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Original Article

A Markov model for fate and transport of *Staphylococcus aureus* at a swine barn and proposed interventions to reduce worker exposures

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Abstract

Swine workers may be occupationally exposed to *Staphylococcus aureus* (*S. aureus*) during time spent inside swine barns. Exposure may occur by inhaling *S. aureus*-containing particles or by touching contaminated surfaces or infected animals. Despite strong evidence that swine production work is a risk factor for increased nasal carriage of *S. aureus*, pathways of worker exposure within the swine barn setting have not been well characterized. We developed a Markov chain model to address this research gap by first describing the fate and transport of *S. aureus*-containing particles within a swine finishing barn. We defined 7 possible physical locations in and around the barn in which *S. aureus*-containing particles may exist and used published data to determine the probability that a particle will transition from any of these locations to the other locations during a 1-s time interval. We then used our model to estimate worker exposure to *S. aureus* during a period of 1 s to 30 min spent inside the swine barn. Finally, we modified inputs to simulate interventions to protect workers, such as ventilation controls, respirator use, and handwashing. Increasing the ventilation rate (ie the rate at which outdoor air replaces indoor air in the barn) in our model from the recommended rate for cold weather to the rate for mild weather resulted in a 59% decrease in the number of *S. aureus*-containing particles in the worker's respiratory system after 30 min. Increasing ventilation rates further to the recommended rate for hot weather resulted in an additional 58% decrease. Models simulating floor and surface cleaning prior to the worker's entry into the barn had little impact on the air concentration of *S. aureus* (<1% change) but reduced worker exposure to facial membranes by up to 13%. Simulations of N-95 respirator wearing had the greatest impact on worker exposure. As modeled, a well-fitting N-95 respirator may reduce worker inhalation exposure from 1,772 to 72 *S. aureus*-containing particles after 30 min in the barn, a 96% reduction. In our model, a poorly fitting N-95 respirator reduced exposure by about 30%, indicating that the type and fit of respirator worn has an important impact on the level worker protection.

Keywords: exposure modeling; livestock-associated *S. aureus*; swine workers

What's Important About This Paper?

Swine workers may be occupationally exposed to *Staphylococcus aureus* through multiple exposure routes during time spent inside swine barns. This study used a Markov chain model to describe the fate and transport of *S. aureus*-containing particles within a swine finishing barn, and estimate workers' exposures. Such models can help to explore potential determinants for increased nasal carriage of *S. aureus* among swine workers, and the effectiveness of potential control strategies.

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Introduction

Staphylococcus aureus (*S. aureus*) is a gram-positive bacterial pathogen that causes a variety of adverse health effects ranging from minor skin infections to life-threatening bacteremia, bone infections, and pneumonia. In humans, *S. aureus* commonly lives on the skin and in the nose and throat, with up to 30% of the population having permanent colonization in their anterior nares (Gorwitz et al. 2008; Sakr et al. 2018). Although healthy people may be persistently or intermittently colonized with *S. aureus* without showing symptoms, colonization is a risk factor for clinical *S. aureus* infection (Nguyen et al. 1999; von Eiff et al. 2001). Despite a vast body of clinical and public health research and an ongoing focus on infection control efforts within healthcare environments and in communities, *S. aureus* remains an important public health concern associated with high morbidity, mortality, and economic costs (Ortwine and Bhavan 2018).

Animals may become infected with *S. aureus* and function as a reservoir for transmission to humans in agricultural settings (Fitzgerald 2012; Haag et al. 2019; Park and Ronholm 2021). Transmission of *S. aureus* is known to occur from humans to animals and vice versa, resulting in strains of *S. aureus* evolving within different hosts and gaining adaptive features such as antibacterial resistance (Matuszewska et al. 2020). Swine production workers are at increased risk for nasal carriage of livestock-associated strains of *S. aureus* (Armand-Lefevre et al. 2005; Sahibzada et al. 2018), and workers with nasal carriage are more likely to report skin and soft tissue infections than those without nasal carriage (Nadimpalli et al. 2016). Additionally, individuals living in households with workers who have contact with swine have increased odds of nasal carriage of livestock-associated *S. aureus* (Nadimpalli et al. 2018). Thus, interventions that focus on reducing exposure to *S. aureus* among swine workers may reduce the burden of disease among this population and their close contacts.

In the swine barn environment, *S. aureus* particles rarely exist as individual bacterium. Rather, a research study by Madsen et al. indicates that most *S. aureus* on pig farms associate with dust particles of size 7 to 12 μm (Madsen et al. 2018). *Staphylococcus aureus*-containing particles can be transported in the air, deposited on surfaces, and resuspended throughout the barn. Workers can be exposed to *S. aureus* by inhaling *S. aureus*-containing particles and by physical contact with contaminated surfaces or infected swine. Unfortunately, the movement of *S. aureus*-containing particles within the environment and the pathways of worker exposure are not well-characterized. This is further complicated by the dynamic viability of *S. aureus*, as bacteria can either multiply or decay in the environment depending on local conditions and strain characteristics (Onyango and Alreshidi 2018).

Biosecurity measures to reduce *S. aureus* infections in swine farms are primarily designed to protect livestock from exposures brought into the facility from outside sources (Levis 2011), and data on interventions that protect swine production workers from *S. aureus* exposure is limited. In 1 example, Nadimpalli and colleagues (2018) found that face mask use is associated with reduced odds of multidrug-resistant *S. aureus* and livestock-associated *S. aureus* nasal carriage among workers. Hatcher and colleagues (2017) found a higher prevalence of *S. aureus* among children living with workers who reported bringing home personal protective equipment (eg coveralls and work boots) versus those who did not. Aside from these few studies, little published literature examines measures for the reduction of swine worker exposure to *S. aureus*. Experimental studies that test the impact of worker exposure controls such as ventilation, hand hygiene, and use of personal protective equipment could be used to determine the most appropriate ways to protect workers from *S. aureus* exposure. These types of experimental studies are ideal and would be extremely informative, but they are resource-intensive and often impractical to conduct.

Mathematical models present an alternative method to examine exposure pathways, understand the relative contribution of airborne transmission and surface contamination, and evaluate the effectiveness of various exposure controls. This study attempts to elucidate the movement of *S. aureus*-containing particles within a swine barn and characterize worker exposure to environmental *S. aureus* by developing a model that accounts for both airborne and surface exposure. Specifically, we develop a Markov chain model to represent the random path that individual infectious particles take in the environment. A Markov model can be used as a multizone model to describe the movement of particles in the environment, including the movement of pathogens in the workplace. Markov models have previously been proposed as a strategy for describing the fate and transport of chemical and biological particles in the air (Nicas 2000; Jones et al. 2009; Nicas and Jones 2009; Jones and Nicas 2014).

In this paper, we use the simplest form of a Markov model, a Markov chain, which comprises multiple states and corresponding transition probabilities. A Markov chain is particularly useful in this situation, where transition probabilities can be estimated mathematically.

Methods

We present a Markov chain model to describe the fate and transport of *S. aureus*-containing particles in a typical grow-to-finish hog barn. We used this model to estimate worker exposure to *S. aureus* while within

the barn. We varied input parameters to test the impact of exposure control measures on total worker exposure and proposed potential interventions to reduce worker nasal carriage of *S. aureus*. We partially validated our model using data reported in published literature.

To develop our model, we applied a similar approach as used by Paccha and colleagues (2016) to model the risk of occupational zoonotic influenza infection in swine workers. In their model, they estimated the probability of a finite number of infectious influenza A virus particles moving between different physical locations in a swine barn and the subsequent risk that a particle reaches and infects a worker (Paccha et al. 2016). We used this same premise, but we accounted for the continuous generation of *S. aureus* by infected hogs within the barn. Additionally, we varied several model parameters to evaluate the efficacy of multiple potential interventions that may be used to protect workers from exposure to airborne and surface *S. aureus*.

Hypothetical confinement building

We modeled a typical grow-to-finish swine confinement building intended to house swine from the time of weaning until they reach market weight. The parameters of our hypothetical building are based on recommendations from the US Pork Board's Swine Care Handbook (National Pork Board 2018). We modeled a fully enclosed, mechanically ventilated swine barn with 15 m × 30 m of animal living space designed to house approximately 700 hogs. Additional barn parameters of the grow-to-finish building are shown in Table 1. A schematic of the model barn is shown in the Supplementary Materials.

Model overview

We developed a discrete-time, 7-state, Markov chain model to describe the movement and distribution of *S. aureus*-containing particles throughout a hypothetical swine finishing barn containing *S. aureus*-infected hogs. The model quantifies the exposure to *S. aureus*-containing particles for a worker during a 30-min period inside the barn to represent a typical amount of time a worker might spend in the barn during 1 entry. We also estimated the effectiveness of interventions to minimize exposure, such as respirator wearing, increased ventilation rates, and cleaning of surfaces.

We defined 7 discrete states where *S. aureus*-containing particles produced by hogs in the barn might be found. The model includes these 7 states: (1) barn air, (2) floor dust and other nontouching surfaces, (3) exhausted outside of the barn, (4) worker's respiratory system, including anterior nares, (5) worker's hands, (6) touchable surfaces, including tools and personal protective equipment, and (7) biological inactivation of bacteria via natural processes or disinfection. The parenthetical numbers represent the state numbers that will be used throughout this manuscript.

$\boldsymbol{N(t)}$ is a vector containing the numbers of *S. aureus*-containing particles in each of the 7 states at time t, and t (s) is the product of the time step (1 s) and the integer number of time steps. In other words, $\boldsymbol{N(t)}$ is a 1 × 7-row vector, $[A_1^{(t)}\ A_2^{(t)}\ A_3^{(t)}\ A_4^{(t)}\ A_5^{(t)}\ A_6^{(t)}\ A_7^{(t)}]$, where $A_i^{(t)}$ represents the number of *S. aureus*-containing particles in state i at time t. The initial state vector, $N(0)$, is an input to our model and represents the number of particles with *S. aureus* present on or in the particle (henceforth *S. aureus*-containing particles) in each state at the start of our modeling period (the time that the worker enters the barn).

We modeled time in 1-s intervals. We assumed that newly generated *S. aureus*-containing particles are constantly emitted directly into the barn air by hogs, so we defined a generation rate, G, in which a constant number of particles are added to the (1) barn air state in each time step. Information on how G is estimated is in the Supplementary Materials. As shown in Fig. 1, particles that have entered the system can transition from 1 state in the model to another or remain in the same state. We assumed that each particle would transition only once during each time step and that the probability of transitioning from any 1 state to another during a time step (ie the transition probability) can be estimated. We also make the simplifying assumption that particles are uniformly distributed in each state. The transition probabilities are represented by $\boldsymbol{X}$, where $\boldsymbol{X}$ is a 7 × 7 matrix:

$$\boldsymbol{X}=\begin{bmatrix} P_{11} & P_{12} & P_{13} & P_{14} & P_{15} & P_{16} & P_{17} \\ P_{21} & P_{22} & P_{23} & P_{24} & P_{25} & P_{26} & P_{27} \\ P_{31} & P_{32} & P_{33} & P_{34} & P_{35} & P_{36} & P_{37} \\ P_{41} & P_{42} & P_{43} & P_{44} & P_{45} & P_{46} & P_{47} \\ P_{51} & P_{52} & P_{53} & P_{54} & P_{55} & P_{56} & P_{57} \\ P_{61} & P_{62} & P_{63} & P_{64} & P_{65} & P_{66} & P_{67} \\ P_{71} & P_{72} & P_{73} & P_{74} & P_{75} & P_{76} & P_{77} \end{bmatrix}$$

The probability of moving between 2 states in 1 Markov cycle is represented by P_{ij}, where the *S. aureus*-containing particle transitions from the ith state at time t to the jth state at time $t+1$. Since our model assumes that particles can only reside in 1 of 7 finite states, the probabilities in each row must always sum to 1.

We estimated the number of *S. aureus*-containing particles within each state in the model at a future time point by multiplying the initial state vector with the transition probability matrix raised to the number of time steps that have passed. The expected distribution of a finite number of *S. aureus*-containing particles at time t is denoted by:

$$E[N(t)] = N(0) \times X^t \quad (1)$$

where $E[N(t)]$ is a vector of the same size as $\boldsymbol{N(0)}$. The expected number of particles in any state i is the ith

Table 1 Barn parameters used in base model.

Variable	Parameter	Value used in model	Notes
W_{barn}	Barn width	15 m (49.2 ft)	Assumed
L_{barn}	Barn length	30 m (98.4 ft)	Assumed
H_{barn}	Barn height	2.5 m (8.2 ft)	Assumed
SA_{barn}	Barn floor area	450 m^2 (4,843.8 ft^2)	$W_{barn} \times L_{barn}$
V_{barn}	Barn volume	1,125 m^3 (39,729 ft^3)	$W_{barn} \times L_{barn} \times H_{barn}$
Q	Ventilation rate	690 m^3/min in base model	Recommended ventilation for mild weather for the number and size of animals housed. In simulations we modeled ventilation rate at 200 and 2,380 m^3/min, as well, based on industry recommendations (MWPS 1983; NPB 2018)
$Weight_{hog}$	Average hog weight	90.7 kg (200 lb)	Assumed
N_{hog}	Number of hogs in barn	700	Assumed
	Stocking density	6.92 ft^2/hog	SA_{barn}/N_{hog} Recommended stocking density for 200 lb hog: 7 ft^2/hog (MWPS 1983; NPB 2018)
G	Generation of *S. aureus*-containing particles	1,000,000 particles/min	Generation of inhalable dust: 1.386 mg/s (Anthony et al. 2014; Park et al. 2017) (83.16 mg/min) Concentration of MRSA in dust: 39 CFU-MRSA/mg-dust (range: 0.1 CFU-MRSA/mg-dust to 230 CFU-MRSA/mg-dust) (Friese et al. 2012) Concentration of MRSA in dust: 404 CFU-MRSA/mg-dust (Madsen et al. 2019) MSSA: MRSA ratio in sampled air: 2000:419 CFU/m^3 (Madsen et al. 2019)
C_{ss}	Starting concentration of *S. aureus*-containing particles in the air	1,376 particles/m^3 (1.5×10^6 particles)	Value based on running the model for 60 min with no worker states
C_{surf}	Starting concentration of *S. aureus*-containing particles on surfaces	7,295 particles/m^2 (3.3×10^5 particles)	Value based on running the model for 60 min with no worker states

The notes column includes information on how the values were determined.

entry on vector $E[N(t)]$, denoted $A_i^{(t)}$. For example, $A_4^{(15)}$ is the expected number of particles contained in a worker's respiratory system (state 4) after 15 s within the swine barn. The above equation assumes a finite number of particles exist and no new particles are added to the system. However, new *S. aureus*-containing particles are added to the system by infected hogs. To mathematically account for this, we added particles at a rate of G to $A_1^{(t)}$ (barn air state) at each time step. Details of how the generation rate was calculated and incorporated into the model are included in the Supplementary Materials. All models were created and run using the open-source R programming software and the markovchain package. R code is included in the Supplementary Materials.

Establishing the starting probability vector

We assumed that a worker entered the barn with no prior exposure to *S. aureus* (ie the number of particles in the (4) worker's respiratory system and on the (5) worker's hands is zero). We also began with a starting value of zero for the (3) exhausted and the (7) deactivated states. To determine the starting number of particles in the (1) barn air state, (2) floor dust state, and (6) touchable surface state, we ran the model without any worker states for 60 min. We then used the number of particles in each of these states as entries in the starting probability vector, $\boldsymbol{N(0)}$. Thus, the starting probability vector for the base model was defined:

$$N(0) = [1, 548, 660\ \ 2, 954, 556\ \ 0\ \ 0\ \ 0\ \ 328, 284\ \ 0\ ]$$

Calculating transition probabilities for a base model

We calculated transition probabilities for the base model by using scenario-based assumptions, well-established knowledge on the physical properties and behaviors of particles, and values obtained from the literature review.

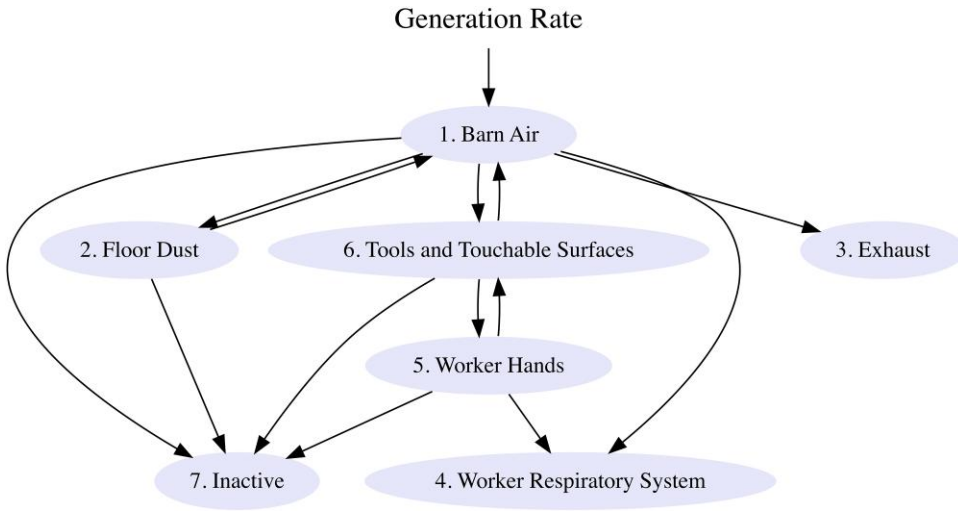

Figure 1 Transition state diagram. Ovals represent the states of the model, which are physical locations where *S. aureus*-containing particles may exist. The model contains 7 states: (1) barn air, (2) floor dust and other non-touchable surfaces, (3) exhaust, (4) worker respiratory system, (5) worker hands, (6) tools, personal protective equipment, and other touchable surfaces, and (7) biologically inactivated. The arrows represent possible transitions that can occur in a 1-min time step. Particles may move to another state as indicated by the arrows or remain in their current state. Particles are added to the (1) barn air state to represent the generation of new *S. aureus*-containing particles into the workplace.

We assumed that transitions between certain states in our model to certain other states occur at a probability of zero. That is, a *S. aureus*-containing particle cannot move directly from one state to another without first transitioning to an intermediate state. For example, we set the value of P_{15}, that is, the transition from the (1) barn air state to the (5) worker hands state, to zero. This is based on the assumption that the number of particles deposited from the air to the worker's hands in 1 s is negligible. Additionally, we assumed that some states in the model are absorbing states. Once *S. aureus*-containing particles enter that state, they remain in that state indefinitely, and the transition probability for staying in the state is 1. For example, we assumed that once a particle leaves the barn via the ventilation exhaust, it remains in the (3) exhausted state and does not transition back into any other state. Therefore, the probability that a particle in the (3) exhausted state stays in the exhausted state after a 1-s time step, P_{33}, is 1. This logic is applied to several other transitions, such that the majority of transition probabilities are either zero or 1.

Other transition probabilities are calculated based on known physical properties of particles. For example, the transition probability from the (1) barn air state to the (3) exhausted state, P_{13}, is calculated based on the exponential decay function, where the decay rate is determined by the ventilation rate in the barn and the volume of the barn. This is consistent with the well-mixed room model, a widely used model in the fields of industrial hygiene and occupational exposure assessment.

Finally, we also determined transition probabilities based on values obtained from a targeted literature search. For example, the transition probability from the (6) touchable surfaces state to (5) worker hands, P_{65}, is calculated as the product of the contact rate of hands to surfaces, the transfer efficiency of *S. aureus* from surfaces to skin, and the ratio of hand surface area to the surface area of all touchable surfaces in the barn. Values for typical contact rates, transfer efficiencies, and hand surface area were obtained from published studies.

Table 2 summarizes values used to calculate the transition probabilities for our base model, and Table 3 summarizes the equations. A detailed description of how each transition probability was calculated can be found in the Supplementary Materials.

Simulating interventions

We simulated interventions to test the impact of each intervention on the air concentration of *S. aureus*-containing particles in the barn, the worker's respiratory system exposure, and the worker's dermal exposure. The tested interventions included adjusting the ventilation rate in the barn, performing surface cleaning prior to worker entry into the barn, and the wearing of an N-95 respirator by the worker. We tested each intervention by modifying the value of 1 or more input variables which resulted in a new transition probability matrix that was used in the model. We compared values for $A_1^{(900)}$, $A_1^{(1,800)}$, $A_4^{(900)}$, $A_4^{(1,800)}$, $A_5^{(900)}$, and $A_5^{(1,800)}$,

Table 2 Input variables used to determine transition probabilities for base model.

Variable	Input variable	Values used	Notes
V_{TS}	Terminal settling velocity of *S. aureus*-containing particle	0.0937 m/min (1.5617×10^{-3} m/sec)	Calculated. $V_{TS} = \frac{\rho_p d^2 g}{18\eta} = \frac{1\frac{g}{cm^3} \times (7.2 \times 10^{-4} cm)^2 \times 981 \frac{cm}{s^2}}{18(1.81 \times 10^{-4})} = 0.0937$ m/min (1.5617×10^{-3}m/sec)
d	Aerodynamic diameter of dust particle with *S. aureus*	7.2 µm (Madsen et al. 2018)	Particle size range of 7 to 12 µm reported, geometric mean of 7.2 µm
Q	Ventilation rate	200; 690; 2,380 m^3/min	See Supplementary File S2 for ventilation recommendations.
Worker inhalation rate	Worker inhalation rate	0.035 m^3/min (5.8×10^{-4} m^3/sec) (EPA 2011)	—
R_{part}	Particle resuspension rate	0.001 particles/min (1.6667×10^{-5} particles/sec) (Salimifard et al. 2017)	Particle resuspension during human walking in clean environment reported as approximately 10^{-4} min^{-1}. Value adjusted for dusty environment with high movement.
$t_{\frac{1}{2}}$	Half-life of *S. aureus*	5.5 d or 7,920 min (474,000 s) (Feld et al. 2018)	—
$CR_{hand\ to\ face}$	Hand to facial membrane contact rate	15.7 contacts/h (0.26167 contacts/min, 4.3×10^{-3} contacts/sec) (Nicas and Best 2008)	—
$TE_{skin\ to\ skin}$	Skin to skin transfer efficiency	0.4099 per touch (Rusin et al. 2002)	Transfer efficiency of *M. luteus* from fingertip to lip.
$CR_{hand\ to\ surfaces}$	Hand to touchable surfaces contact rate	1.26 contacts/min (0.021 contacts/s) (Paccha et al. 2016)	—
$TE_{skin\ to\ surface}$	Hand to touchable surface transfer efficiency	0.392 per touch (Arinder et al. 2016)	Transfer efficiency based on transfer of *S. aureus* from skin to stainless steel.
$TE_{surface\ to\ skin}$	Touchable surface to hand transfer efficiency	0.053 per touch (Arinder et al. 2016)	Transfer efficiency based on transfer of *S. aureus* from stainless steel to hand.
SA_{hands}	Surface area of worker hands	0.107 m^2 (EPA 2011)	Mean surface area of adult male hands from EPA Exposure Factors Handbook.
SA_{barn}	Barn floor area	405 m^2 (4,359.4 ft^2)	Calculated. $W_{barn} \times L_{barn} - SA_{surfaces}$
$SA_{surfaces}$	Total surface area of touchable surfaces within the barn.	45 m^2 (484.3 ft^2)	Assumed to be 10% of the SA_{barn}.

Input variables were determined by search of published literature. The Notes column provides additional information on inputs, when applicable. When possible, we selected values from studies on *S. aureus* in swine barn environments. If this was not available, it is indicated in the notes.

Table 3 Calculation of transition probabilities for base model.

From state	To state	Equation	Value
Barn air	Barn air	$P_{11}\ (1-(P_{12}+P_{13}+P_{14}+P_{15}+P_{16}+P_{17}))$	$P_{11}=(1-(5.6232\times10^{-4}+1.0170\times10^{-2}+5.1849\times10^{-7}+0+6.2480\times10^{-5}+1.45864\times10^{-6}))=0.9892$
Barn air	Floor dust	$P_{12}\ 0.9\ (1-e^{-\lambda_{12}t})$, where $\lambda_{12}=\frac{V_{TS}}{H_{barn}}$	$\lambda_{12}=\frac{0.001562\ \text{m/s}}{2.5\ \text{m}}=6.248\times10^{-4}$ $P_{12}=0.9\ (1-e^{-6.248\times10^{-4}})=5.6232\times10^{-4}$
Barn air	Exhausted	$P_{13}\ P_{13}=(1-e^{-\lambda_{13}t})$, where $\lambda_{13}=\frac{Q}{V}(\text{sec}^{-1})$	$\lambda_{13}=\frac{11.5\ \text{m}^3/\text{s}}{1,125\ \text{m}^3}=0.01022$ $P_{13}=1-e^{-0.01022}=1.0170\times10^{-2}$
Barn air	Worker respiratory system	$P_{14}\ P_{14}=(1-e^{-\lambda_{14}t})$, where $\lambda_{14}=\frac{\text{worker inhalation rate}}{V_{barn}}(s^{-1})$	$\lambda_{14}=\frac{5.8\times10^{-4}\ \text{m}^3/\text{s}}{1,125\ \text{m}^3}=5.1556\times10^{-7}$ $P_{14}=1-e^{-5.1556\times10^{-7}}=5.1849\times10^{-7}$
Barn air	Touchable surfaces	$P_{16}\ 0.1\ (1-e^{-\lambda_{16}t})$, where $\lambda_{16}=\frac{V_{TS}}{H_{barn}}$	$\lambda_{16}=\frac{1.5617\times10^{-3}\ \text{m/s}}{2.5\ \text{m}}=6.2467\times10^{-4}$ $P_{16}=0.1\ (1-e^{-6.2467\times10^{-4}})=6.2480\times10^{-5}$
Barn air	Inactivated	$P_{17}\ P_{17}=\frac{\ln(2)}{t_{\frac{1}{2}}}$	$P_{17}=\frac{\ln(2)}{475,200\ \text{s}}=1.45864\times10^{-6}$
Floor dust	Barn air	$P_{21}\ P_{21}=(1-e^{-\lambda_{21}t})$, where $\lambda_{21}=R_{part}$	$\lambda_{21}=1.6667\times10^{-5}$ $P_{21}=(1-e^{-1.6667\times10-5})=1.6667\times10^{-5}$
Floor dust	Floor dust	$P_{22}\ P_{22}=(1-(P_{21}+P_{23}+P_{24}+P_{25}+P_{26}+P_{27}))$	$P_{22}=(1-(1.6667\times10^{-5}+0+0+0+0+1.45864\times10^{-6}))=0.9999$
Floor dust	Inactivated	$P_{27}\ P_{27}=\frac{\ln(2)}{t_{\frac{1}{2}}}$,	$P_{27}=\frac{\ln(2)}{475,200\ \text{s}}=1.45864\times10^{-6}$
Worker hands	Worker respiratory system	$P_{54}\ P_{54}=CR_{\text{hand to face}}\times TE_{\text{skin to skin}}$,	$P_{54}=4.362\times10^{-3}\frac{\text{touches}}{\text{s}}\times0.4099\ \text{per touch}=1.7876\times10^{-3}$
Worker hands	Worker hands	$P_{55}\ P_{55}=(1-(P_{51}+P_{52}+P_{53}+P_{54}+P_{56}+P_{57}))$	$P_{55}=(1-(0+0+0+1.7876\times10^{-3}+6.909\times10^{-3}+1.45864\times10^{-6}))=0.3987$
Worker hands	Touchable surfaces	$P_{56}\ P_{56}=CR_{\text{hand to surfaces}}\times TE_{\text{skin to surface}}$	$P_{56}=0.021\frac{\text{touches}}{\text{s}}\times0.329\ \text{per touch}=6.909\times10^{-3}$
Worker hands	Inactivated	$P_{57}\ P_{57}=\frac{\ln(2)}{t_{\frac{1}{2}}}$,	$P_{57}=\frac{\ln(2)}{475200\ \text{s}}=1.45864\times10^{-6}$
Touchable surfaces	Barn air	$P_{61}\ P_{61}=(1-e^{-\lambda_{61}t})$, where $\lambda_{61}=R_{part}$	$\lambda_{61}=1.6667\times10^{-5}$ $P_{61}=(1-e^{-1.6667\times10-5})=1.6667\times10^{-5}$
Touchable surfaces	Worker hands	$P_{65}\ P_{65}=CR_{\text{hand to surfaces}}\times TE_{\text{surface to skin}}\times\frac{SA_{hands}}{SA_{surfaces}}$	$P_{65}=0.021\ \text{touches/s}\times0.0531\times\frac{0.107\ \text{m}^2}{45\ \text{m}^2}=2.6515\times10^{-6}$
Touchable surfaces	Touchable surfaces	$P_{66}\ P_{66}=(1-(P_{61}+P_{62}+P_{63}+P_{64}+P_{65}+P_{67}))$	$P_{66}=(1-(1.6667\times10^{-5}+0+0+0+2.6515\times10^{-6}+1.45864\times10^{-6}))=0.9999$
Touchable surfaces	Inactivated	$P_{67}\ P_{67}=\frac{\ln(2)}{t_{\frac{1}{2}}}$,	$P_{67}=\frac{\ln(2)}{475200\ sec}=1.45864\times10^{-6}$

Table 4 Input ranges used for Monte Carlo analysis and partial validation.

Variable	Range of values
Aerodynamic particle diameter, d (μm)	Lognormal (7.2, 1.5)
Particle resuspension, R_{part} (min^{-1})	Uniform (1.66×10^{-6}, 1.66×10^{-5})
Q (m^3/s)	Uniform (10, 13.33)
G (particles/s)	Normal (33, 333, 3, 333)
Starting number of particles in air	Uniform (1.3×10^{6}, 1.7×10^{6})
Starting number of particles on surfaces (floor dust, tools, and touchable surfaces)	Uniform (2.9×10^{6}, 3.0×10^{6}) Uniform (3.2×10^{5}, 3.3×10^{5})

Values are listed in the following format: lognormal (geometric mean, geometric standard deviation), uniform (min, max), and normal (mean, standard deviation).

representing the air concentration of *S. aureus*-containing particles in the barn, the expected number of *S. aureus*-containing particles in the worker's respiratory system, and the expected number of *S. aureus*-containing particles on a worker's hands or gloves, at intervals of 900 s (15 min) and 1,800 s (30 min) each.

To simulate adjusting the ventilation rate, we modified the value of the ventilation rate in the barn, Q, according to recommended ventilation parameters (MWPS 1983). We ran the model with ventilation rates of 200, 690, and 2,380 m^3/min (see the Supplementary Materials for ventilation recommendations). Because the probability of a particle transitioning from the (1) barn air state to the (3) exhausted state and the probability of staying in the (1) air state after 1 time step depends on the ventilation rate, modifying the value of Q resulted in changes to the values of both P_{13} and P_{11} in our transition probability matrix.

To simulate surface cleaning, we modified $A_2^{(0)}$ and $A_6^{(0)}$, which are the second and sixth entries on the starting probability vector $\mathbf{N(0)}$, representing the starting number of *S. aureus*-containing particles on the floor and the touchable surfaces within the barn, respectively. In our base model, the starting number of *S. aureus*-containing particles in the (2) floor dust state was $A_2^{(0)} = 2.95\times10^{6}$, and the starting number of particles on the tools and (6) touchable surfaces state was $A_6^{(0)} = 3.28\times10^{5}$. This corresponds to a concentration of particles on floors and surfaces of approximately 7,300 *S. aureus*-containing particles/m^2. We ran the model using values for $A_2^{(0)}$ and $A_6^{(0)}$ that are 10%, 25%, and 50% of the value of the base model, to simulate the impact of different cleaning efficiencies on the model.

Finally, to simulate N-95 respirator-wearing, we directly adjusted P_{14}, P_{54}, P_{11}, and P_{55}. To simulate a well-fitting N-95 respirator, we reduced P_{14} (the probability of transitioning from the barn air to the workers respiratory system) by 95%, and we reduced P_{54} (the probability of transitioning from worker hands to worker respiratory system) to 0, assuming that a worker will not touch the nose or mouth while wearing a well-fitting N-95 respirator. To simulate an N-95 with inadequate fit, we reduced P_{14} by 90% and P_{54} to 0. For a poorly fitting N-95, we reduced P_{14} by 40% and left P_{54} unchanged. We kept P_{54} unchanged to represent the fact that a poorly fitting N-95 respirator may not interfere with hand to nose/mouth contact, particularly since workers may bring their hands to their face to reposition their N-95 respirator and inadvertently touch their nose or mouth when doing so. The values of P_{11} and P_{55} are dependent on the values of P_{14} and P_{54}, respectively, and were adjusted accordingly. These N-95 respirator effectiveness levels are based on a correctly fitting N95 filtering 95% of *S. aureus*-containing particles out of the air and inadequately fitting and poorly fitting N-95 respirators having increasingly more inward leakage of particles. All respiratory protection modeled in our simulation is N-95 filtering face piece respirators. We did not model simple dust masks or cartridge respirators.

Partial model validation using Monte Carlo analysis

We performed partial validation using Monte Carlo analysis to ensure that our model produced reasonable estimates of worker exposure. We used a range of values for several of our input parameters to account for uncertainty and variability in these values. We ran 500 iterations of the model to produce a range of possible outcomes (see Table 4). We compared outputs from our model to air and surface concentration to values obtained in the literature.

Results

The transition probability matrix used for our base model is shown in Fig. 2. For all states in our model, the probability that an *S. aureus*-containing particle will stay in that state in the next time step is approximately 1. This

States	Transition probability matrix						
	1. Barn air	**2. Floor dust**	**3. Exhaust**	**4. Worker's respiratory system**	**5. Worker's hands**	**6. Tools, PPE, and touchable surfaces**	**7. Inactivation**
1. Barn air	0.9892	5.6232×10^{-4}	1.0170×10^{-2}	5.1849×10^{-7}	0	6.2480×10^{-5}	1.4586×10^{-6}
2. Floor dust	1.6667×10^{-5}	0.9999	0	0	0	0	1.4586×10^{-6}
3. Exhaust	0	0	1	0	0	0	0
4. Worker's respiratory system	0	0	0	1	0	0	0
5. Worker's hands	0	0	0	1.7876×10^{-3}	0.9999	8.2320×10^{-3}	1.4586×10^{-6}
6. Tools, PPE, and touchable surfaces	1.6666×10^{-5}	0	0	0	2.6515×10^{-6}	0.9999	1.4586×10^{-6}
7. Inactivation	0	0	0	0	0	0	

Figure 2 Transition probability matrix for base model (no interventions).

represents the fact that after a 1-s time interval, only a small fraction of particles will move from any one state to another.

Running the model for 30 min using 1-s time steps resulted in the distribution of *S. aureus*-containing particles within the barn shown in Fig. 3. Figure 4 shows the concentration of particles in the barn air, touchable surfaces, and barn floor states. The number or concentration of *S. aureus*-containing particles in each state after 15 and 30 min is shown in Table 5. After 15 and 30 min of running the model, the concentration in the barn air is 1,378 and 1,379 particles/m^3, respectively, indicating that the transition of *S. aureus*-containing particles from the air state to other states in the model results in negligible changes in air concentration. The concentration of *S. aureus*-containing particles in the floor dust state at 15 and 30 min is 9,097 and 10,872 particles/m^2, and the concentration on tools and touchable surfaces is 9,092 and 10,862 particles/m^2. The number of particles that enter the worker's respiratory system after 15 and 30 min is 861 and 1,772, respectively. Unlike the (1) barn air state, the number of particles on surfaces and in the worker's respiratory states does not level off after 15 or 30 min of running the model.

The results from the simulations of workplace interventions are shown in Table 6. Increasing the ventilation rate lowers the concentration of *S. aureus*-containing particles in the air and the number of particles in the worker's respiratory system. For example, increasing the ventilation rate from 200 to 690 m^3/min results in a 59% decrease in the number of particles to which the worker's respiratory tract is exposed at 30 min (from 4,331 to 1,772 particles). Increasing ventilation further to 2,380 m^3/min results in an additional 58% decrease (from 1,772 to 740 particles). However, this is an extremely high ventilation rate that may not be practically achieved in all situations, indicating diminishing returns for additional ventilation changes beyond this. Increased ventilation also impacted the number of particles on worker hands. When the ventilation rate was changed from 200 to 690 m^3/min, the number of particles on the worker's hands after 30 min decreased from 199 to 127.

Floor and surface cleaning prior to entry into the swine barn is simulated by lowering the starting number of particles in the floor dust and touchable surfaces states at $t = 0$. This intervention appears to have almost no impact on the concentration of particles in the barn air but has a greater impact on worker exposure. For example, when the number of *S. aureus*-containing particles in the floor dust is decreased to 10% of the value used in the base model, the model shows that the number of particles in the worker's respiratory system after 30 min is reduced by 13%, from 1,772 to 1,534. This impact of and surface cleaning is greater on worker

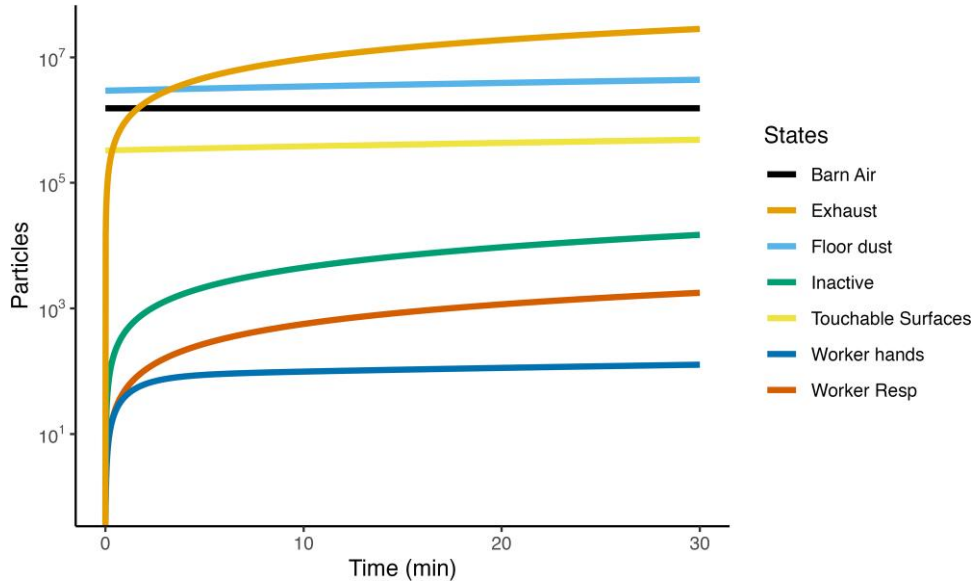

Figure 3 Distribution of *S. aureus*-containing particles during 30-min time interval.

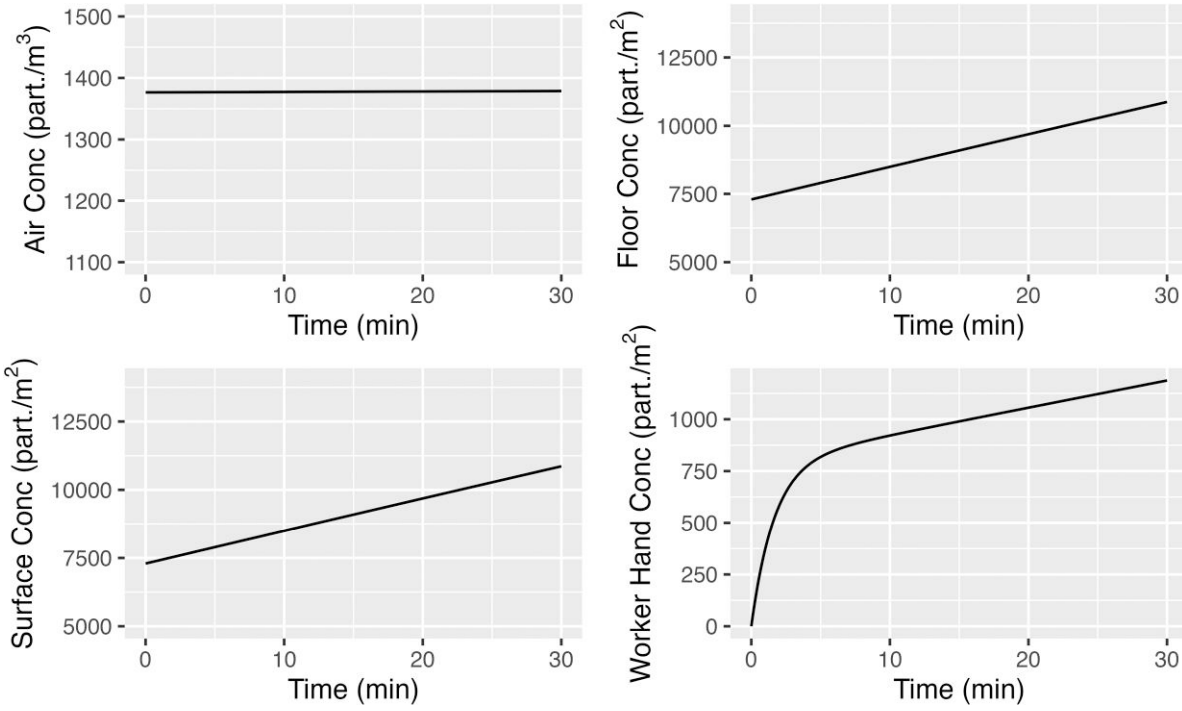

Figure 4 Concentration of *S. aureus*-containing particles in the air and on surfaces during a 30-min time interval. Units are in particles/m^3 for air concentration and particle/m^2 for surface concentrations.

hands, where the number of particles after 30 min is reduced by 60% from 127 to 51.

As modeled, the N-95 respirator-wearing intervention has the greatest impact on worker exposure via the respiratory system. Logically, N-95 respirator-wearing has virtually no impact on the concentration of *S. aureus*-containing particles in the air. However, a well-fitting N-95 respirator may reduce worker

Table 5 Results from running the base model.

State	Number of particles at 15 min	Number of particles at 30 min	Concentration at 15 min	Concentration at 30 min
Barn air	1,549,839	1,551,073	1,378 particles/m^3	1,379 particles/m^3
Floor dust	3,684,445	4,403,145	9,097 particles/m^2	10,872 particles/m^2
Exhaust	14,180,231	28,371,778	n/a	n/a
Worker respiratory system	861	1,772	n/a	n/a
Worker hands	106	127	990 particles/m^2	1,187 particles/m^2
Tools and touchable surfaces	409,141	488,794	9,092 particles/m^2	10,862 particles/m^2
Inactivation	6,876	14,811	n/a	n/a

Number of particles is reported for all states, while concentration is reported for barn environment states.

inhalation exposure from 1,772 to 72 particles after 30 min in the barn, a 96% reduction. A poorly fitting N-95 is modeled to reduce exposure by about 33%, indicating that the type and fit of the N-95 respirator worn has an important impact on worker protection.

The results from our Monte Carlo analysis are shown in Fig. 5. We ran 500 iterations of the model, with each iteration randomly selecting inputs from the distributions shown in Table 4. Due to the uncertainty added to our input variables, the range of possible values for the number of particles in each state after running the model increases with time. Table 7 shows the median number of particles and the range of values for each state obtained from the Monte Carlo analysis after running the model for 30 min.

To partially validate our model, we compared model outputs for air and surface concentrations to ranges reported in the literature for similar environments.

For air concentrations, we compared the results of our model to Madsen et al. (2019), Masclaux et al. (2013), and Friese et al. (2012) (see Fig. 6). Each of these authors measure colony forming units (CFUs) of *S. aureus* in swine barns. We consider CFUs equivalent to number of *S. aureus*-containing particles for the purpose of our comparison. Madsen and colleagues (2019) collected airborne dust from a swine farm in Denmark using multiple sampler types, including the Anderson 6-stage cascade impactor (ASCI) sampler and the Gesamtstaubprobenahme (GSP) sampler with 3 filter options (Teflon, polycarbonate, and gelatin). Of the air samples that were collected that were positive for *S. aureus* and able to be quantified, the geometric mean air concentration was reported for each filter type. Geometric mean concentrations ranged from 1,450 CFU/m^3 for the GSP sampler with a polycarbonate filter to 2,000 CFU/m^3 with the ASCI (Madsen et al. 2019). Masclaux and colleagues (2013) collected air samples (in nutrient media with an impactor sampler) from 37 swine barns in Switzerland. Twelve of those barns were positive for *S. aureus*. Of the positive samples, they reported a geometric mean concentration of 1,011 CFU/m^3 and a range of 100 to 4,000 CFU/m^3 (Masclaux et al. 2013). Friese and colleagues (2012) collected air samples from 27 swine farms in Germany using both impingement and filtration (polycarbonate filter). Their study primarily addressed the occurrence of MRSA in the air and the environment, but they also reported *S. aureus* and total bacteria concentrations. Mean *S. aureus* concentrations for impingement and filtration were 1.4×10^4 and 2.6×10^4 CFU/m^3, respectively (Friese et al. 2012).

We obtained values for comparison to our model outputs for surface concentrations from Feld et al. (2018), as shown in Fig. 7. In their investigation, they used electrostatic dust fall collectors to passively collect settled dust within 6 swine farm stables in Denmark (Feld et al. 2018). Their study was primarily concerned with the half-life of MRSA over time. For comparison, we use the values they report as mean initial MRSA concentration, which range from 6×10^3 to 7×10^4.

Discussion

The results of our model indicate that short periods of time within the swine barn environment can result in significant worker exposure to *S. aureus*-containing particles. In a dusty environment such as the scenarios modeled here, inhalation is an important exposure pathway and may have a greater impact on worker nasal carriage compared to hand to nose/mouth contact. This is demonstrated by the large decrease in the number of particles reaching the worker's respiratory system state following interventions that focus on reducing the number of particles in the air or reducing the transition probability from the air to the respiratory system (up to 96% reduction after 30 min). This is

Table 6 Simulation results showing the number of particles in the barn air, worker respiratory system, and worker hands states after 15 and 30 min of running the model.

Intervention simulated		Variable modified	Values	Air concentration at 15 min (particles/m^3)	Air concentration at 30 min (particles/m^3)	Worker resp at 15 min (number of particles)	Worker resp at 30 min (number of particles)	Worker hands at 15 min (number of particles)	Worker hands at 30 min (number of particles)
Adjusting ventilation rate		Q (m^3/min)	200	4,042	4,157	1,899	4,331	133	199
			690	1,378	1,379	861	1,772	106	127
			2,380	421	422	366	740	92	98
Floor and surface cleaning		Starting concentration of *S. aureus* on floor and surfaces (particles/m^2)	730 (10% of base model)	1,374	1,375	748	1,534	29	51
			1,824 (25% of base model)	1,374	1,375	767	1,574	42	64
			3,648 (50% of base model)	1,375	1,377	798	1,640	63	85
			7,296 (base model)	1,378	1,379	861	1,772	106	127
N-95 respirator-wearing	Well-fitting N-95	P_{14}, P_{54}	$P_{14} = 2.592 \times 10^{-8}$ $P_{54} = 0$	1,378	1,379	36	72	128	154
	N-95 with inadequate fit	P_{14}, P_{54}	$P_{14} = 5.185 \times 10^{-8}$ $P_{54} = 0$	1,378	1,379	72	145	128	154
	Poorly fitting N-95	P_{14}, P_{54}	$P_{14} = 1.87 \times 10^{-5}$ $P_{54} = 1.79 \times 10^{-3}$	1,378	1,379	572	1,193	106	127

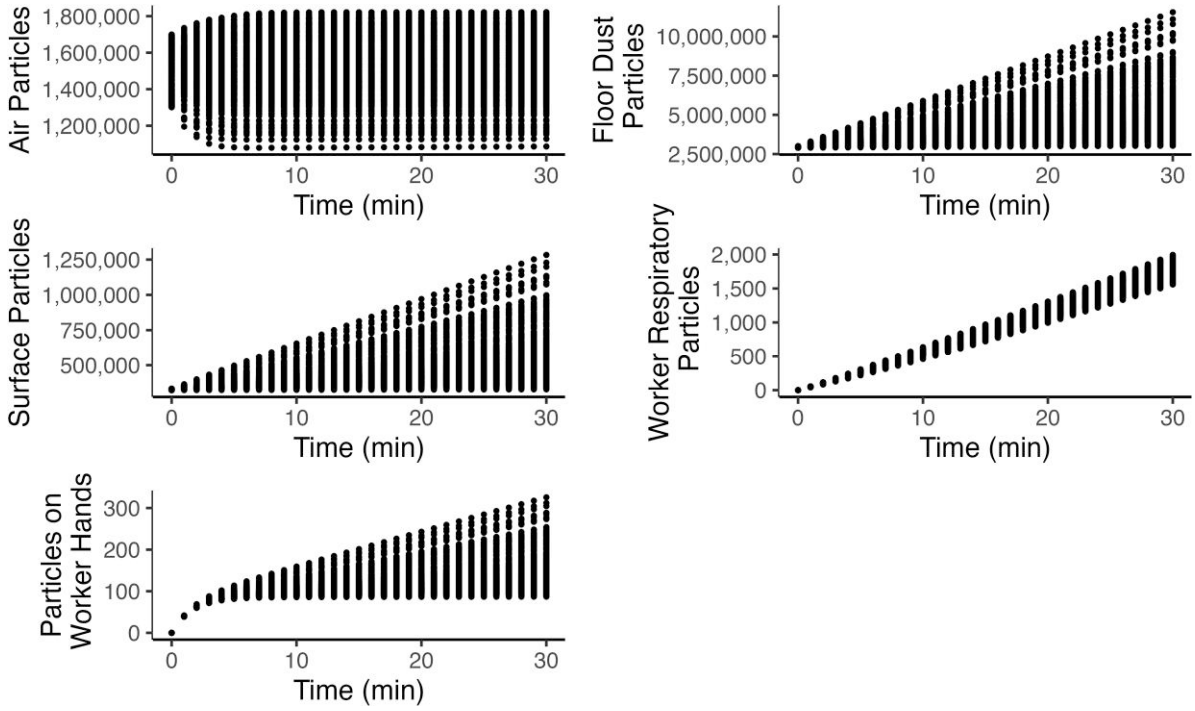

Figure 5 Output from Monte Carlo analysis. We ran 500 iterations of the model to produce a range of possible outcomes. The top 3 graphs display the range of expected number of particles in the 3 barn environment states over a 30-min model run. The bottom 2 graphs display the range of expected number of particles in the worker states over 30 min.

compared to lower reductions to the respiratory system following interventions that focused on reducing the number of particles on the hands via surface cleaning.

Our models also showed substantial decreases in worker exposure to *S. aureus* when we simulated donning a well-fitting N-95 respirator, supporting previously published findings about mask use and exposure control of infectious agents in agricultural settings (Paccha et al. 2016; Nadimpalli et al. 2018; Edmondson et al. 2022). Adjusting ventilation rates to increase airflow and conducting enhanced surface cleaning both reduced worker exposure but appeared to have diminishing returns in terms of effectiveness compared to N-95 respirator use. However, both strategies should be considered as potential workplace control strategies.

The outputs generated from this model should be used as one of many considerations in a risk management strategy. Decisions about workplace controls need to be comprehensive and should consider both feasibility and effectiveness of controls. For example, ventilation rates must be appropriate to maintain the optimum temperature and humidity needed for the developmental stage of the hogs being raised, given ambient climate conditions. Large adjustments in airflow rates may be cost-prohibitive or mechanically impossible, depending on the limitations of the ventilation system. Respirator use was highly effective in our models; however, personal protective equipment should typically only be relied upon when other attempts to control exposures are insufficient. In practice, there are many additional factors that must be addressed before implementing a respiratory protection program, including respirator selection, worker training, and storage and care of respirators. Employers must also fully adhere to the requirements of the Occupational Safety and Health Administration's Respiratory Protection Standard. Additionally, there are limitations and drawbacks to relying on personal protective equipment to control exposures. A well-fitting N-95 respirator may protect from inhalation exposures but can increase the risk of other hazards, such as heat stress and dehydration (Li et al. 2005). According to the Hierarchy of Controls, personal protective equipment should be considered the last among all exposure control approaches (NIOSH 2015). Relying on personal protective equipment as a primary control strategy places large responsibility of workplace safety on the worker, rather than the employer, and requires a significant amount of effort and discomfort to the worker.

The use of Markov modeling for this type of application is currently theoretical, yet this research represents an important step in exploring a new way of conducting exposure modeling and predicting future exposures. A

Table 7 Output of Monte Carlo analysis after 30 min.

	State	Median value, number of particles (concentration, if applicable)	Minimum value, number of particles (concentration)	Maximum value, number of particles (concentration)
Environmental states	1. Barn air	1.500×10^6 (1,333 particles/m^3)	1.086×10^6 (966 particles/m^3)	1.821×10^6 (1,619 particles/m^3)
	2. Floor dust	4.465×10^6 (11,024 particles/m^2)	3.027×10^5 (7,479 particles/m^2)	1.154×10^7 (28,512 particles/m^2)
	6. Touchable surfaces, including tools and PPE	4.932×10^5 (10,961 particles/m^2)	3.28×10^4 (7,311 particles/m^2)	1.283×10^6 (28,513 particles/m^2)
Worker states	4. Worker respiratory system	1,743	1,559	1,994
	5. Worker hands	128	87	326

The median, minimum, and maximum number of particles (and concentration, where applicable) resulting from the Monte Carlo analysis are displayed for relevant environmental and worker states.

strength of this research is that it proposes an alternative method for predicting worker exposures and evaluating interventions. Given the cost and logistical advantages, models may be considered as an initial approach to exposure assessment, providing the opportunity to refine field sampling strategies. We use Markov modeling to coalesce and build upon the current understanding of how workers are exposed to and infected with *S. aureus* in agricultural settings. We accounted for both inhalation exposure and exposure via hand to facial mucous membrane (specifically the nose and mouth) contact in our model. Further, we modeled the relative impact of multiple interventions on worker exposures during brief periods within a swine barn. Another strength of the model is that it can be modified to be used for other infectious agents that are spread via inhalation or by exposure to fomites. Adjusting the value of variables such as particle size, transfer efficiency, and inactivation rate would allow this model to extend to both chemical and biological exposures.

The partial validation of our model using Monte Carlo analysis suggested that our model outputs were reasonable and within the range of values reported in the literature. The predicted ranges for air concentration include the mean values reported by Madsen et al. (2019) and Masclaux et al. (2013). The range of values reported by Friese et al. (2012), however, are significantly higher than we predict and what is seen in other studies. Sampling methods, sampling media, and handling and storage of viable samples can all impact the final concentration reported. Additionally, the farms in the Friese study were preselected based on known MRSA-positive status in the prior 3 mo, which could mean that these were more highly contaminated facilities.

We recognize many limitations in our model. The outputs of our study support the implementation of interventions; however, experimental or observational studies are needed to confirm these results. For instance, an experimental study that measures and compares air concentrations of *S. aureus* in a finishing barn under different ventilation parameters would be ideal to confirm if our model accurately captures the impact of changing the ventilation rate. We were not able to obtain data for other states in our model. Personal breathing zone samples and wipe samples from worker hands would further confirm that our model reflects the true exposure pathways within a swine barn.

Another important limitation of our model is that it is used to estimate exposure but does not currently examine the dose to the worker. For example, we modeled how many particles make it to the worker's respiratory system after 30 min of exposure; however, we do not differentiate between particles that deposit in the workers nose or mouth and those that penetrate deeper into

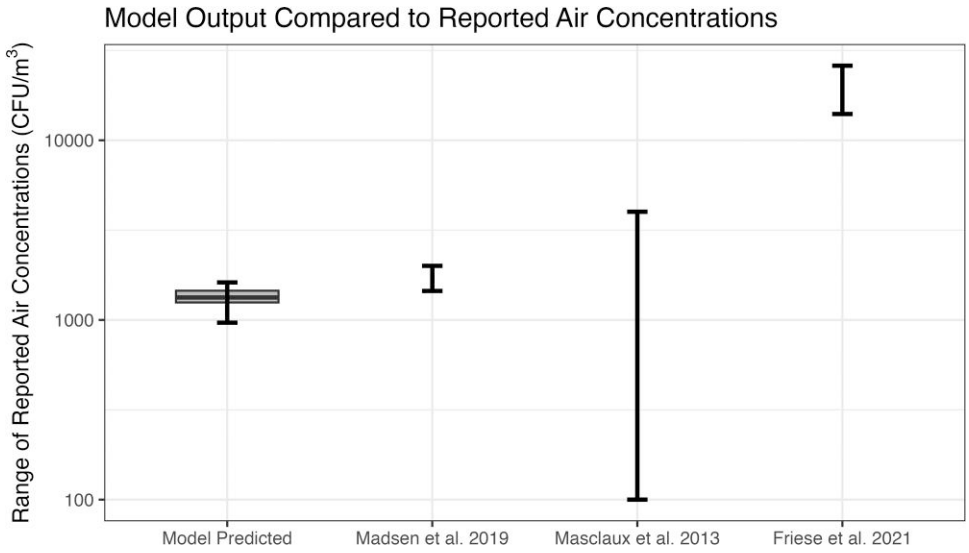

Figure 6 Comparison of model output for air concentrations with published literature. For our model, a box and whisker plot displays the 5 number summary for our Monte Carlo analysis. For the other studies, the minimum and maximum reported values are displayed, as quartile information was not available.

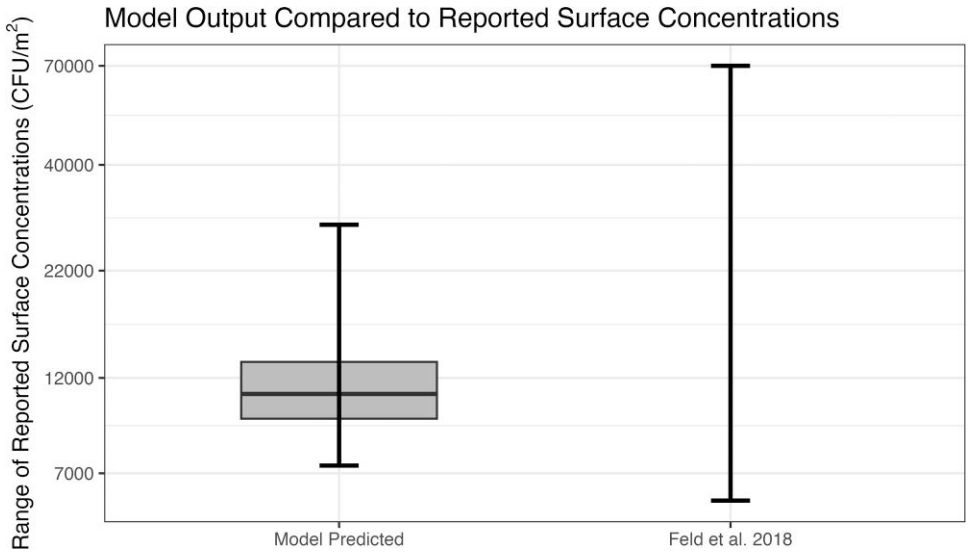

Figure 7 Comparison of model output for surface concentrations with published literature. For our model, a box and whisker plot displays the 5 number summary for our Monte Carlo analysis. For Feld et al., the range of mean values of MRSA concentration are reported, as quartile information was not available.

the respiratory system. Depending on the particle size, airborne *S. aureus*-containing particles may deposit in different parts of the respiratory system, including the nasal cavity, tracheae, bronchi, or alveoli. Exposures due to hand to face contact will likely stay on the face or in the nasal cavity. Additionally, our model does not estimate the risk of disease. We might assume that exposure is proportional to risk, but additional models are needed to confirm this.

We compared the results of our model to values in the literature and found reasonable overlap. However, discrepancies between our model and empirical data collected from real life scenarios can be due to several factors, including variations in barn design, particle sampling methods, animal density, environmental conditions, and model assumptions. When comparing model output to sampling data collected from real environments, the ability of the model to capture important

variables within that environment will impact the ability of the model to make exposure predictions. As such, models should be modified and refined to capture relevant parameters of the real-world environment where plausible.

Our model is a simple representation of the true movement of particles in the swine barn. We make several simplifying assumptions in our model. For example, we assume that particles are uniformly distributed in each state. In reality, the distribution of particles is nonuniform, and some areas within 1 state may have a higher concentration of particles than others. We also assume that only 1 transition occurs in each time step, but it is possible that particles may undergo multiple transitions within a short period of time—even within 1 s.

Another simplifying assumption in our model concerns the representation of hand-to-face transfer pathways. We use the hand-to-facial membrane contact rate reported by Nicas and Best (2008)—which includes touches to the mouth, nose, and eyes—as an approximation for overall face-touching behavior. This approach reflects the possibility that contact with adjacent facial regions may indirectly contribute to contamination of the anterior nares through subsequent touches. However, we acknowledge that this is a substantial simplification of the complex and dynamic processes governing microbial transfer between the hands and the facial membranes.

Adding complexity to the model may more accurately describe how *S. aureus*-containing particles are distributed throughout the physical states within the barn. For example, we modeled a constant generation rate; however, the generation rate will change based on the activities of the hogs (eg feeding or sleeping) and the prevalence of *S. aureus* carriage among the hogs. Future iterations for these types of models could consider the inclusion of a variable generation rate. There are several additional factors that should be considered for future models. Environmental factors (eg season, temperature, and humidity), the size and type of facility (eg weaning vs finishing), and types of worker activities (eg administering medication, feeding, and power washing) can impact worker exposure. While important, these factors were beyond the scope of our model.

Subdividing the respiratory system compartment into additional compartments that include physiologically relevant regions of the respiratory system (eg anterior nares) may improve the utility of the model. Future models could incorporate physiological and exposure data like nose-to-mouth breathing ratios, particle hygroscopicity, and flow-dependent regional deposition efficiencies, to capture specifically where transferred or inhaled particles are likely to deposit. Such refinements extend beyond the scope of the current study, which aims to provide a broader, system-level representation of inhalation exposure and bacterial fate. A future direction of this work could include adding additional complexity to the model to improve model outputs.

Conclusions

We developed a 7-state Markov model to predict the distribution and movement of *S. aureus*-containing particles in a hypothetical swine barn. Workers may experience significant exposure to *S. aureus* during brief periods within a contaminated swine barn environment. In our model, exposure occurred primarily via inhalation, but hand to nose/mouth membrane contact also played a role in worker exposure. We simulated various workplace controls, including increased ventilation, surface cleaning, and the use of respiratory protection. We found that simulation of well-fitting N-95 respirators resulted in a decrease in worker exposure to the respiratory system greater than 90%. Simulation of increased ventilation and surface cleaning also showed important decreases in worker exposure but may have diminishing returns or be impractical in some barn scenarios. A combination of respiratory protection, increased cleaning, and ventilation changes may result in decreased worker exposure to *S. aureus* or other airborne particles and pathogens. Modeling can be used to estimate the exposure reduction and determine which combination of interventions are most effective and practical for a given exposure scenario.

Future research is needed to further validate our model by comparing model outputs to field measurements. Future iterations of this model should include additional parameters that account for variable generation rate of *S. aureus* containing particles, the size and type of hog facility, temperature and humidity, among other factors.

Supplementary material

Supplementary material is available at *Annals of Work Exposures and Health* online.

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Conflicts of interest

None declared.

Data availability

The data underlying this article will be shared on reasonable request to the corresponding author.

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