American Journal of Infection Control 46 (2018) 620-6

Contents lists available at ScienceDirect

American Journal of Infection Control

journal homepage: www.ajicjournal.org

Major Article

Asymmetric transfer efficiencies between fomites and fingers: Impact on model parameterization

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Key Words:
Transfer efficiency
Hand hygiene
Mathematical model
Parameterization
Environmental transmission
Hospital surfaces
Healthcare-associated infections
Fomite
Acinetobacter baumannii

Background: Healthcare-associated infections (HAIs) affect millions of patients every year. Pathogen transmission via fomites and healthcare workers (HCWs) contribute to the persistence of HAIs in hospitals. A critical parameter needed to assess risk of environmental transmission is the pathogen transfer efficiency between fomites and fingers. Recent studies have shown that pathogen transfer is not symmetric. In this study,we evaluated how the commonly used assumption of symmetry in transfer efficiency changes the dynamics of pathogen movement between patients and rooms and the exposures to uncolonized patients.

Methods: We developed and analyzed a deterministic compartmental model of *Acinetobacter baumannii* describing the contact-mediated process among HCWs, patients, and the environment. We compared a system using measured asymmetrical transfer efficiency to 2 symmetrical transfer efficiency systems.

Results: Symmetric models consistently overestimated contamination levels on fomites and underestimated contamination on patients and HCWs compared to the asymmetrical model. The magnitudes of these miscalculations can exceed 100%. Regardless of the model, relative percent reductions in contamination declined after hand hygiene compliance reached approximately 60% in the large fomite scenario and 70% in the small fomite scenario.

Conclusions: This study demonstrates how healthcare facility-specific data can be used for decision-making processes. We show that the incorrect use of transfer efficiency data leads to biased effectiveness estimates for intervention strategies. More accurate exposure models are needed for more informed infection prevention strategies.

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BACKGROUND

Healthcare-associated infections (HAIs) are a major concern worldwide, with an estimated 722,000 cases reported in the United States in 2011.[1] The cost of HAIs in the United States is estimated to total as much as $45 billion, with excess mortality, increased hospital stays, development of multidrug-resistant microorganisms, and overall increased healthcare costs for the patient and their families.[1,2] *Acinetobacter baumannii* (*A. baumannii*) is a gram-negative pathogen that is most commonly associated with HAIs, particularly in intensive care units, producing a variety of illnesses including pneumonia, bacteremia, wound infections, and urinary tract infections.[3] The environment[4,5] and healthcare workers (HCW)[6,7] play a significant role in the transmission of this microorganism in hospitals. Understanding the environmentally mediated transmission dynamics of pathogens such as *A. baumannii* is critical for identifying a more targeted approach to effective infection control. To study pathogen transfer through fomite contamination, we evaluated the assumption of symmetry used in estimating the transfer efficiency, which is an important parameter that describes the proportion of pathogens transferred from skin to fomite and from fomite to skin.

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https://doi.org/10.1016/j.ajic.2017.12.002

In recent years, mathematical models have been developed to study the transmission of communicable pathogens such as *Mycoplasma pneumonia*, methicillin-resistant *Staphylococcus aureus*, and vancomycin-resistant enterococci in a hospital framework.[8-10] Due to the importance of the environment in the transmission process, researchers have developed new models to specifically include the fomite in the environmental transmission process, both in general systems[11-13] and the hospital setting.[14-17] In general, these models incorporate HCW-mediated transmission dynamics with patients and the environment. For instance, Nicas et al[16] included multiple pathways in their study by modeling pathogen concentration in the air and in 2 types of fomites (textile and non-textile).

Owing to the lack of bi-directional (skin to/from fomite) studies on pathogen transfer efficacy, a common simplifying assumption in such mathematical models is that the transfer during a touching event is symmetrical and equal to whichever direction of transfer data are available. Typically, the pick-up transfer efficiency is measured, and the deposit transfer efficiency is assumed to equal this measured value. Using the same transfer efficiency value for both pick-up and deposit events may be appropriate when the 2 contacting surfaces are composed of the same material (eg, skin-to-skin contact). However, we recently reported that the transfer efficiency of *A. baumannii* from the fomite to the skin (ρ_{PU}, for pick-up) is statistically significantly greater (4.3 times) than that from the skin to the fomite (ρ_D, for deposit).[18] In this study, we evaluted how the assumption of symmetry in pathogen transfer efficiencies affects the exposure dynamics of pathogens in the environment. For this purpose, we constructed an *A. baumannii* fate and transport model that simulates the touching interactions among the HCW, patients, and nonporous environmental fomites using either symmetrical or asymmetrical transfer efficiencies.

METHODS

A deterministic compartmental model of *A. baumannii* describing the contact-mediated process among the HCW, patients, and the environment was developed and analyzed. Numerical simulations were performed using R (version 3.2.5 © 2016) and Berkeley Madonna® (Version 8.3.18 © 2009) software. This model is based on the exposure assessment model developed by Plipat et al.[17] Our model treats the HCW and the hospital environment as vectors for the transmission of *A. baumannii*. The model simulates 1 colonized patient and 1 uncolonized patient who are located in separate hospital rooms over a 7-day simulation period. Transfer efficiencies in bacterial transfer by touch are parameterized to simulate both symmetrical and asymmetrical transfer events, to evaluate the robustness of predictions under both scenarios. We use the overall mean fomite-to-skin (ρ_{PU}), skin-to-fomite (ρ_D), and skin-skin transfer efficiencies (ρ_S) for *A. baumannii* reported by Greene et al. (Table 1),[18] who found that the touching event between 2 unlike surface types is an asymmetrical event.

We studied the effect of asymmetrical and symmetrical transfer efficiencies in 3 scenarios: i) large environmental fomite areas; ii) small environmental fomite areas; and iii) glove use in large fomite areas. The large fomite scenario (2000 cm^2) approximates the touchable fomite area surrounding the patient, which could be the bed rails, equipment, and counter space. In the small fomite scenario, the total available space was reduced to 200 cm^2—the size of the bed remote control or a keypad.

Table 1
Parameter values[18] of the overall mean fomite-to-skin (ρ_{PU}), skin-to-fomite (ρ_D), and skin-skin (ρ_S) transfer efficiencies for *A. baumannii* used in the ATE (asymmetric), STE (symmetric), and MTE (symmetric application of geometric mean) models.

	Description	ρ_{PU}	ρ_D	ρ_S
ATE	Asymmetrical transfer efficiencies	0.2412	0.056	0.3253
STE	Symmetrical transfer efficiency	0.2412	0.2412	0.3253
MTE	Mean, bi-directional transfer efficiency	0.1162	0.1162	0.3253

For each of the 3 scenarios, 3 different parameterizations for transfer efficiencies for a skin-environment touching event are compared (Table 1): asymmetrical transfer efficiency (ATE), symmetrical transfer efficiency (STE), and mean bi-directional transfer efficiency (MTE). The ATE model uses a measured ρ_{PU} value to describe the pick-up transfer rate and a measured ρ_D to describe the deposit transfer rate. The STE model applies only 1 measured ρ_{PU} to describe both the pick-up and the deposit transfer rates. The MTE model applies the geometric mean of the ρ_{PU} and ρ_D values (calculated by $\sqrt{\rho_{PU} * \rho_D}$) to describe both the pick-up and deposit transfer rates. Thus, the MTE is symmetrical but without the measurement error inherent to the STE system, which ignores ρ_D altogether. Because MTE uses a transfer efficiency value derived from the ATE measured values, the total amount of pathogen transferred in each touching event with the environment remains the same as that for the ATE and provides a good method for assessing the effects of assuming asymmetrical transfer.

Model description

The model describes concentration levels of *A. baumannii* (cfu/cm^2) on the HCW, a colonized and an uncolonized patient, and the nonporous fomites in their respective hospital rooms. Figure 1 shows a graphical representation of the 5-compartment model.

The colonized patient's skin is assumed to be the only source of contamination by (1) shedding squamous skin cells that instantaneously settle on the surrounding surfaces and (2) touching fomites with their contaminated hands. Because there is little evidence of colonization of the nares by *A. baumannii*, transfer or self-inoculation via nose touching was not considered here. In addition to touching the environment, the colonized patient can also undergo touching events with the HCW. Once the initially uncolonized patient is contaminated, this individual sheds *A. baumannii* from his/her skin and can undergo touching events with the environment and HCW as well.

In this model, the HCW spends the first 20 minutes of an hour in the colonized patient's room, followed by a second 20-minute visit to the uncolonized patient's room. During this time, touching events with patients and environment occur. Depending on a hand washing compliance/effectiveness parameter (λ_C), the HCW washes their hands after each patient visit. The remaining 20 minutes of the hour are spent at the nurse's station where touching events are not considered. At the beginning of an 8-hour shift, the HCW is assumed to be uncolonized.

A. baumannii can survive in the environment for extended periods of time, ranging from several weeks to 4 months.[19-21] The parameters μ_E and μ_S are used to model natural die-off; all viable cells are assumed to be available for pick-up and transport by the HCW or the patient. Contamination occurs by (1) the shedding of colonized squamous skin cells and (2) touching fomites with contaminated hands (patients or HCW). Both rooms undergo cleaning (disinfection), which occurs either once, twice, or 3 times a day.

There are 4 relevant events included in the model: shedding, natural die-off, touching, and interventions (hand hygiene and surface decontamination).

1) Shedding: Approximately 10^7 particles are dispersed from the healthy skin per day, and 10% of these squamous skin cells contain viable bacteria.[22] The concentration of shed pathogen (cfu/cm^2) is determined by the product of the shedding rate (α)

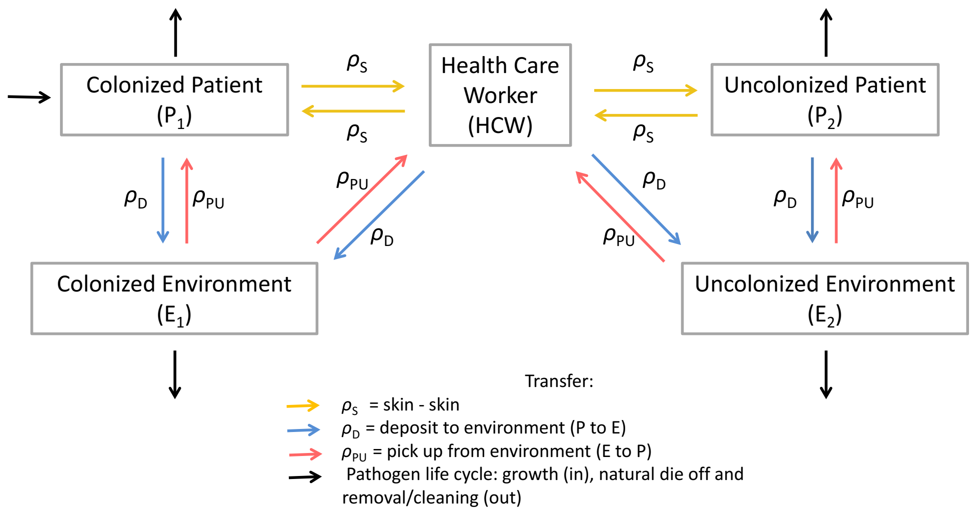

Fig 1. Schematic of fate and transport mathematical model.

and the concentration of pathogen on the contaminated patient, or $\alpha * P_1$.[22]

2) Natural die-off: *A. baumannii* die-off rates from environmental surfaces were quantified via the desiccation tolerance experiments described in the supplementary data.
3) Touching: The exchange of pathogens between 2 surfaces (hands of HCW, colonized and uncolonized patients, and/or environment) depends on the concentrations of pathogen, the fomite areas involved in the contact process, and the transfer efficiency, which can be symmetric or asymmetric. Based on the model developed by Plipat,[17] it is assumed that the total exposed skin area of the patients is 2000 cm^2 each. For the HCW, however, we consider only the hands to be exposed (300 cm^2). Touching frequency rates are set to produce 8 HCW-patient and HCW-fomite touching events per 20-minute visit. Faster and slower rates were tested; although small numerical differences were observed, the main conclusion remains unchanged.
4) Hand hygiene and surface decontamination: The washing of hands by the HCW is assumed to occur after each room visit, according to the compliance parameter (λ_C). Hand-hygiene efficacy is assumed to be 96%.[23-25] Surface decontamination events are controlled by the parameter λ_D and are set to occur once a day. Numerical results were also conducted for a cleaning schedule twice or 3 times a day. Our main results remained unchanged.

A number of simplifying assumptions were made to better focus the model on the issue of symmetric versus asymmetric effects: 1) *A. baumannii* is assumed to be of 1 clonal strain that instantaneously and homogenously mixes, settles and distributes on fomites, skin, and hands; 2) *A. baumannii* is assumed to replenish itself on the skin and hands of the colonized patient only, and this occurs at the same rate at which it is shed off into the environment; 3) the transmission probability from a person to the environment is assumed the same for all persons and for all nonporous fomite types; 4) exposed pathways to the uncolonized patient are limited to a contact-mediated process; and 5) airborne transmission, environmental transport by visitors or hospital staff, and movement of patients outside their room were not included in the model.

The large and the small environmental fomite area scenarios were achieved by modifying the total exposed areas. The glove use scenario was achieved by replacing the skin-skin transfer efficiency ($\rho_S = 0.3253$) with the pick-up transfer efficiency for glove use ($\rho_G = 0.1063$) and assuming that (1) a large environmental fomite area (2000 cm^2) is available, (2) the HCW uses the same pair of gloves during their entire 8-hour shift, and (3) the HCW removes the gloves for touches with the environment and then puts them back on for touches with the patient. Although assumptions (2) and (3) are unrealistic, these assumptions are appropriate to simulate a diminishing impact of skin-skin transfer due to glove use.

The model, as described by a system of ordinary differential equations, can be found in the supplementary material. A list of parameter values used in the model is presented in Table 2.

RESULTS

We calculated cumulative contamination levels of *A. baumannii* (cfu/cm^2) in all 5 compartments by computing the integral of the concentrations. Figure 2 shows the predicted contamination levels (cfu/cm^2) for 3 days on the uncolonized patient environment, the uncolonized patient, and the HCW. Table 3 presents concentrations per hour, as well as the percent change in pathogen concentration of the STE and MTE parameterizations from the baseline ATE. The values reported in Table 3 were obtained by simulating the dynamics for 7 days, to ensure that the equilibrium was reached and to eliminate bias from initial conditions. The glove scenario was included to evaluate the system dynamics when the HCW wears gloves to confirm that reducing the skin-skin transfer efficacy (ρ_S) will effectively reduce the role of the HCW in the transmission of pathogen between patients.

We assess the effectiveness of hand washing as a control strategy by varying the parameter (λ_C), and include how often and how effectively HCWs wash their hands, from 0% to 100%. In previous simulations λ_C was set to 50%. As expected, the hourly exposure levels in the uncolonized room (E_2), uncolonized patient (P_2), and HCW decrease as λ_C increases, and pathogen presence in E_2 and P_2 can be dropped to almost 0 as hand washing compliance (λ_C) reaches 100%. However, once hand hygiene compliance in this scenario reaches above 60%, the reduction in predicted exposures to the HCW begins to decline (Fig 3).

DISCUSSION

Using the asymmetric transfer efficiencies determined experimentally in our prior work,[18] the model analysis presented here suggests that the assumption of symmetry for *A. baumannii* results in an overestimate of environmental contamination and an

Table 2
List of model parameters used in all 3 models (STE, ATE, and MTE). Only transfer efficiency parameters (ρ_{PU}, ρ_D and ρ_S) are model specific (see Table 1).

Symbol	Values	Description	Reference
Attenuation and Die-off Rates			
α	0.1	Fraction of shed squamous cells with viable bacteria	22
μ_E	0.00533	Die-off rate from (nonporous) environmental fomites (min^{-1})	21
μ_S	0.00353	Die-off rate from human skin and tissue (min^{-1})	26
Transfer Efficiencies			
ρ_{PU}	0.2412	Fraction transferred from fomite to skin/hands (pick-up)	18
ρ_D	0.056	Fraction transferred from the skin/hands to fomite (deposit)	18
ρ_S	0.3253	Fraction transferred from a person's hand/skin to another's hand/skin (symmetrical)	18
ρ_G	0.1063	Fraction transferred between fomite and glove	18
Decontamination			
λ_D	0.75	Daily surface decontamination efficiency	27
λ_H	0.96	Hand hygiene product efficiency	23,24
λ_C	0.50	% compliance with precautionary methods (ie, hand washing)	25
Touching Frequency Rates			
τ_{PE}	0.134	Touching rate of patient hands with nonporous environment (min^{-1})	
τ_{WE}	0.400	Touching rate of HCW with nonporous environment during each 20-min visit with patient (min^{-1})	
τ_{WP}	0.400	Touching rate of HCW with each patient during 20-min visit (min^{-1})	
Surface Areas			
A_T	1	Contact surface area of fingertip (cm^2)	
A_{PL}	150	Contact surface area of palm (cm^2)	
A_H	300	Hand surface area (cm^2)	
A_E	2000	Total exposed surface area for all nonporous fomites (cm^2)	
A_P	2000	Total exposed skin area for patients (cm^2)	
A_W	300	Total exposed skin area for HCW (cm^2)	

ATE, asymmetrical transfer efficiency; HCW, healthcare worker; MTE, mean bi-directional transfer efficiency; STE, symmetrical transfer efficiency

underestimate of the contamination on patients and HCWs. This assumption also overestimates the hand washing compliance needed to achieve overall reduction goals. The following sections highlight the implication of these findings.

Transfer efficiency symmetry over-predicts contamination in the environment and under-predicts contamination on patients and HCWs. For the ATE method, we applied the bi-directional transfer efficiencies previously reported for *A. baumannii*,[18] where the transfer from fomite-to-finger, ρ_{PU}, is approximately 4 times greater than the transfer from finger-to-fomite, ρ_D (0.2412 and 0.056, respectively). As a result, the fraction of pathogens deposited to the environment will be small in the ATE model relative to what is picked up in any given touch. In contrast, we assumed that the ρ_D is equal to the measured ρ_{PU}, (0.2412 and 0.2412) for the STE model, and we applied the geometric mean of the measured bi-directional transfer efficiencies for the MTE model. Thus, for both of these symmetric systems, the fraction of pathogens deposited equals the fraction picked up. Since the symmetrical models have a much higher ρ_D compared to the ATE model, both the STE and MTE models overestimate the amount of pathogens removed from the skin and deposited to the environment and underestimate the contamination levels on the patients and the HCW. The purpose of the MTE model was to evaluate the effect of symmetry while controlling the total amount of transfer potential in the system. Although the MTE model better approximates the results generated by the ATE model compared to the STE model, the MTE model produced trajectories for pathogen levels more similar to the STE model in the environment (Fig 2). This has implications for the transfer of microorganisms to the uncolonized patient. For example, compared to the ATE model, the STE and MTE models overestimated the contamination levels to the uncolonized patient's environment in the large fomite scenario by around 150% and 100%, respectively (Table 3). These differences in contamination levels are amplified in the small fomite scenario, for which the predicted contamination levels are more than 200% above the ATE (both models, see Table 3). We defined the large environment to be 10 times larger than the small environment (2000 cm^2 and 200 cm^2, respectively); therefore, the concentration of bacteria on the 200 cm^2 fomite will be 10 times more concentrated than that on the 2000 cm^2 fomite. For this reason, both the HCW and the patient will have 10 times the amount of bacteria available for pick-up in small environment scenario compared to the large environment, and this explains why the overestimation is even greater in the small fomite scenario. This demonstrates that the differences observed between the symmetrical and asymmetrical systems remain consistent, regardless of the level of environmental influence. In the STE model, the environment is essentially cleaning the skin with every touch, leaving important levels of pathogen on the surfaces. The flow will travel from areas of high to low concentrations, thereby inflating the flow of contamination from the environment in the uncolonized patient's room (E2) to the uncolonized patient (P2). In contrast, the underestimation by the MTE model is due to the use of the mean pick-up and deposit transfer efficiency value of 0.1162, which (1) reduces overall available contamination on the E2 for pick-up and (2) cuts the cleaning effect by the environment in half. Therefore, the MTE model marginally underestimates the flow from E2 to P2 compared to the ATE model.

When gloves are worn, symmetry still overestimates environmental contamination levels and underestimates contamination on patients. The differences observed between symmetric and asymmetric models remains even when the influence of skin-skin transfer between the HCW and the patient is minimized by using gloves. We verified this by simulating HCW glove use during direct patient care only (the HCW continues to have barehanded touches with the environment). Under this scenario, where we assume the presence of a large fomite environment, we found that environmental contamination levels were again overestimated in the STE and MTE models compared to the ATE model. As discussed earlier, the symmetrical models use a larger environmental deposit rate compared to the asymmetrical model, and the reduction in skin-skin transfer due to glove use is not enough to compensate for differences seen between symmetric and asymmetric models. For example, the STE model, which has 4 times greater ρ_D than ATE, resulted in a 150% inflation of contamination on E_2 compared to ATE when gloves were worn, a similar value to the non-glove scenario (158% inflation). The MTE model, which has a ρ_D that is 2 times greater than that used in the ATE model, overestimated E_2 contamination by almost 90% (Table 3) under the glove-use scenario, again a similar value to the non-glove scenario (92%). Thus, even when we minimize the

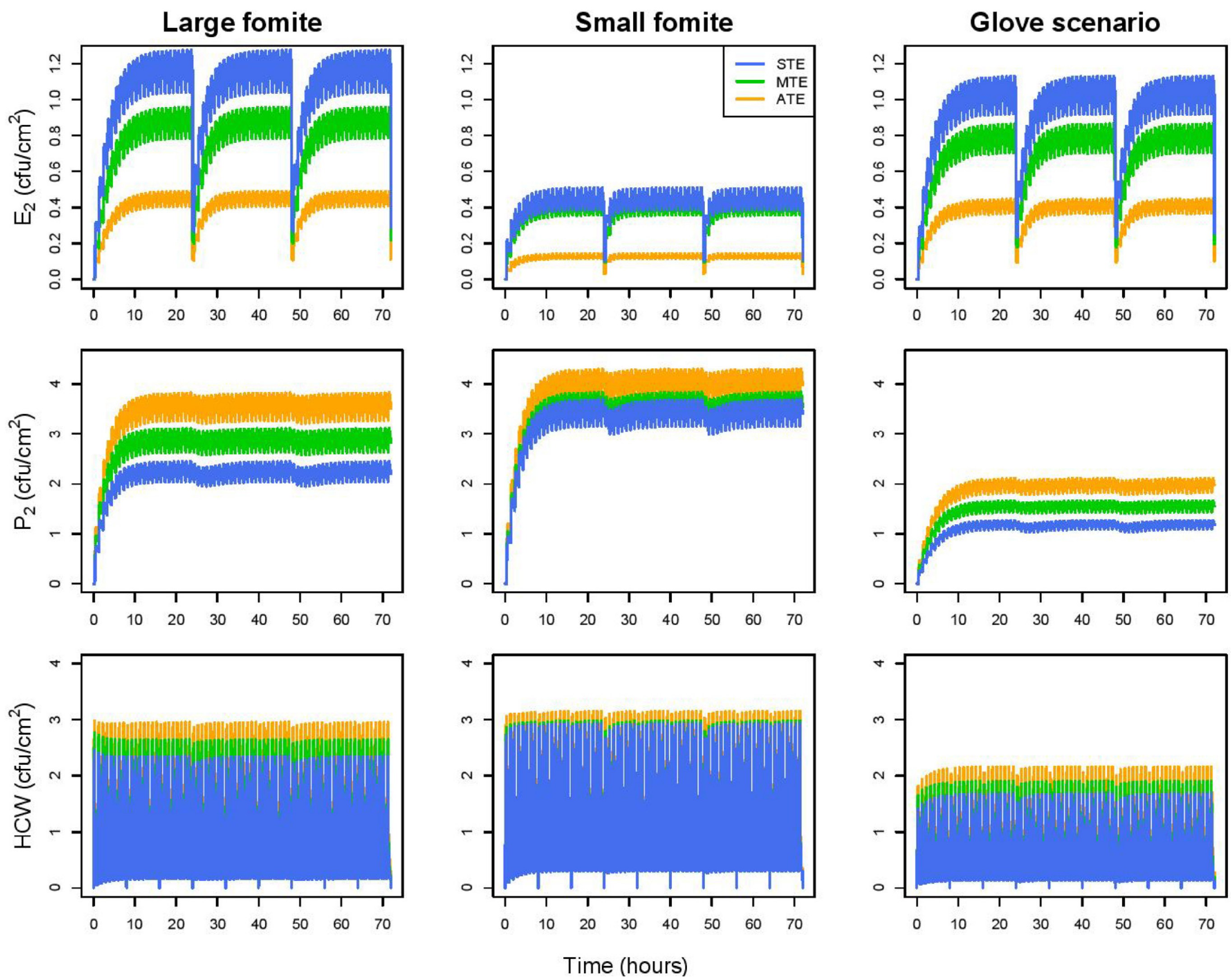

Fig 2. Concentration of *A. baumannii* (cfu/cm^2) on the uncolonized patient environment, E_2 (top row), the uncolonized patient, P_2 (middle row), and the healthcare worker(bottom row). The 3 scenarios shown are large fomite, 2000 cm^2 (left column), small fomite, 200 cm^2 (middle column), and glove use (right columns). The 3 models—asymmetrical transfer efficiencies (yellow), symmetrical transfer efficiencies (blue) and mean bi-directional transfer efficiencies (green)—are contrasted.

Table 3
Predicted *A. baumannii* concentrations per hour during a 7-day period derived from the model using asymmetrical transfer efficiencies (ATEs), symmetrical transfer efficiencies (STEs), and the mean bi-directional transfer efficiencies (MTEs) within a large fomite area (2000 cm^2), small fomite area (200 cm^2), and glove use scenario.

	ATE cfu/cm^2 per hour			STE % Change from ATE			MTE % Change from ATE		
	Large	Small	Glove	Large	Small	Glove	Large	Small	Glove
Colonized patient	23.6	24.3	27.76	−8.2	−2.9	−3.95	−4.0	−2.4	−1.90
Fomite colonized patient's room	1.3	0.4	0.98	215.6	260.8	191.15	105.2	204.3	94.08
Uncolonized patient	3.5	4.0	1.94	−37.4	−15.0	−40.67	−19.2	−11.3	−21.25
Fomite uncolonized patient's room	0.4	0.1	0.38	158.3	245.1	150	92.1	213.6	89.67
Health Care Worker	1.1	1.2	0.85	−24.9	−8.3	−29.84	−12.9	−7.2	−16.25

contamination via the HCW by reducing the skin-skin transfer efficiency (ie, glove use), the higher skin-to-fomite transfer efficiency in the symmetrical models results in higher contamination levels in the environment compared to the ATE model.

Hand washing cannot completely eliminate pathogen exposure for the HCW. If compliance is high, regardless of the model used (ATE, STE, or MTE) or scenario considered (large fomite, small fomite, or glove use), hand washing can reduce the levels of *A. baumannii* on the uncolonized patient and their room to almost 0; however pathogen levels on HCWs cannot be eliminated. Reductions in pathogen exposure begin to level off once a hand washing compliance rate above 60% is reached (Fig 3). Since the patient in room one is assumed to be a constant source of contamination through shedding, the HCW will always be exposed to a certain amount of contamination. For this reason, even a perfect scenario of 100% hand washing compliance (λ_C) will not be enough to completely prevent exposure.

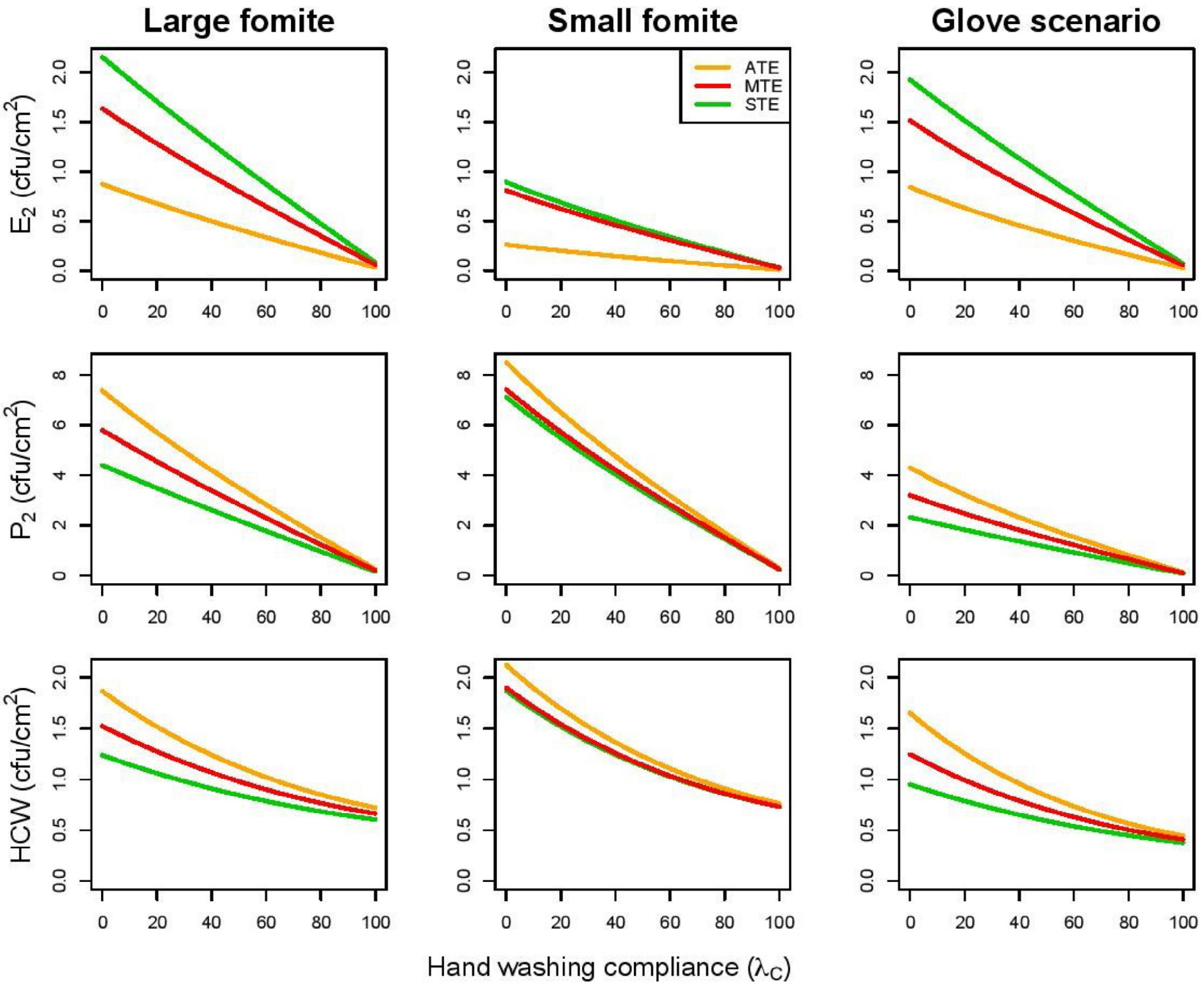

Fig 3. Exposures (cfu/cm^2) of *A. baumannii* per hour on the uncolonized room, E_2 (top row), uncolonized patient, P_2 (middle row). and the healthcare worker (bottom row), as a function of the hand washing parameter λ_C. The 3 scenarios shown are large environment (left column), small environment (middle column), and glove use (right columns). The 3 models—asymmetrical transfer efficiencies (yellow), symmetrical transfer efficiencies (green), and mean bi-directional transfer efficiencies (red)—are contrasted.

Models using symmetric transfer efficiency predicted higher hand washing compliance levels needed to achieve environmental contamination reduction goals. To keep pathogen contamination on surfaces below a certain threshold, our STE and MTE models call for a higher hand washing compliance requirement than our ATE model. The predicted environmental contamination differences observed between the symmetric and asymmetric systems is larger in the large fomite scenario (Fig 3). On the other hand, when it comes to the patient and the HCW, the ATE model requires a higher compliance than the STE and MTE models (Fig 3). When compliance is low (<40%), the discrepancies between the 3 models are magnified. It is in this situation when precise estimates for bi-directional transfer efficacies become crucial to accurately predict the lowest hand washing compliance rate needed to achieve a given reduction goal.

Although model assumptions could potentially have affected the patterns presented here, our conclusions remain robust to these simplifications. In particular, to simplify the environment, the current model assumes that the contamination deposited to a surface is instantaneously and evenly distributed over the entire available surface area. This assumption provides a constant (or total) pick-up of pathogens by subsequent touches. A more realistic approach would be to assume that the contamination will stay where the first (depositing) touch actually occurred and that the second (pick-up) touch may or may not actually touch the area containing the contamination, resulting in a random pick-up of pathogens. This would be the average pick-up of pathogens under the assumption of instantaneous dissemination to the entire surface. If the current model were to relax the simplifying assumption of instantaneous dissemination with constant pick-up of pathogens, and assume an average pick-up of pathogens, we would still expect the same pattern of over- or underestimation of contamination seen using symmetry because the deposit transfer efficiencies in the STE and MTE models are markedly greater than that in the ATE model. The use of a large and a small environmental area serves to cover the extremes of distortions from the combination of the assumptions of pathogen coverage of surfaces and the assumption about where the HCW is touching. The only way to truly realistically relax this immediate dissemination assumption is to model touching space continuously. However, using 2 different surface sizes provides a sense of the possible effects of realistically relaxing our simplifying assumptions. With respect to the pick-up transfer efficiencies, the pick-up transfer efficiency in the STE and ATE model are the same ($\rho_{PU} = 0.2412$), so relaxing the simplifying assumption of instantaneous dissemination would reduce the mean pick-up of pathogens equally between these 2 models. The pick-up transfer efficiency in the MTE model is half that of the ATE model ($\rho_{PU} = 0.1162$ and 0.2412, respectively), so relaxing the simplifying assumption of instantaneous dissemination would reduce the mean pick-up of pathogens proportionally between these 2 models. Compared to the ATE model, the deposit transfer efficiency in the STE model is 4.3 times greater than that in the ATE model, and the deposit transfer efficiency in the MTE model is 2 times greater than that in the ATE model. Thus, the relaxation of this simplifying assumption would not eliminate the cleaning effect occurring by the environmental surfaces in the symmetrical models. Therefore, the current model is adequate for assessing the general effects of using symmetrical versus asymmetrical transfer efficiencies.

Clinical Effect. In the ATE model, the value of hand hygiene compliance begins to decline after compliance reaches about 60% in the large fomite scenario and at approximately 70% in the small fomite scenario (Fig 3). For the scenarios evaluated here, efforts made to increase hand hygiene compliance rates greater than 70% may have a diminishing return on investment for the effort put into compliance. This model should be developed further so that facility-specific evaluations can be performed to determine the optimal combination of hand hygiene compliance with additional intervention strategies to achieve the maximum value in preventing the spread of contamination. Such additional initiatives could include increased surface cleaning with more targeted monitoring programs, increased training and education, or new technology that supports a systems approach for hospital-wide HAI reduction goals.

While *A. baumannii* is certainly a clinically relevant organism, it is not the only organism of relevance in the healthcare arena. Other organisms such as methicillin-resistant *Staphylococcus aureus*, *Clostridium difficile*, Orthomyxoviridae, and vancomycin-resistant *Enterococcus* are equally important. It is pertinent to investigate if the ATE model proposed in this article can be applied to assess the effect of hand hygiene on the above organisms as well as many others.

CONCLUSION

In this study, we evaluated the differences in pathogen exposure outcomes when asymmetrical transfer efficiencies were used in the exposure model rather than the standard assumption of symmetrical transfer efficiencies. We demonstrate that more accurate exposure assessments are achieved when both the pick-up and deposit transfer efficiencies are measured and used as separate parameters in the exposure model. The next step is to expand on this work and develop more robust mathematical models that can speak to the clinical implications of infection prevention interventions, such as hand hygiene compliance, cleaning regimens, and other preventive measures. This includes additional research quantifying the bidirectional transfer efficiencies of other microorganisms. As the robustness of exposure models improves, so will the quality of the information derived from them for policymakers and risk assessors.

Acknowledgements

This work was partially funded by the National Institutes of Health (NIGMS MIDAS program: grant# U01GM110712) and the National Institutes of Health grant (NIGMS R01GM098350) to C.X.

SUPPLEMENTARY DATA

Supplementary data related to this article can be found at https://doi.org/10.1016/j.ajic.2017.12.002.

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