

- When faced with a hand-hygiene opportunity, an agent i performs hand hygiene with probability γi (at the beginning of the simulation, agents are randomly assigned an intrinsic hand-hygiene compliance probability γi drawn from a normal distribution with mean γ and standard deviation 0.1). The aggregate compliance rate γ is allowed to vary from 0 to 1 in increments of 0.1.
- The efficacy of hand hygiene, λ, depends on the sanitizing agent used (e.g., soap and water vs. alcohol rub) as well as the individual agent's hand hygiene technique.

Previous studies [24] have empirically set the probability of pathogen control per hang-hygiene event at 0.58 for soap and water, and 0.83 for alcohol rub.

- The transmission probability, p, for various nosocomial pathogens such as MRSA and VRE are not well established and may vary significantly from site to site. Based loosely on rates reported in [25] (where the transmission probability was determined to be between 0.008 to 0.043), we set p to range between 0.005 and 0.05 in 0.005 step increments, representing the probability that a pathogen is transmitted from a colonized/infected agent to a susceptible agent over the course of a 30-second contact period (longer duration contacts get multiple draws from the same distribution).
- Like the transmission probability, appropriate values for the contamination probability, ε, are difficult to establish empirically. Here, we allowed ε to vary between 0 and 0.05 in 0.005 step increments, representing the probability of colonization for a susceptible healthcare worker in a 30-second period outside of a patient room. Longer periods outside the patient room get multiple draws from the same distribution.

Simulations. 1000 replicates were performed for each of the 2442 combinations of simulation parameters, or a total of 2.442 million simulation-months.

3 Results

The first set of simulation results are shown in Figure 1. Here, the contamination probability ε=0, hence the only source of infection is from the originally-infected patient (i.e., healthcare workers are never colonized by interacting with the environment). The plot on the left shows results for soap and water (λ=0.58) while the plot on the right is for alcohol rub (λ=0.83); each curve represents a different value of p (see legend). The x-axis represents the aggregate compliance rate γ and the y-axis represents the number of observed infections averaged over the 1000 replicates at each data point. A few trends are clear and merit notice. First, as aggregate compliance rate γ increases, the mean number of cases decline, regardless of the transmission probability. Second, the decline in infections is not a linear function of compliance; that is, as γ increases, the number of infections does not decrease evenly, an effect that is especially evident for smaller values of p. Finally, the larger model efficacy of alcohol rub with respect to soap and water produces a downward shift of the plotted curves, but does not distort the general trends of the plots themselves.

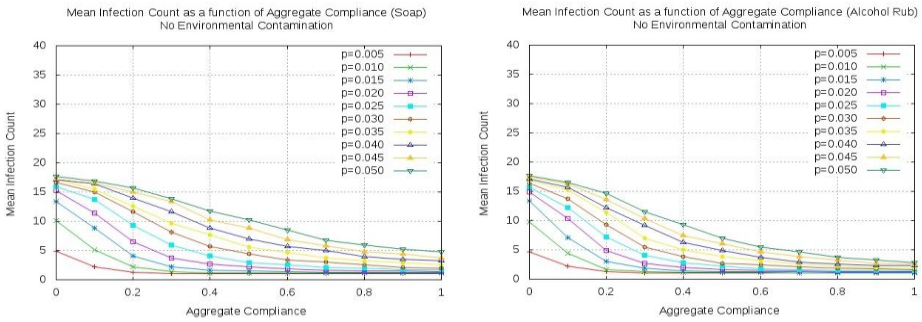

Fig. 1. Mean infection count as a function of aggregate hand-hygiene compliance level for soap (left) and alcohol rub (right). Each curve corresponds to a different transmission probability, with more virulent pathogens displaying higher values. These simulations do not admit the possibility of environmental contamination.

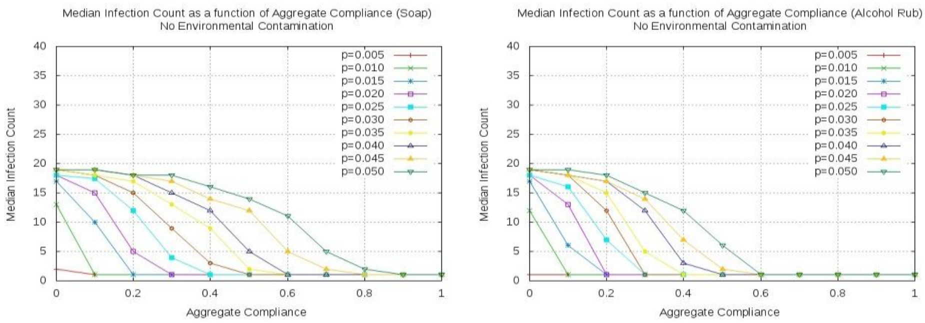

Fig. 2. Median infection count as a function of aggregate hand-hygiene compliance level for soap (left) and alcohol rub (right). These plots are identical to those of Figure 1, except that median values, which are less sensitive to outliers, are reported instead of mean values.

The use of mean values in Figure 1 obscures the statistical distribution across replicates. In actuality, the means are overly affected by extreme values in just a few replicates. Figure 2 shows the same results as Figure 1, but reporting medians across replicates instead. While these plots display the same broad trends as the corresponding plots in Figure 1, the nonlinear relation between γ and the observed number of infections is even clearer. The outlying values that cause inflation of the mean scores are likely due, at least in part, to the fact that different workers are assigned varying compliance probabilities at the start of each simulation. Because workers' interactions are not themselves modeled uniformly in these empirically-driven simulations, it is not surprising that the variation in the outcomes does not follow a normal distribution. Nevertheless, the same broad trends that were observed in Figure 1 are also present in Figure 2, if only in more accentuated form.

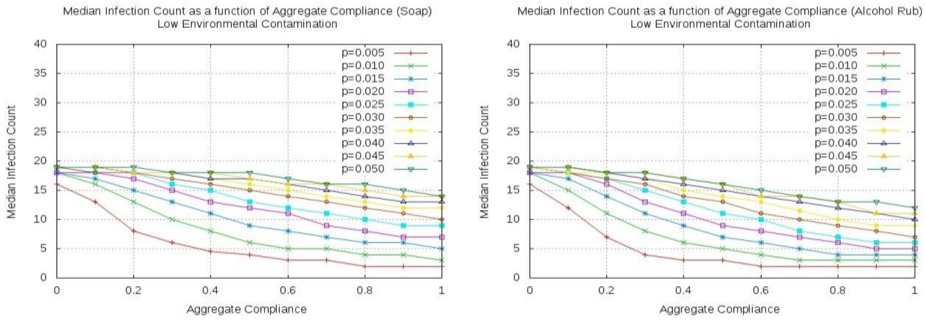

Fig. 3. Median infection count as a function of aggregate hand-hygiene compliance level for soap (left) and alcohol rub (right) in the presence of low levels of environmental contamination (ε=0.01). In these simulations, each healthcare worker has a small probability of being colonized by contact with the environment outside of the patient room. The flattening of the curves reflects the diminishing importance of improved hand-hygiene compliance in contaminated environments: note the advantage of alcohol rub over soap has also nearly disappeared. In such environments, all things being equal, reducing environmental factors may well be a more cost-effective goal than improved hand-hygiene compliance when rates are already moderately high.

Figure 3 explores the effect of environmental contamination on the observed number of infections. As in Figure 2, the plot on the left shows median results for soap and water (λ=0.58) while the plot on the right is for alcohol rub (λ=0.83); each curve again represents a different value of p (see legend). Here, median infection counts are reported over the same range of γ and p as before, but with ε=0.01. Similar plots can be made for other values of ε, with the expected results. Direct comparison with Figure 2 again yields the same broad trends, but with the curves shifted individually upwards and somewhat flattened, representing the additional infections observed attributable to environmental contamination.

All of plots shown here confirm that, as long as the parameters are not extreme (e.g., transmission and contamination probabilities are not too high, and compliance rates are not too low) there is a definite “knee” in the curve that represents a compliance rate beyond which additional efforts to increase compliance levels yield diminishing returns.

4 Discussion

Our results, over a broad range of parameters, demonstrate diminishing marginal returns with increasing hand-hygiene compliance. At the low extremes of reported compliance (20%) there are clear benefits to increasing hand-hygiene compliance (i.e., increasing rates from 20% to 40%). However, if rates are at 80% increasing them to 90% seems, from our results, to be a less effective, unless the transmission probability is extremely high, representing a particularly virulent pathogen. In such cases the return on increasing compliance is linear. From a practical perspective, these results imply that, for a given environment, there will be a point where resources are better applied to reducing environmental contamination than to increasing hand-hygiene compliance.

In addition to hand-hygiene compliance, the results of our simulations clearly demonstrate the importance of the effectiveness of hand-hygiene practice. For example, using an alcohol-based product not only overcomes many of the limitations ascribed to washing with soap and water, but also appears to be more effective in terms of eliminating pathogens from the hands of healthcare workers. Thus, increasing use of these alcohol products has a very important effect on the control of the spread of infections especially at lower compliance rates. Hand-hygiene technique is also important; proper administration requires administration of the product over all areas of the hands including harder-to-reach places (under the finger nails). Thus, improving technique may also help control infections without actually increasing hand-hygiene compliance via improving the effectiveness of the hand-hygiene events that do occur.

Our study has several limitations. First, our simulations define hand-hygiene opportunities as “in room” or “out of room”; this is easy for us to measure, but it is an under-representation of what is occurring within patient rooms, as it fails to capture the WHO 5 moments of hand hygiene [11]. Second, there was a brief 20-40 minute period between day and night shifts during badge distribution where we did not capture contacts or hand-hygiene opportunities (i.e., we do not have a complete 24/7 sample for the entire period). However, since the badge distribution period corresponds to report, there were relatively fewer patient contacts, and so the coherence of our results are not unduly affected. Third, we did not distribute motes to “external” healthcare workers who visited the unit to see patients in the MICU (e.g., consulting physicians). This is an important group of healthcare workers to consider, especially as we extend our models beyond a single unit. Finally, the empirical data that underlies our simulations were collected in a single unit in a single medical center: the results may not necessarily be generalizable to other healthcare settings.

Simulations are used in fields where experiments are not possible or where observational data is sparse; healthcare epidemiology is arguably such a discipline. However, past efforts have focused on assumed healthcare worker behavior. In contrast, our agent based models are based on real-world healthcare worker movement data. Future efforts currently underway will fuse our mote-based movement data with actual hand hygiene compliance data to study behavior at the individual level.

Acknowledgements. Special thanks to Deepti Sharma and all of the other CompEpi (http://compepi.cs.uiowa.edu/) students who helped with this project. Support for this research was provided by a University of Iowa College of Medicine Translational Research Pilot Grant (AMS and PMP), by a National Institutes of Health Career Investigator Award AI75089 (PMP), by a National Institutes of Health Grant NIAID-R21-AI081164 (AMS and PMP), and by the Centers for Disease Control and Prevention.

5 References

1. W.R. Jarvis, "Selected Aspects of the Socioeconomic Impact of Nosocomial Infections: Morbidity, Mortality, Cost, and Prevention," Infection Control and Hospital Epidemiology 17 (1996), pp. 552-557.
2. R.L. Klevens, J.R. Edwards, C.L. Richards, T.C. Horan, R.P. Gaynes, D.A. Pollock, and D.M. Cardo, "Estimating Health Care-Associated Infections and Deaths in US Hospitals, 2002," Public Health Reports 122 (2007), pp. 160-166.
3. J.M. Boyce and D. Pittet, "Guidelines for Hand Hygiene in Health-Care Settings: Recommendations of the Healthcare Infection Control Practices Advisory Committee and the HICPAC/SHEA/APIC/IDSA Hand Hygiene Task Force," Infection Control and Hospital Epidemiology 23 (2002), pp. S3-S41.
4. D.K. Henderson, "Managing Methicillin-Resistant Staphylococci: A Paradigm for Preventing Nosocomial Transmission of Resistant Organisms," American Journal of Infection Control 34:5 (June 2006), pp. S46-S54.
5. J. Devine, R.P.D. Cooke, and E.P. Wright, "Is Methicillin-Resistant Staphylococcus Aureus (MRSA) Contamination of Ward-Based Computer Terminals a Surrogate Marker for Nosocomial MRSA Transmission and Handwashing Compliance?" Journal of Hospital Infection 48:1 (May 2001), pp. 72-75.
6. W.A. Rutala, E.B.S. Katz, R.J. Sherertz, and F.A. Sarubbi, "Environmental-Study of a Methicillin-Resistant Staphylococcus-Aureus Epidemic in a Burn Unit," Journal of Clinical Microbiology 18:3 (1983), pp. 683-688.
7. A. Aiello and E.L Larson, "What is the Evidence for a Causal Link Between Hygiene and Infections?" Lancet Infectious Diseases 2 (2002), pp. 103-110.
8. G. Kampf, H. Loffler, and P. Gastmeier, "Hand Hygiene for the Prevention of Nosocomial Infections," Deutsches Arzteblatt International 106:40 (2009), pp. 649-655.
9. D. Pittet, B. Allegranzi, H. Sax, S. Dharan, C.L. Pessoa-Silva, L. Donaldson, and J.M. Boyce, "Evidence-Based Model for Hand Transmission During Patient Care and the Role of Improved Practices," Lancet Infectious Diseases 6 (2006), p. 641.
10. B. Allegranzi, H. Sax, L. Bengaly, H. Richet, D.K. Minta, M.N. Chraiti, F.M. Sokona, A. Gayet-Ageron, P. Bonnabry, and D. Pittet, "Successful Implementation of the World Health Organization Hand Hygiene Improvement Strategy in a Referral Hospital in Mali, Africa," Infection Control and Hospital Epidemiology 31:2 (2010), pp. 133-141.
11. D. Pittet, B. Allegranzi, and J.M. Boyce, "The World Health Organization Guidelines on Hand Hygiene in Health Care and Their Consensus Recommendations," Infection Control and Hospital Epidemiology 30, World Health Organization World Alliance for Patient Safety First Global Patient Safety Challenge Core Group of Experts (2009), pp. 611-622.
12. C. Maskerine and M. Loeb, "Improving Adherence to Hand Hygiene Among Health Care Workers," Journal of Continuing Education in the Health Professions 26:3, pp. 244-251.
13. J.P. Haas and E.L. Larson, "Measurement of Compliance with Hand Hygiene," Journal of Hospital Infection 66 (2007), pp. 6-14.

14. E.L Larson, “Skin Hygiene and Infection Prevention: More of the Same Or Different Approaches?,” Clinical Infectious Diseases 29 (1999), pp. 1287-1294.
15. E.L Larson and M. Killien, “Factors Influencing Handwashing Behavior of Patient Care Personnel,” American Journal of Infection Control 10 (1982), pp. 93-99.
16. J. Zimakoff, A.B. Kjelsberg, S.O. Larsen, C. Scient, and B. Holstein, “A Multicenter Questionnaire Investigation of Attitudes Toward Hand Hygiene, Assessed by the Staff in Fifteen Hospitals in Denmark and Norway,” American Journal Infection Control 20 (1992), pp. 58-64.
17. E.L. Larson, E. Early, P. Cloonan, S. Sugrue, and M. Parides, “An Organizational Climate Intervention Associated with Increased Handwashing and Decreased Nosocomial Infections,” Behavior Medicine 26:1 (Spring 2000), pp. 13-22.
18. R. Barrett and J. Randle, “Hand Hygiene Practices: Nursing Students’ Perceptions,” Clinical Nursing 17:14 (July 2008), pp. 1851-1857.
19. M.G. Lankford, T.R. Zembower, W.E. Trick, D.M. Hacek, G.A. Noskin, and L.R. Peterson, “Influence of Role Models and Hospital Design on Hand Hygiene of Healthcare Workers,” Emerging Infectious Diseases 9:2 (February 2003), pp. 217-223.
20. D. Pittet, A. Simon, S. Hugonnet, C.L. Pessoa-Silva, V. Sauvan, and T.V. Perneger, “Hand Hygiene Among Physicians: Performance, Beliefs and Perceptions,” Annals of Internal Medicine 141:1 (July 6, 2004), pp. 1-8.
21. D. Aragon, M.L. Sole, and S. Brown, “Outcomes of an Infection Prevention Project Focusing on Hand Hygiene and Isolation Practices,” AACN Clinical Issues 16:2 (2005), pp. 121–132.
22. K.L. Cummings, D.J. Anderson, and K.S. Kaye, “Hand Hygiene Noncompliance and the Cost of Hospital-Acquired Methicillin-Resistant Staphylococcus aureus Infection,” Infection Control and Hospital Epidemiology 31 (2010), pp. 357-364.
23. L. Temime, L. Opatowski, Y. Pannet, C. Brun-Buisson, P. Yves Boelle, and D. Guillemot, “Peripatetic Health-Care Workers as Potential Superspreaders,” Proceedings of the National Academy of Sciences 106 (2009), pp. 18420-18425.
24. E. Girou, G. Pujade, P. Legrand, F. Cizeau, and C. Brun-Buisson, “Selective Screening of Carriers for Control of Methicillin-Resistant Staphylococcus aureus (MRSA) in High-Risk Hospital Areas with a High Level of Endemic MRSA,” Clinical Infectious Diseases 25 (1998), pp. 543-550.
25. C.B. Beggs, S.J. Shepherd, and K.G. Kerr, “How Does Healthcare Worker Hand Hygiene Behavior Impact upon the Transmission of MRSA Between Patients? An Analysis Using a Monte Carlo Model,” BMC Infectious Diseases 9 (2009) pp. 64.