Effects of patient room layout on viral accruement on healthcare professionals' hands

Running title: Effect of patient room layout on viral exposures

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Code availability: Under a Creative Commons Zero v1.0 Universal license (CC-BY), code can be accessed at: https://github.com/awilson12/room-orientation_behavior

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Author contributions: AM Wilson led the code development, exposure model development, CFD/human behavior/surface contact model integration, and the manuscript writing. M-F King co-led CFD/human behavior/surface contact model integration, designed and conducted the CFD modeling, implementation, and interpretation; led the collection of human behavior data; contributed to the design of exposure scenarios and model integration methods; and contributed to manuscript writing. M López-García provided input on modeling methods and interpretation and contributed to manuscript writing. I Clifton provided medical perspective on interpretation of results. Jessica Proctor contributed to the collection of human behavior data. Kelly A. Reynolds provided input on microbial assumptions on the microbial transfer model. Catherine J. Noakes provided input on the model scenarios, manuscript development, and CFD methodology.

Abstract

Healthcare professionals (HCPs) are exposed to highly infectious viruses, such as norovirus, through multiple exposure routes. Understanding exposure mechanisms will inform exposure mitigation interventions. The study objective was to evaluate the influences of hospital patient room layout on differences in HCPs' predicted hand contamination from deposited norovirus particles. Computational fluid dynamics (CFD) simulations of a hospital patient room were investigated to find differences in spatial deposition patterns of bioaerosols for right-facing and left-facing bed layouts under different ventilation conditions. A microbial transfer model underpinned by observed mock care for three care types (intravenous therapy (IV) care, observational care, doctors' rounds) was applied to estimate HCP hand contamination. Viral accruement was contrasted between room orientation, care type and by assumptions about whether bioaerosol deposition was the same or variable by room orientation. Differences in sequences of surface contacts were observed for care type and room orientation. Simulated viral accruement differences between room types were influenced by mostly by differences in bioaerosol deposition and by behavior sequences when deposition patterns for the room orientations were similar. Differences between care types were likely driven by differences in hand-to-patient contact frequency, with doctors' rounds resulting in the greatest predicted viral accruement on hands.

Practical Implications

Understanding spatial deposition of bioaerosols containing norovirus and the influence of space on human behavior are crucial to increasing accuracy of predicting exposure

on hands and subsequent infection risks from self-inoculation behaviors. As demonstrated in the simulations in this work, the timing of glove donning/doffing and hand sanitizer use can have important implications for their ability to protect healthcare workers, especially considering hand-to-patient contacts. These models can inform the design of healthcare rooms and their ventilation as well as administrative controls, such as training that quantitatively illustrates concepts such as the importance of proper donning/doffing technique and the 5 moments for hand hygiene (which include after a patient contact) for lowering occupational microbial exposures.

Introduction

Healthcare professionals (HCPs) face a number of unique occupational hazards including exposures to infectious agents that may be present in the work environment due to infected patients, visitors, co-workers or contamination in the environment. In the U.S., more than 18 million workers are in the healthcare industry, and as this number continues to increase, HCPs have some of the highest rates of occupationally-related illness.[1] Worldwide, the prioritization of the health of HCPs has been emphasized due to increased healthcare demands in response to the COVID-19 pandemic.[2,3] By July 16, 2020, the U.S. Centers for Disease Control and Prevention (CDC) reported HCPs accounting for approximately 4% (100,570 out of 2.5 million) of U.S. COVID-19 cases.[4] However, the proportion of cases attributable to HCPs could be higher due to only having HCP status data for 22% of total reported cases.[4] In a study of 120,075 UK essential and non-essential workers, HCPs had a 7.43 (95% CI: 5.52, 10.00) times greater risk of severe COVID-29 relative to non-essential workers.[5] This risk ratio was greater than that of “social and educational workers” and of “other essential workers” relative to non-essential workers.[5]

Even outside of pandemic conditions, HCPs may be regularly exposed to other highly infectious agents, such as norovirus, a non-enveloped, single-stranded RNA enteric virus[6,7] that is generally spread via a fecal-oral pathway and can be transmitted via person-to-person, fomite, and airborne routes where aerosols are inhaled into the mouth.[8–10] Healthcare workers have been shown to be at high risk for norovirus infection during outbreaks in occupational settings.[11] Norovirus infection of HCPs can lead to not only health risks and loss of time at work but also risks to patients, especially

100 considering the potential for asymptomatic infection and high viral shedding.[11] Analysis
101 of the burden of norovirus in UK hospitals over a 3 year period suggests an annual
102 median of 290,000 bed-days were attributable to norovirus, displacing 57,800 other
103 patients and costing £107.6 million.[12] The same study analyzed reported data on the
104 impacts on HCPs, estimating that a median of 4,200 members of staff were absent
105 annual during norovirus outbreaks.

106 While norovirus has been shown to be transmitted via a fomite route, exposure
107 routes in the environment are often interconnected, where norovirus on fomites may
108 originate from bioaerosol deposition. Bioaerosols may originate from vomit or fecal
109 shedding events. In this way, exposures via air, surfaces, and direct person-to-person
110 contact (such as contacts between HCPs and patients) are a part of a larger system
111 contributing to exposure.

112 The potential for fomite contamination spread via hand-to-surface contacts,
113 especially for HCPs, has been a long-recognized mechanism of nosocomial disease
114 transmission.[13,14] The frequency and sequence of contacts with different surface
115 types,[15,16] for different care types during simulated vs. actual procedures,[16,17] and the
116 effect of these differences on microbial exposures have been explored.[18] However, it is
117 unknown how spatial differences between patient rooms may affect deposition patterns,
118 hand-to-surface behaviors of healthcare professionals, and subsequent exposures.
119 Understanding the influence of spatial differences on behavior and contamination
120 spread via the air-surface interface is important for advancing efforts for developing
121 environment-specific infection control protocols.

Study Objective

The objective of this study was to evaluate the influence of differences in HCP behavior and differences in airflow and subsequent bioaerosol deposition on surfaces for two single patient room layouts on norovirus accruement on HCP hands. A secondary objective was to demonstrate how a calibrated microbial transfer model can be utilized in exposure modeling. To meet these objectives, an integrated exposure model composed of a finite volume Navier Stokes computational fluid dynamics (CFD) model using Lagrangian particle tracking,[19] a human behavior model informed by real-world data,[17] and a viral transfer model calibrated for representation of transfer of enteric viruses[20] was developed.

Methods

Behavior Observations & Simulation of Behaviors

Hand-to-surface and hand hygiene events (glove donning/doffing and hand sanitizer use) were recorded for healthcare professionals in single patient rooms conducting mock IV-care, observational care, or doctors' rounds. A hand-to-surface contact event was defined as a single hand making physical contact with the object. Details regarding behavioral observations have been described by King et al.[16] Discrete Markov chains informed by observed behaviors were used to simulate sequences of hand-to-surface contacts, glove donning/doffing, or hand hygiene, as has been done in other healthcare worker behavior modeling.[21]

Six transitional probability matrices were created for right- and left-facing rooms for observational care, IV-drip care, and doctors' rounds using the function "markovchainFit" from the R statistical software package, *markovchain*. For each

probability matrix, behavior states included entrance into patient room, exit from patient room, use of alcohol gel, hand-to-equipment contact, hand-to-far patient surface contact, hand-to-near patient surface contact, hand-to-patient contact, doffing of gloves, donning of gloves, and hand-to-hygiene surface contact. Categories of surfaces matching these surface type designations for categorizing observed behaviors have been described previously by King et al. (2020).[17] Transitional probability matrices were altered so that exit from patient room was an absorbing state and the probability of an "entrance into patient room" event after the initial entrance was zero.

When generating behavior sequences, each sequence began with entrance into the patient room. New events would be generated until exit from the patient room occurred. To evaluate the effect of iteration choice on mean accruement on hands over the number of contacts, mean concentrations on the right hand were compared for 1,000; 5,000; and 10,000 iterations per room type (left- and right-facing) and care type (IV-care, observational care, doctors' rounds) combination. There were no notable differences in mean concentration on the hand over the number of contacts between results for the 5,000 and 10,000 iteration runs (Supplemental Materials Figures S1-S3). Therefore, 5,000 iterations were used.

Exposure Model Scenarios

In Scenario 1, the same concentrations of norovirus on surfaces were used regardless of patient bed orientation. Heterogeneity in concentrations between surfaces was informed by CFD simulations for the right-facing room orientation, and these results were then used for both the right- and left-facing rooms. Therefore, any differences between exposures by room orientation or procedure type could then be determined to

be behavior driven. In Scenario 2, CFD was used to predict the likely effect of patient bed orientation and room layout on heterogeneous deposition of bioaerosols on surfaces of different surface types (near patient vs. far patient surfaces, for example).

Changes in Norovirus Concentration on Hands

During the contact, k, with a surface, a change in norovirus concentration on either a gloved or ungloved hand was estimated as a function of transfer efficiency (λ, in hand-to-surface and surface-to-hand directions), fraction of the hand in contact with the surface (S_H), the concentration of norovirus on the surface ($C_{surface}$), and the concentration of norovirus on the hand before this contact ($C_{hand,k-1}$) (viral particles/cm^2) (eq 1), an adapted version of a model by Julian et al. (2009).[22] It was assumed HCP hands were uncontaminated at the start of care.

$$C_{hand,k} = C_{hand,k-1} - \lambda S_H (C_{hand,k-1} - C_{surface}) \quad (1)$$

While asymmetrical transfer efficiencies have been reported for certain organisms and it has been noted that assuming transfer efficiency is the same in both directions can result in substantial modeling errors,[23–25] MS2 and PhiX174, enteric viruses, have been shown to transfer similarly from hand-to-surface and surface-to-hand.[20,24]

Changes in concentration on surfaces were not tracked, as it was assumed that different portions of the same surface may be contacted and that deposited virus on that surface was spread homogeneously across the entire surface area. Inactivation of virus was not incorporated, as non-enveloped viruses can persist in the environment for

longer periods relative to the duration of episodes of care. For example, Fedorenko et al. (2020) demonstrated that MS2 and PhiX174, non-enveloped enteric viruses, in evaporated saliva microdroplets on a glass surface only reduced by approximately 1 $\log_{10}$ over a 14-hour period for a range of relative humidities.[26] By comparison, observed mock care episodes used to inform simulated behaviors in this study ranged from 0.6 to 11.7 minutes.[17]

Transfer Efficiency

Values for transfer efficiency (λ) were informed by a probability distribution calibrated to the model through previous work relevant for hand-to-surface contacts and enteric viral exchange between two contaminated surfaces.[20] It is acknowledged that these transfer efficiencies are not specific to the wide variety of surfaces anticipated in this exposure scenario. However, to our knowledge, other transfer efficiencies available in the literature[27,28] are limited in that they do not account for both surfaces being contaminated. While the first contact in the simulation assumes an uncontaminated hand contacts a surface, following contacts involve exchange of norovirus between surfaces and hands. Since this distribution was calibrated for hand-to-surface contacts, specifically, a different value was used for hand-to-patient contacts.

King et al. found that *Escherichia coli* transfer efficiencies for ungloved contacts (49%, 95% CI = 32-72%) were higher than for gloved contacts (30%, 95% CI=17-49%).[29] This has been demonstrated for other organisms as well.[23] Transfer efficiency for a gloved contact was therefore assumed to be 0.61 times smaller than the randomly sampled transfer efficiency from the posterior distribution of transfer efficiencies from Wilson et al. (2020).[20]

While microbial transfer between hand-to-hand contacts has been demonstrated, transfer efficiency values were not available for application in the microbial transfer model. Therefore, we assumed that transfer efficiency between the gloved or ungloved hand of a healthcare worker and the skin or clothing of a patient could span a wide range of transfer efficiencies. We assumed a uniform distribution with a minimum of 0.0001 and a maximum of 0.406, as these are minimum and maximum transfer efficiencies for MS2 reported by Lopez et al. (2013) that capture both nonporous and porous surfaces under low relative humidity conditions (15-32%).[27]

Fraction of Total Hand Surface Area of Contact

Different distributions to describe the fraction of the hand used per hand-to-surface contact (S_H) were used depending upon the contact type. For entrance and exit from the patient room, it was assumed that an open hand grip would be used. Therefore, a uniform distribution was randomly sampled with a minimum of 0.10 and a maximum of 0.21, the minimum and maximum S_H of left and right hands measured by AuYeung et al. (2008).[30] For patient contacts, it was assumed that a partial front palm without fingers up to a full front palm with fingers may be used.[30] Therefore, a uniform distribution with a minimum of 0.03 and a maximum of 0.25 was randomly sampled, where these minimum and maximum values were informed by AuYeung et al. (2008).[30] The fractions of the hand used for partial front palm without finger contact configurations are similar to those for front partial fingers,[30] so this range includes values that could represent this configuration as well. For all other contacts it was assumed that various grip and hand press contact types could be used, aside from hand immersion contacts described by AuYeung et al. (2008).[30] Therefore, a uniform distribution with a minimum

of 0.008 (the minimum of front partial fingers/ 5 fingers to represent a single fingertip contact) and a maximum of 0.25 (the maximum of full front palm with fingers) were used.[30]

Glove Donning/Doffing

It was assumed at the start of the simulation that HCPs were not wearing gloves. If a glove event occurred, this was not donning or doffing specific, but, rather, the current state was changed from either gloved to ungloved or from ungloved to gloved. This prevented instances such as a glove donning event following a later glove donning event without an intermediary doffing event or sequential glove doffing events without an intermediary donning event. For hand hygiene events, it was ensured that this was under ungloved conditions. If a hand hygiene event was selected when gloves were on the hands, a new event was randomly sampled until a non-hand-hygiene event was selected.

Hand Hygiene Efficacy

When a hand sanitizer event was selected and if gloves were not on, norovirus concentration on hands was reduced by an efficacy informed by Wilson et al. (2020), where efficacies with an alcohol-based hand sanitizer were measured with human norovirus for 30- and 60-second contact times.[31] Due to a low sample size for efficacies reported by Wilson et al. (2020), a uniform distribution was used with a minimum (0.15 $\log_{10}$) and a maximum (2.07 $\log_{10}$) informed by minimum and maximum reductions for the nonresidual alcohol-based hand sanitizer for both 30- and 60-second contact times.[31] If gloves were on for this hand hygiene moment, a new event was randomly

sampled to replace the hand sanitizer event under the assumption that hand sanitizer would not be applied with gloves on.

Infection Risk

Infection risks were estimated to evaluate how differences in viral concentration on hands would relate to risk differences between care types and room orientations. Due to lack of sequence data to include hand-to-face contacts within the simulation, a single hand-to-face contact was assumed at the end of the simulation to estimate an infection risk based on the concentration on the hands at the end of the episode of care. Single hand-to-face contacts have been used in other exposure modeling studies to compare risks between different scenarios.[32] However, it is acknowledged that these risks do not reflect those of reality, as they do not account for the timing and frequency of expected hand-to-face contacts and are only using these risks for comparison purposes.

To estimate an infection risk, a viral dose was first estimated by multiplying a transfer efficiency, hand surface area, and fraction of the total hand surface area to be used by the concentration on the right or left hand, where either hand had a 50/50 chance of being chosen based on reported lack of differences in contact sequences for right and left hands in a micro-activity study.[33] If no gloves were on, a transfer efficiency was randomly sampled from a normal distribution informed by Rusin et al.[28] and left- and right-truncated at 0 and 1, respectively. If gloves were worn, these transfer efficiencies were reduced, consistent with how transfer efficiencies for hand-to-fomite contacts were handled, described above. Total hand surface area for a single hand was randomly sampled from a uniform distribution (min=445 cm^2, max=535 cm^2) informed by

Beamer et al. (2015)[34] and the U.S. EPA's Exposure Factors Handbook (2011).[35] It was assumed a single fingertip or a fraction of the palm would be used for the contact, and this fraction of total hand surface area that this represents was randomly sampled from a uniform distribution (min=0.006, max=0.012). The minimum and maximum fractions of the hand that all fingertips represent reported by AuYeung et al.[30] for adult hands were divided by 5 to inform the distribution.

To relate these doses to infection risk, an approximate beta-Poisson curve was used, where α =0.104 and β =32.3 (eq 2)[36]:

$$P(infection) = 1 - \left(1 + \frac{dose}{\beta}\right)^{-\alpha} \quad (2)$$

Although this curve is being used to estimate risks for comparison purposes, it is acknowledged that multiple dose-response curves for norovirus exist and should be considered when predicting risks for risk assessments.[36]

CFD Methodology

The CFD methodology by King et al. (2013)[19] was closely followed. A steady state simulation assuming isothermal conditions and natural ventilation from three windows open 10 cm with an air exchange rate of 6 was modeled using Fluent v.19.4 (ANSYS, Canonsburg, PA, USA). The door (pressure outlet) had a surface area of 1.9 m^2 while the large window (velocity inlet) had a surface area of 0.18 m^2 and the small windows (velocity inlets) each had a surface area of 0.08 m^2. A velocity mesh sensitivity analysis was conducted with three sequentially size-halved cell sizes. A hex-dominant mesh with 4 cm element size and 2 cm cells was used for the bulk volume and close to surfaces, respectively. A k-omega transition shear stress transport turbulence model with standard omega wall function formulation was used. A point near the patient mouth

was set as the inert water particle injection site, where particles were injected at a velocity of 1.9 m/s, in part informed by Tang et al. (2013).[37] This is based on breathing due to a lack of data on velocity and aerosols associated with vomiting events, but is considered as representative of a small aerosol source from a person. We assume that large droplets and splashes would be cleaned immediately post event, so are concerned about the surface contamination that may occur sometime later following the event. Addressing aerosol emissions due to breathing also increases the generalizability of this work, providing insights into how emissions of respiratory viruses via breathing may deposit on surfaces and contribute to fomite-mediated exposure routes as well. However, experimental data used to calibrate the microbial transfer model used in this integrated model more appropriately represent enteric viruses, such as norovirus. The particle size range (0.14 to 8.13 μm) was informed by Alsved et al. (2020).[38] This range reflects a range of aerosols in which Alsved et al. (2020) detected norovirus.[38] The particle diameter remained constant throughout the simulation, assuming that all particles were their fully evaporated size. Deposition of particles on surfaces were then tracked using a Lagrangian particle methodology with discrete random walk and trap boundary condition on surfaces, including the walls.

The fraction of injected particles that landed on specific surface types were related to expected viral concentrations on surfaces by estimating a number of viral particles to be released by a patient, informed by Alsved et al. (2020) and the U.S. Environmental Protection Agency's Exposure Factors Handbook (2011).[35,38] The fraction of virus expected to land on each respective surface was then calculated, divided by the total surface area to obtain viral particles/cm^2. Surface areas of surfaces

are listed in Table S1. Sizes of particles were not tracked upon deposition, meaning that the fraction of deposited particles does not account for differences in particle size or virus concentrations across ranges of particle sizes. However, the distribution of particle sizes in this study was low, with most of the distribution of sizes being below 5 μm, meaning we would not expect as much error due to assuming homogeneous deposition of particle sizes across surfaces as if we considered a range of larger aerosol sizes in which larger aerosols may settle considerably faster than fine aerosols <5 μm.

For the right-facing room orientation, estimated particle deposition on the desk was used to inform the concentration anticipated on far patient and hygiene area surfaces. For the left-facing room orientation, surface concentrations on far patient and hygiene area surfaces were informed by the concentration on the walls. For the right-facing room orientation, near patient and equipment surface concentrations were informed by estimated particles deposited on the side table, bed, and chair, while for left-facing rooms, near patient and equipment surface concentrations were also informed by deposition on the desk in addition to these other surfaces.

For both room orientations, particles deposited on the patient were used to inform concentrations on the patient. The “in” and “out” event, entrance and exit from the patient room, respectively, involved contact with the door handle. In this case, it was assumed that concentrations on the door handle were zero since the focus of this study was on fomite-mediated exposures as a result of particle deposition alone.

Exposure Model Sensitivity Analysis

Spearman correlation coefficients were calculated to quantify monotonic relationships between model inputs and the mean and maximum concentrations on

hands. Since some parameters, such as transfer efficiency, surface concentration, and the fraction of the hand used for a contact, varied by contact, the mean value of these parameters per iteration was used. Spearman correlation coefficients were also calculated to investigate relationships between input parameters, since some inputs were related, where a greater amount of patient contacts could relate to a greater mean transfer efficiency since larger transfer efficiencies were used for hand-to-patient contacts than for hand-to-surface contacts, for example. Since some relationships between model inputs and mean or maximum viral concentration on hands may not be monotonic, scatter plots were also visually inspected.

Particle Deposition Sensitivity Analysis

In addition to the baseline model with a ventilation rate of 6 ACH and the windows acting a velocity inlet and the door acting as a pressure outlet, particle deposition patterns for a number of other scenarios were explored: the door acting as a velocity inlet and windows acting as a pressure outlet, the small windows acting as velocity inlets and the large window acting as a pressure outlet, and exploring 2.5 ACH and 10 ACH in addition to 6 ACH. This reflects guidance for UK hospitals which recommends 6 ACH for bedrooms and 10 ACH for treatment rooms and isolation rooms,[39] and also recognizes that many hospitals, especially those that are older or naturally ventilated, have air change rates below the current standards. Mean viral concentrations on hands for left- and right-facing rooms were then compared for these 9 scenarios (3 ACHs x 3 velocity inlet, pressure outlet scenarios).

Results

Deposition

The predicted deposition of particles on surfaces between the left- and right-facing rooms in the primary model (6 ACH, windows as velocity inlets, door as pressure outlet) were notably different (Figure 1). The left-facing room resulted in 51.18% of emitted particles depositing on the patient, while the right-facing room only resulted in 16.82% (Figure 1). High passage of particles through the door surfaces was expected, such as for the right-facing room (79.32% of particles passing through the door) as this was the airflow outlet and windows were velocity inlets. While not within the scope of this exposure assessment, this would suggest that these particles would be those that would be extracted by ventilation in the corridor or potentially to another patients room. Viewing the particle tracks, it can be seen that in the right-facing room, the incoming air from the open windows may be directing air from the injection point near the patient mouth out the door, whereas in the left-facing room, particles appear to remain in the room longer, leaving more opportunities for deposition on the patient, floor and surrounding surfaces (Figures 1 and 2).

Slightly more deposition occurred on the floor for the left-facing room (1.44%) than for the right-facing room (0.22%). While no interactions with the floor were modeled in this study, this may have infection control implications beyond the focus of this work, as pathogens have been detected on floors,[40] and floors make contact with some fomites and can participate in wider facility contamination via shoe movement and portable equipment.[41]

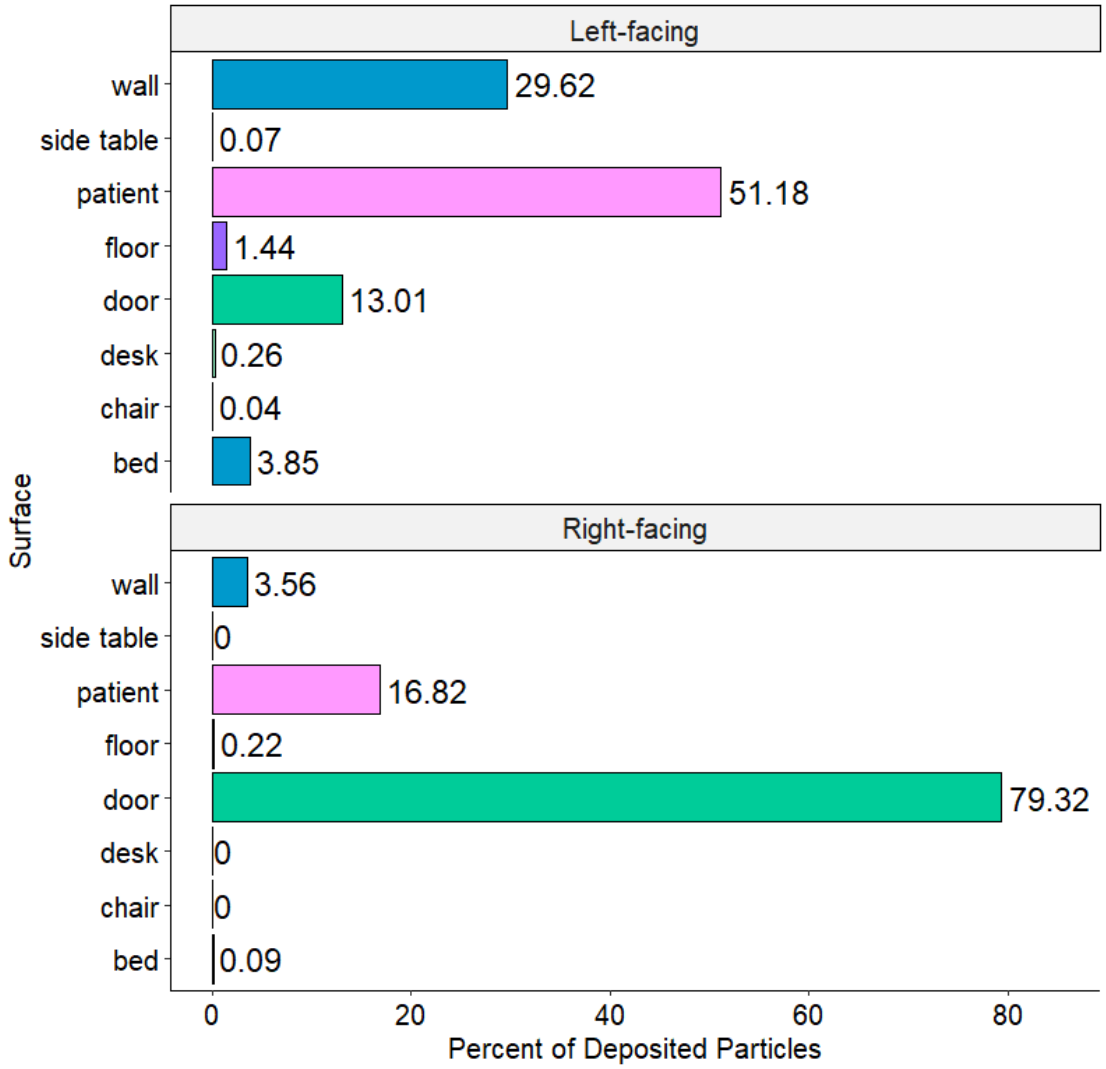
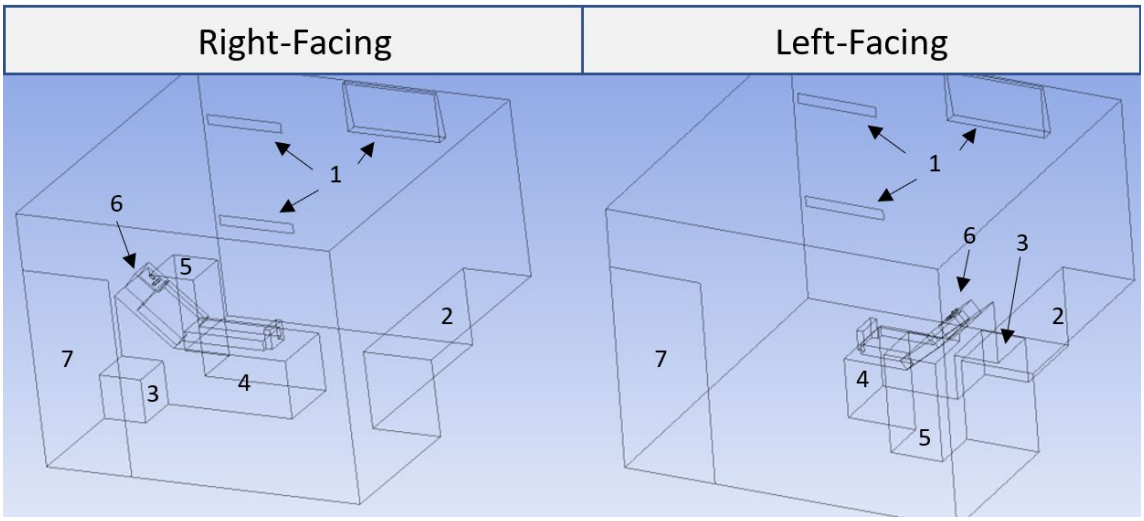


Figure 1. Deposition and surface areas of surfaces in the CFD modeling for left- and right-facing rooms in the baseline scenario at 6 ACH and windows as velocity inlets and the door as a pressure outlet

A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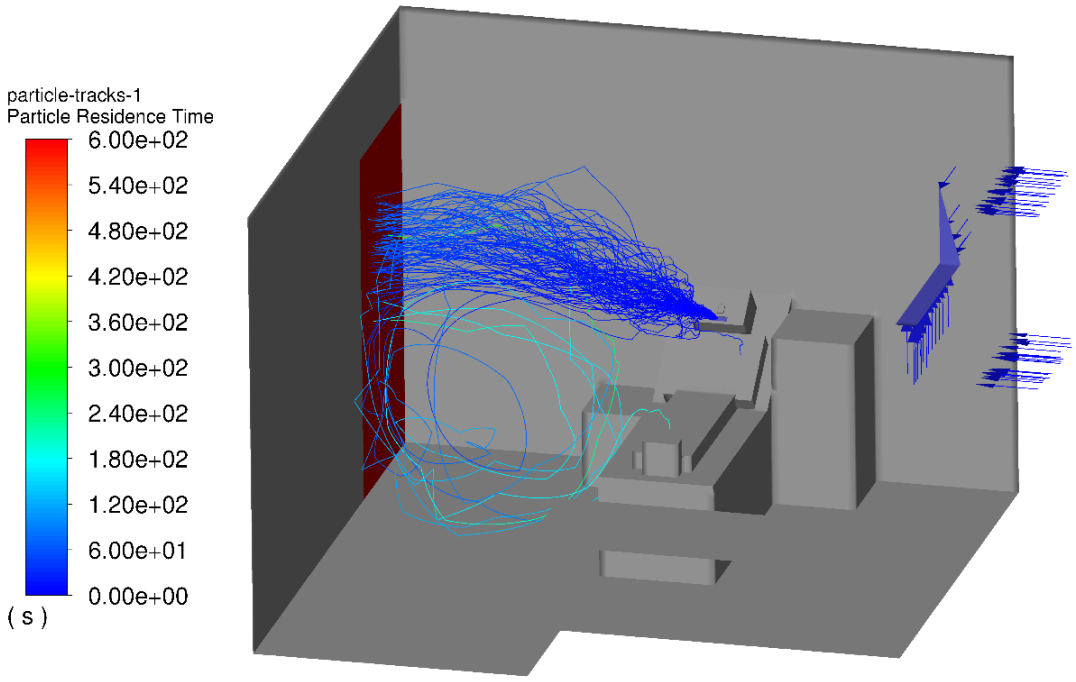
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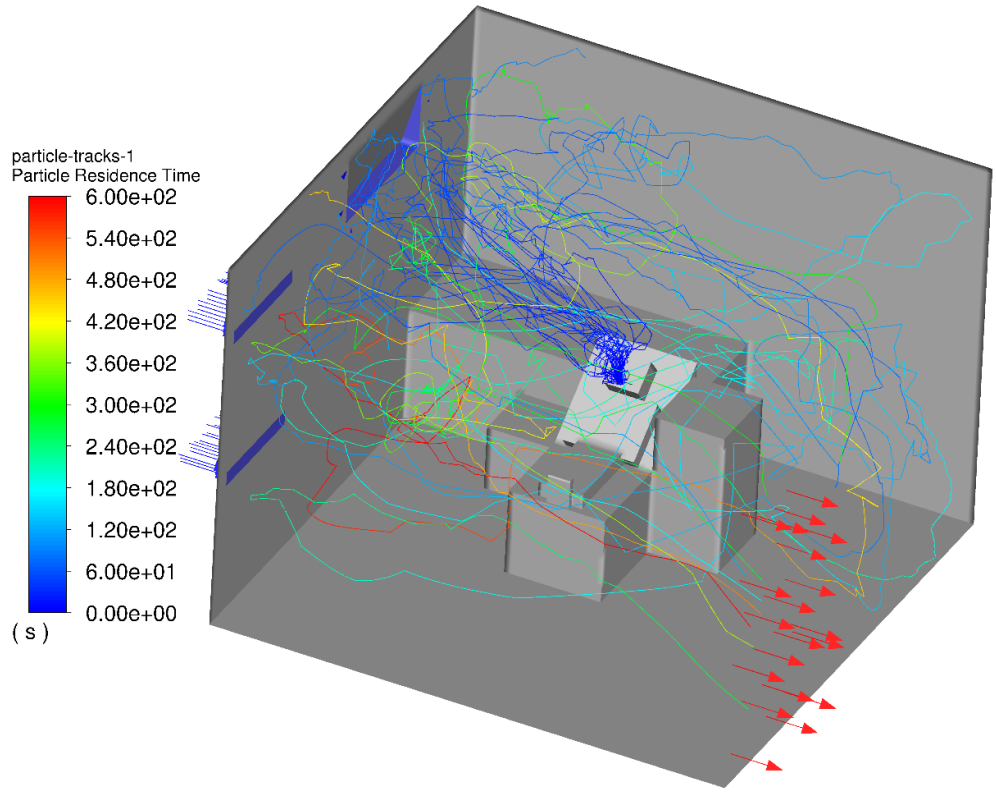

Figure 2. Right- and left-facing room A) Geometry (1=windows, 2=desk, 3=chair, 4=bed, 5=side table, 6=patient, 7=door) and particle tracking illustrations colored by residence time for the B) right-facing room and C) left-facing room for the baseline scenario at 6 ACH and windows as velocity inlets and the door as a pressure outlet

Simulated Behaviors

The transitional probability matrices for doctors' rounds, regardless of room orientation, demonstrated a high probability of repetitive contacts with the patient (Figure 3), where the left- and right-facing orientation probabilities of the next event being a hand-to-patient contact given a current hand-to-patient contact were 0.68 and 0.81, respectively. This is also reflected in the proportions of events that make up all events in simulations for each room orientation and care type, where patient contacts

made up 32% and 42% for contacts in doctors' rounds in left- and right-facing rooms, respectively (Figure 4).

When investigating how often glove donning or doffing events were resampled (which occurred if glove donning occurred when gloves were already donned or of glove doffing events occurred when gloves were not already donned), the frequency of these occurrences depended upon care type and room orientation. For left-facing rooms, this happened in 15.7% of IV care, 2.8% of doctors' rounds, and 5.1% of observational care episodes that were simulated. For right-facing rooms, this happened in 3.6% of IV care, 3.1% of doctors' rounds, and 8.1% of observational care episodes that were simulated.

All transitional probabilities involved relatively high probabilities of a transition from entrance into the patient room to contact with a far-patient surface (Figure 3), ranging from 0.92 to 1, and this contact type accounted for similar proportions of total events among all care type and room orientation combinations (Figure 4). Contact with the door was considered a far patient contact in informing transitional probability matrices, so this may explain the high probability of a far patient contact following entrance into the room. Contacts with equipment comprised a large proportion of events for left- and right-facing observational care, where this contact type accounted for 57% and 44% of events in left- and right-facing rooms, respectively (Figure 4). This is consistent with many high probability transitions from a given surface or event to a hand-to-equipment contact for observational care, especially for left-facing rooms (Figure 3).

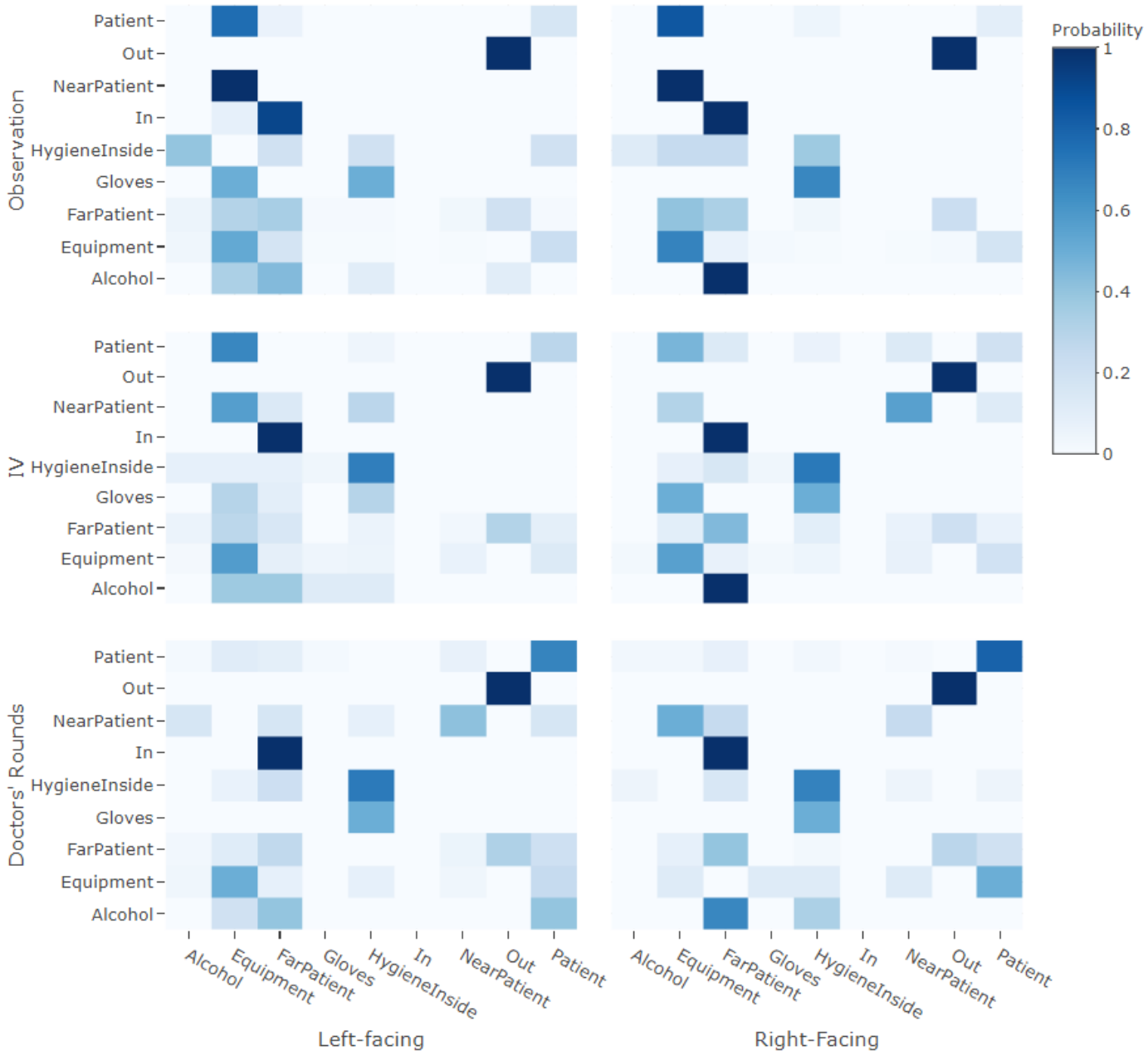

Figure 3. Heatmap of transitional probability matrices for two room orientations (left- and right-facing) and three care types (IV-care, observational care, and doctors' rounds)*

*These matrices represent transition from row-to-column, where probabilities in rows add up to 1.

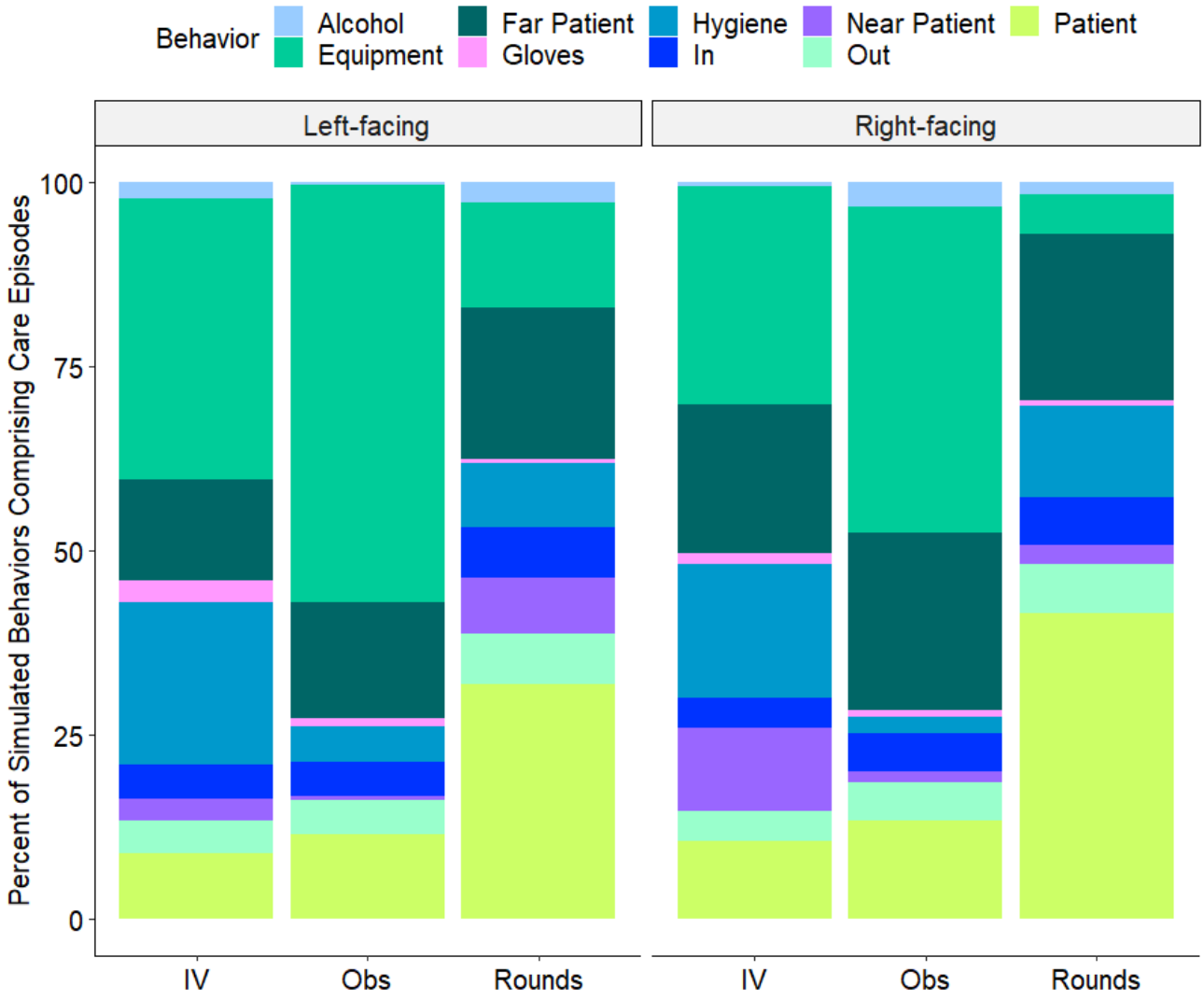

Figure 4. Proportion of simulated behaviors comprising each contact event type per care type (IV-care, observational care, and doctors' rounds) and room orientation (left- and right-facing)

Viral Accruement

When differences in viral deposition on surfaces and differences in behaviors due to room orientation were accounted for, notable differences in viral accruement on hands between the two room orientations were seen for doctors' rounds and less so for IV-care and observational care (Figure 5). For doctors' rounds, left-facing rooms

457 resulted in more viral accruement on hands overall than right-facing rooms, where
458 accruement for IV-care and observational care were more similar for the right-facing
459 than for left-facing room (Figure 5).

460 For left-facing rooms, these differences translated to doctors' rounds resulting in
461 240% and 43% greater mean infection risks relative to IV-care and observational care,
462 respectively. Mean infection risks for the three care types were 3.0×10^{-7} (doctors'
463 rounds), 8.8×10^{-8} (IV-care), and 2.1×10^{-7} (observational care). For right-facing rooms,
464 these differences translated to 122% and 186% greater mean infection risks for doctors'
465 rounds relative to IV-care and observational care, respectively. Mean infection risks for
466 the three care types were 1.4×10^{-7} (doctors' rounds), 6.3×10^{-8} (IV-care), and $4.9 \times 10^{-}$
467 ^{8} (observational care).

468 When comparing infection risks between room orientations, mean infection risk
469 for doctors' rounds in left-facing rooms was 114% greater relative to right-facing rooms.
470 IV-care in left-facing rooms resulted in a mean infection risk that was 40% greater
471 relative to right-facing rooms. For observational care, left-facing rooms resulted in a
472 mean infection risk that was 329% greater relative to right-facing rooms.

473 It should be noted that these are infection risks for only one hand-to-face contact
474 directly after an episode of care. In some simulated cases, a hand-to-face contact was
475 made with a freshly donned glove, resulting in a zero dose. More data are needed to
476 accurately capture infection risks due to self-inoculation behaviors and the effects of
477 personal protective equipment (PPE) on these behaviors.

478 When deposition differences were removed so that only behavioral differences
479 between room orientations were accounted for, differences in accruement on hands

between left- and right-facing room layouts were diminished but with slightly more accruement on the hands for the right-facing orientation than for the left-facing orientation (Figure 5). In both right- and left-facing rooms regardless of deposition differences, the least amount of viral accruement occurred for IV care episodes, while doctors' rounds resulted in the most accruement (Figure 5). This is consistent with doctors' rounds resulting in the greatest mean infection risks, described above. In addition to increased risks for HCPs, greater viral accruement on hands could lead to higher risks to patients as well, as doctors' rounds have larger proportions of patient contacts compared to other care types (Figure 4). The number of iterations used to inform the mean concentration on hands per contact number can be seen in Figure S4.

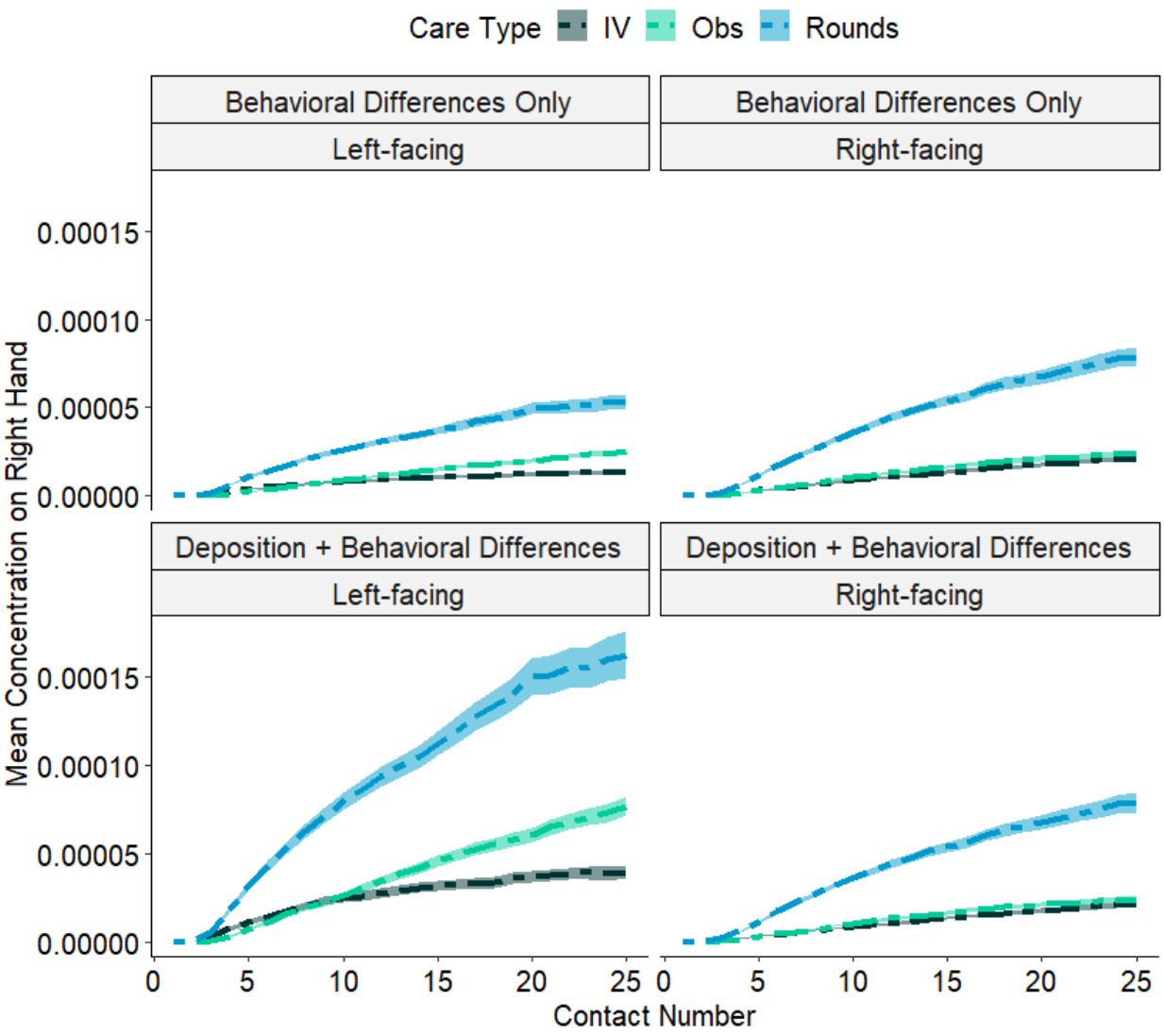

Figure 5. Comparison of accruement on hands over the number of contacts*

*Mean ± SD of virus concentration (viral particles/cm^2) on a single hand, compared by care type (IV-care, observational care, doctors' rounds), room orientation (left-facing, right-facing) and assumptions regarding differences in viral concentrations on surfaces and behaviors based on room orientation. Deposition + Behavioral plots demonstrate the effects of differences in surface concentrations influenced by deposition differences between the left- and right-facing rooms along with differences in transitional probability matrices for simulating sequences of behaviors for the two room orientations. "Behavioral differences only" plots demonstrate the effects of deposition patterns for the right-facing room used for both right- and left-facing rooms so that differences in accruement are only representative of differences in transitional probability matrices for the care types by room orientation. Concentrations here represent average concentrations estimated to be on hands at any given simulated moment, explaining

why some concentrations (viral particles/cm^2) multiplied by the cm^2 of a hand would be less than 1, indicating a less than 100% chance of a viral particle being present on the hand.

Viral Loss from Hands

Because the microbial transfer model in this study assumes transfer of virus in both directions, loss of virus from the hands occurs depending upon a concentration gradient between the hand (gloved or ungloved) and the surface in contact (eq 1). Use of hand sanitizer is one mechanism by which accruement on hands can be lost (Figure 6). This is especially advantageous following contacts that resulted in fast viral accruement, such as contacts with a patient, demonstrated in a plot of viral accruement for one model iteration in Figure 6.

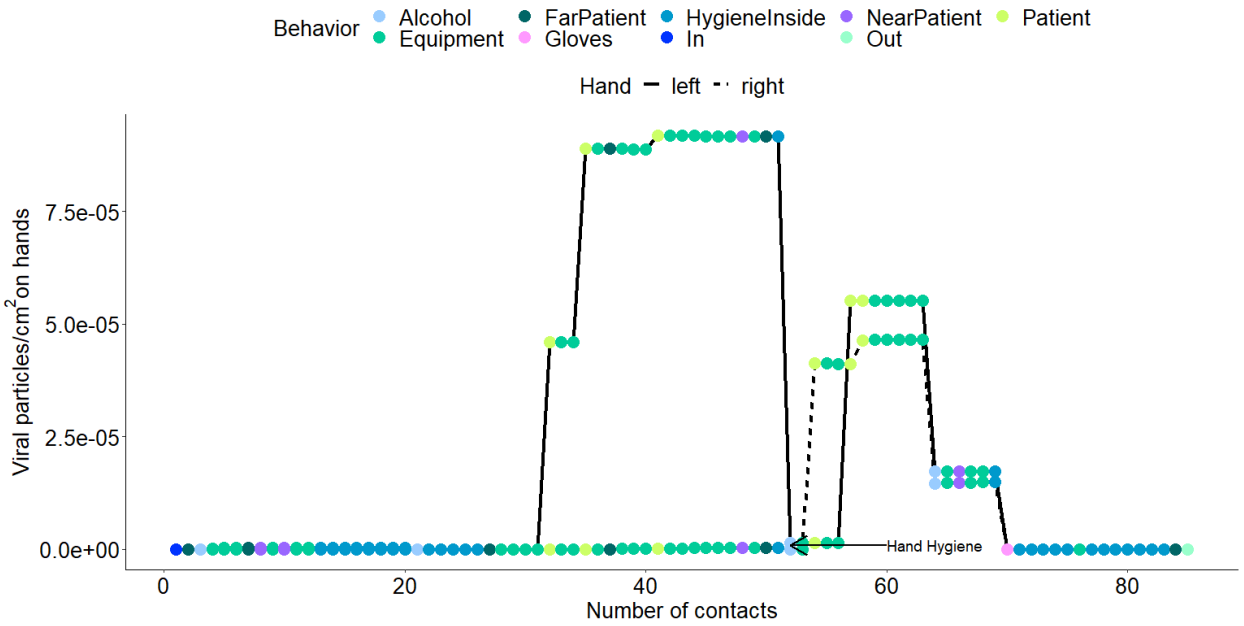

Figure 6. Example of large increases in accruement due to hand-to-patient contacts and decreases due to use of alcohol-based hand sanitizer

While the use of gloves can be an effective means for lowering potential exposures, glove events did not account for most of the losses from hands that occurred over the contacts (Figure 7A), in part potentially due to the low frequency of glove events (Figure 4). More frequent events, such as contacts with equipment surfaces, especially during observational care, contributed to more instances of viral loss from the hands than most of the glove or even alcohol hand sanitizer events (Figure 7A). However, this is related to the number of iterations in which events at specific moments in the behavior sequence resulted in loss. It does not account for the magnitude of loss. When observing the $\log_{10}$ of the mean change in concentrations during these moments of loss, alcohol hand sanitizer and glove events result in larger magnitudes of loss than hand-to-surface events (Figure 7B), even if they contribute to loss of viral accruement less frequently (Figure 7A). The magnitude of viral loss attributable to the alcohol hand sanitizer and glove donning/doffing events is consistent regardless of room orientation or care type, emphasizing their importance and relevance as infection control strategies.

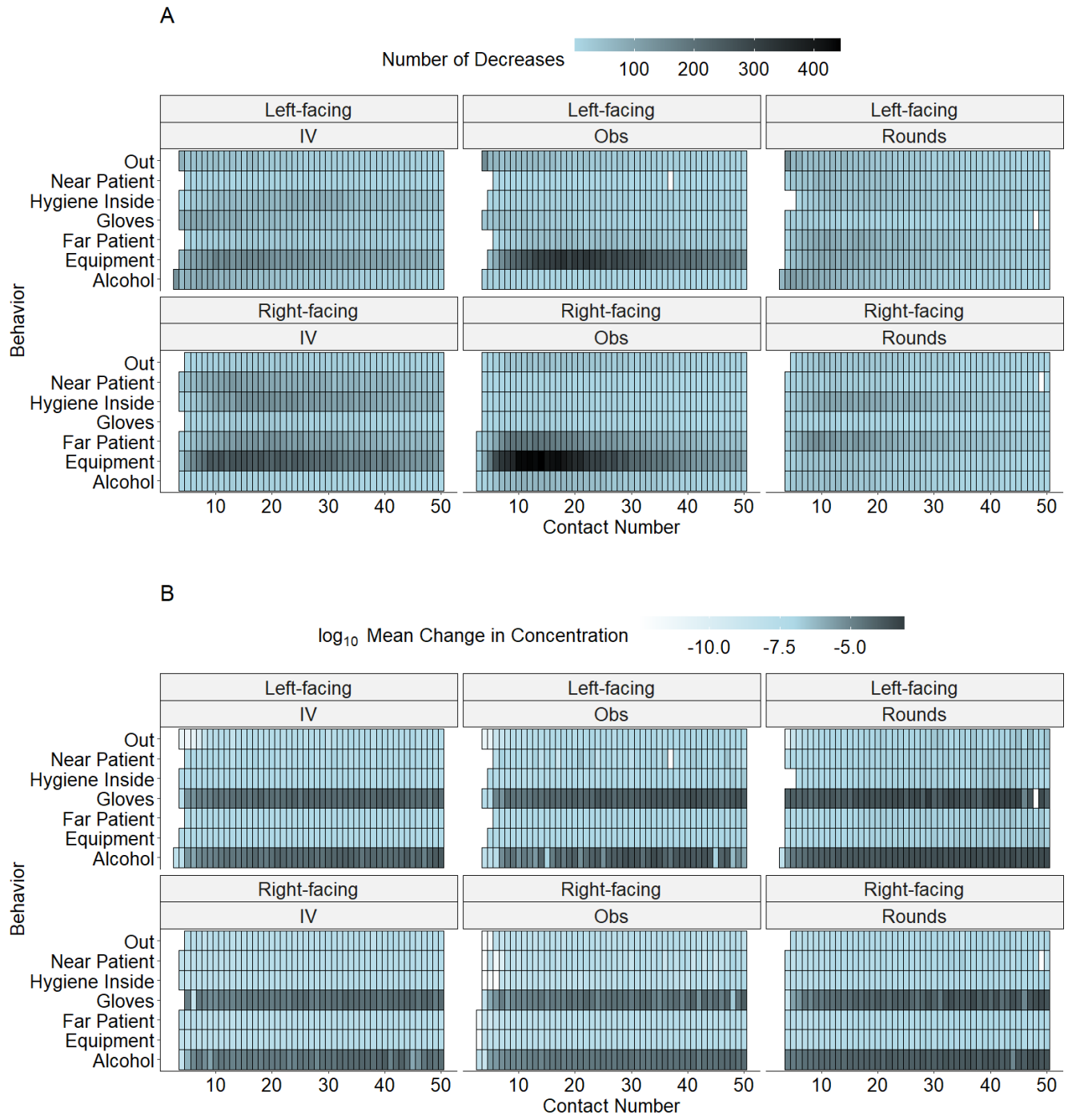

Figure 7. Evaluation of moments of viral loss through **A.)** Number of simulations in which an event resulted in a loss of concentration on hands and **B.)** Log_{10} mean change in concentration for moments of loss associated with these events*

*These results reflect simulations in which both bioaerosol deposition and human behaviors differences for the two room orientations (left- and right-facing)

The ten greatest viral losses occurred during doctors' rounds simulations. The behavior sequences for these simulations were characterized by viral accruement over multiple hand-to-patient contacts followed by alcohol hand sanitizer use or a change in glove status (donning or doffing) (Figure 8).

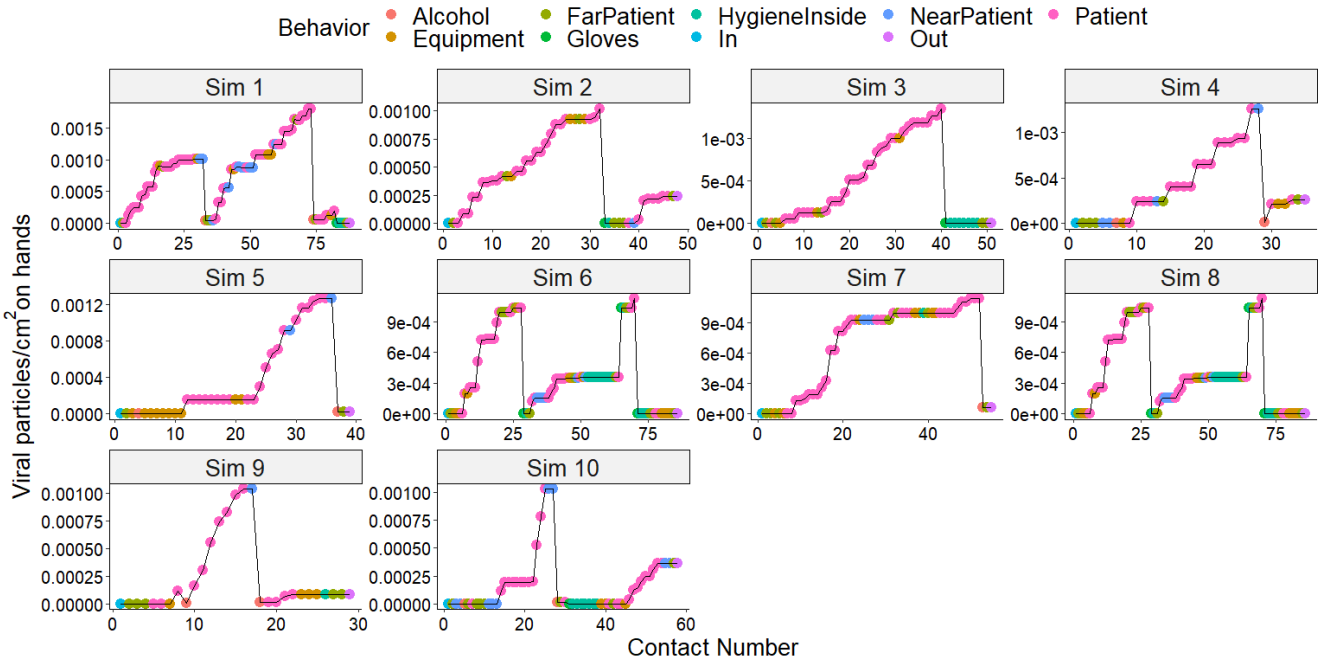

Figure 8. Simulations with the greatest instances of viral loss*

*Viral particles/cm^2 on hands shows the combined concentrations on the right and left hands over the number of contacts in the simulation. These results reflect simulations in which both bioaerosol deposition and human behavior differences for the two room orientations (left- and right-facing)

A greater number of hand sanitizer events per total number of events in a care episode was associated with smaller mean concentrations on the hands, where the $\log_{10}$ concentration had a negative linear relationship with $\log_{10}$ percent of events represented by hand sanitizer events, where at least one hand sanitizer event and one

hand-to-patient contact occurred (Figure 9). This negative relationship was consistent across room orientations and care types (Figure 9).

While a greater number of hand sanitizer events per total events was associated with decreases in mean concentration on hands, the effect of the number of hand sanitizer events alone was less clear due to instances in which there was a high number of hand sanitizer events for a care episode longer than other episodes with more opportunities for viral accruement on hands. Similarly, some care episodes contained no hand hygiene moments but were composed of only 3 contact events, resulting in smaller mean concentrations on the hands relative to simulations in which there were more hand sanitizer events but also more surface contact events. This emphasizes the importance of considering hand hygiene in the form of hygiene consistency over the duration of an entire care episode as opposed to evaluating hand hygiene merely based on frequency.

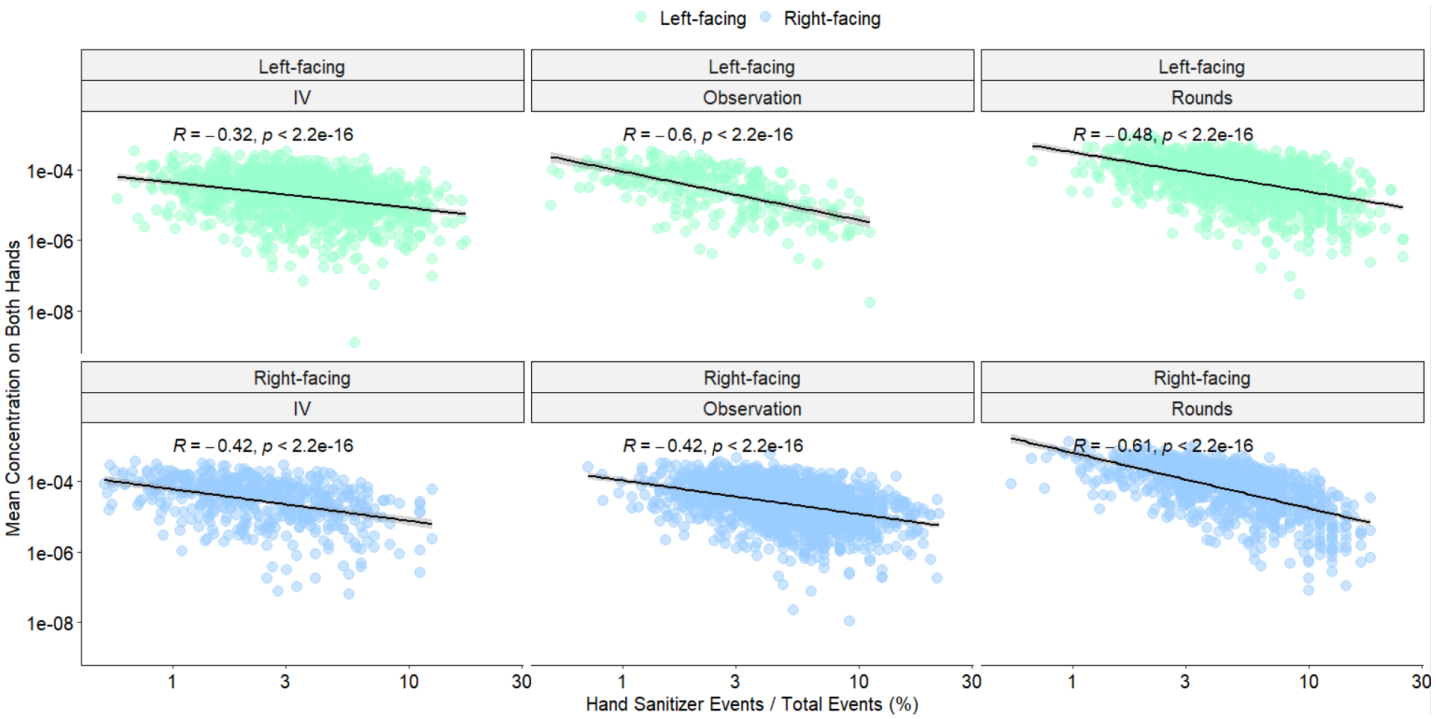

Figure 9. Mean concentration on both hands (viral particles/cm^2) vs. the percent of total events that are hand sanitizer events for scenarios*

*Spearman correlation coefficients and p values calculated for simulations in which at least 1 hand hygiene event and at least 1 hand-to-patient contact occurred are reported per care type and room orientation combination. Concentrations here represent average concentrations estimated to be on hands at any given simulated moment, explaining why some concentrations (viral particles/cm^2) multiplied by the cm^2 of a hand would be less than 1, indicating a less than 100% chance of a viral particle being present on the hand.

Exposure Model Sensitivity Analysis

Mean and maximum concentrations on hands had strong relationships with transfer efficiency, with Spearman correlation coefficients ranging from 0.77-0.82, depending up on the care type and room orientation (Figures S5-S10). While transfer efficiency is traditionally not an influential parameter in similar models, it had a strong relationship with patient contacts (ρ=0.84 for IV-care in left-facing rooms, for example, Figure S5) due to assumed greater transfer efficiencies with patient skin as opposed to with surfaces. For all room orientations and care types with the primary CFD model, the number of patient contacts had the second strongest relationship with mean and maximum concentrations on hands, with surface concentrations being the strongest (Figures S5-S10). When observing distributions of $\log_{10}$ mean concentrations on hands, notable differences in magnitude and shape of distributions can be seen for simulations in which at least 1 patient contact was made versus none (Figure S11). Scatter plots can be seen in supplementary materials, Figures S12-S22.

Particle Deposition Sensitivity Analysis

Notable differences were seen in particle deposition patterns (Figures S23-S25) and subsequent accruement on hands between left- and right-facing rooms between the

ACH and the inlet/outlet scenarios (Figures S26-S28). Regardless of ACH, the left-facing orientation resulted in more particle deposition on the patient than for the right-facing orientation when the windows were the velocity inlets and the door was a pressure outlet and when the windows were velocity inlets and pressure outlets (Figures S23-S25). However, when the windows were the pressure outlets and the door was a velocity inlet, the fractions of particles deposited on the patient were more similar for left- and right-facing rooms (Figures S23-25). When deposition on the patient was more similar, such as for 6 ACH and the window as the pressure outlet and door as the velocity inlet (Figure S26C), greater viral accruement was observed for doctors' rounds for the right-facing rooms as opposed to left-facing. This was also observed when the effect of differences in bioaerosol deposition were removed, such as in the primary model (6 ACH, door as pressure outlet, windows as velocity inlets), where doctors' rounds for the right-facing room resulted in slightly more viral accruement than for the left-facing rooms when the same bioaerosol deposition pattern was used (Figure 5).

In some cases, the ACH did appear to affect which room orientation resulted in greater viral accruement on hands for doctors' rounds for the same inlet and outlet conditions. For example, assuming 2.5 or 6 ACH and the windows acting as pressure outlets and velocity inlets resulted in greater viral accruement on hands for left-facing rooms (Figures S26B and S28B) while for 10 ACH the viral accruement was slightly larger for right-facing rooms (Figure S27B). Despite differences between left- and right-facing orientations and effects of ACH, doctors' rounds remained the care type that resulted in the greatest viral accruement regardless of ACH or inlet/outlet conditions. The effect of having the mouth as another inlet in addition to having an injection point

near the patient mouth was also explored for one of the ventilation scenarios, and it did impact the fraction of particles exiting the door and depositing on the wall but did not greatly influence the fraction of deposition on the patient surface (data not shown). Since the fraction of deposition on patients appears to be driving differences in between room orientations, it is anticipated that treating the mouth as an additional inlet would not have greatly influenced the exposure estimation results. However, variability in emission characteristics should be further explored in future work.

Discussion

Key Findings and Generalizability

This study illustrates that the location of the patient and furniture, alone, could have effects on both the patterns of bioaerosol deposition on surfaces and also on healthcare workers' micro-activity (second-by-second) behaviors. Room ventilation (ACH and flow direction) can affect the magnitudes of the differences in exposures between room layouts. Aside from differences in bioaerosol deposition, human behavioral differences between room layouts were also observed, possibly influenced by training. For example, in UK hospitals, doctors are trained to approach the patient from the right. In the right-facing room orientation, getting to the right side of the patient may take more maneuvering around furniture than in a left-facing room orientation (Figure 2). Greater travel time to the patient may result in more opportunities for hand-to-surface or hand-to-patient contacts. The deposition pattern will be determined by the particular ventilation flow in a room, and the results in this study are specific to the room scenarios modeled. However it serves to illustrate that a simple change in the location of furnishing can change the likely pattern of deposition when the ventilation conditions

653 are kept the same, with implications for pathogen accruement on hands (Figures S23-
654 S28). Further exploration of other ventilation conditions, room orientations, and
655 behaviors for other care types can further elucidate the influence of room orientations
656 on exposures and subsequent risks.

657 Behavioral differences and some differences in bioaerosol deposition between
658 room orientations were seen (Figures 1, 3 and 4), and there were differences in mean
659 infection risks due to single hand-to-face contacts at the end of care episodes. Infection
660 risk estimates should be further explored with scenario-specific hand-to-face contact
661 frequencies as opposed to assuming a single hand-to-face contact. Additionally, the use
662 of both hands for a hand-to-fomite contact as opposed to use of a single hand and use
663 of the right vs. the left hand was not explored. It is possible that use of the right vs. the
664 left hand or the use of both hands vs. a single hand could be procedure-specific. Further
665 development of this work will involve more granularity regarding hand dominance and
666 both vs. single hand touches in addition to using observations containing self-
667 inoculation moments during or after care episodes to estimate infection risks.

668 A notable difference in behaviors between care types was contacts with patients,
669 where doctors' rounds involved more patient contacts, regardless of room orientation
670 (Figure 4). Differences in the number of particles deposited on patients appeared to
671 drive differences in viral accruement on hands for left- and right-facing room orientations
672 (Figures 5, S23-S28). Because contacts with the patient were frequent and the patient
673 generally had greater fractions of bioaerosol deposition than other surface types, patient
674 contacts likely drove differences in viral accruement between care types over the course
675 of multiple contacts, where greater viral accruement was seen for doctors' rounds

(Figure 5). This rationale is also supported by a strong monotonic relationship between number of patient contacts and mean viral concentration on hands ($\rho = 0.88$ for doctors' rounds in left-facing rooms, Figure S9).

These hand-to-patient contacts were not only frequent (Figure 4) but also repetitive for doctors' rounds (Figure 2). This is an important distinction, because repetitive contacts created opportunities for fast viral accruement relative to hand-to-patient contacts spread out over the course of an episode of care. This phenomenon can be seen in simulations in which greatest viral losses due to alcohol hand sanitizer use or glove donning/doffing occurred (Figures 7B and Figure 8), despite the fact that other events, such as contacts with equipment, more frequently contributed to viral losses from hands (Figure 7A).

Overall, an increased rate of hand sanitizer events was related to a decrease in mean viral concentrations on hands for all care types and room orientations (Figure 9). However, there were instances where hand sanitizer was applied after contacts with surfaces that did not result in large viral accruement, where the sanitizer did less to lower exposure. This can be seen in Figure 6 where an early alcohol hand sanitizer behavior occurred before several hand-to-patient contacts that resulted in large increases in viral concentration on hands, later decreased by another hand sanitizer event (Figure 6). The timing of glove doffing is also important, where, when gloves are worn, viral accruement via repetitive hand-to-patient contacts can be removed when gloves are doffed, therefore lowering opportunities for large doses via self-inoculation. However, after a glove doffing event, if more hand-to-patient contacts are made, potential risks of self-inoculation are increased. It is possible a healthcare worker may

more readily make a hand-to-face contact based on a perception of lower contamination on hands and lower risk. The effects of personal protective equipment (PPE) use and sequences of high-risk contacts on self-inoculation frequency should be further explored.

Limitations

While the CFD model in this work was not experimentally validated, natural ventilation models are notoriously difficult to validate, and previous versions of single patient hospital room CFD models that informed this model have been validated.[19] The model presented in the paper is designed to show how simple changes to a room can influence the likely deposition pattern and hence the subsequent infection risk, rather than to accurately model a particular room. Deposition differences between the two room orientations are not representative of true differences under a variety of air flow or weather conditions and are constrained to assumptions used in the CFD modeling such as wind direction and velocity. Additionally, thermal effects were not included and resuspension was not addressed due to uncertainty regarding anticipated amounts of resuspension during hand-to-surface contacts, the force variability of contacts, and lack of information regarding walking patterns in the room that could contribute to resuspension of particles deposited on the floor. Changes in natural ventilation velocities and influence of thermal effects should also be explored to investigate how these parameters affect differences in exposures or infection risks between room orientations.

Despite these limitations, the approach we utilized accomplished the objective of exploring how differences in deposition patterns influenced by room layout may affect

healthcare workers' exposures to pathogens following bioaerosol deposition on surfaces and are therefore non-trivial. Open room doors throughout the day are a frequent feature of UK hospitals during summer months due to overheating,[42] suggesting that the scenarios using the door as a velocity inlet or pressure outlet are more applicable under warm conditions. Future work could involve exploring more real-world scenarios and chamber studies to measure particle deposition patterns and further evaluate the contribution of deposition differences to exposure and infection risk differences with the end goal of informing patient room design and furniture placement.

In these simulations, it was assumed that deposition of bioaerosols across an individual surface was homogeneous. Concentration changes on surfaces were therefore not tracked, as any fraction of the surface could be touched during a contact and the same area of the surface may not be touched. This is untrue for the door handle, but this surface was assumed to have a viral concentration of zero, as the focus of this exposure modeling study was fomite-mediated exposures as a result of bioaerosol deposition alone. It is likely that deposition is heterogeneous both between objects and on each individual object. Further granularity of deposition on high touch areas of surfaces vs. low touch areas will improve accuracy of exposure models and provide insights into areas to focus surface cleaning and disinfection. It should be noted that incorporating this level of detail in exposure models would arguably only be useful if this same level of detail were available in human behavior data, including which parts of objects are more commonly touched than others. This approach would also offer opportunities to incorporate grip-specific hand configurations to more accurately capture the surface area of the hand that was used.[30]

Additionally, transfer efficiencies used here originated from a fingertip-to-surface contact scenario.[20] While the fingertip or “fingerpad” is often used in transfer efficiency studies,[24,27,43] transfer efficiency variability by area of the hand used would provide more contact-specific data to further inform the integration of microbial transfer and human behavior models. In chemical transfer efficiency contexts, hand presses and fingertip presses have been used.[44,45] Characterizing what part of the hand is used for self-inoculation moments would also be important, as loading on the palm but hand-to-face contact with the fingertip may not result in exposure. Assuming viral loading on the hands is homogeneous across the hands may over- or under-estimate doses and subsequent infection risks.

Conclusions

This study demonstrates with exposure modeling that doctors’ rounds may pose greater exposure and infection risks to healthcare professionals than IV-care and observational care, due to faster viral accruement on hands due to a greater frequency of hand-to-patient contacts. Differences between room orientations in fomite-mediated exposures via deposited bioaerosols may be a function of changes in human behavior (different sequences of hand-to-surface contacts) and differences in bioaerosol deposition. This indicates that bioaerosols and ventilation design could have implications for not only inhalation exposures but also fomite-mediated exposures, especially considering the effects of room layout on room- and care type-specific hand-to-surface contact behaviors. Further expansion of integrated exposure models incorporating behaviors related to dose, such as self-inoculation, will allow for risk-informed engineering controls and room design to limit the frequency of hand-to-surface

768 contacts with surfaces experiencing greater bioaerosol deposition. This work also allows
769 for evaluation of other interventions lower in the hierarchy of controls, including use of
770 PPE and hand sanitizer. As demonstrated in the simulations in this work, the timing of
771 glove donning/doffing and hand sanitizer use can have important implications for their
772 ability to protect healthcare workers, especially considering hand-to-patient contacts.
773 These models can inform administrative controls, such as training that quantitatively
774 illustrates concepts such as the importance of proper donning/doffing technique and the
775 5 moments for hand hygiene (which include after a patient contact)[39] for lowering
776 occupational microbial exposures.
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Supplemental Materials for:

Effects of patient room layout on viral accruement on healthcare professionals' hands

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Iteration Evaluation

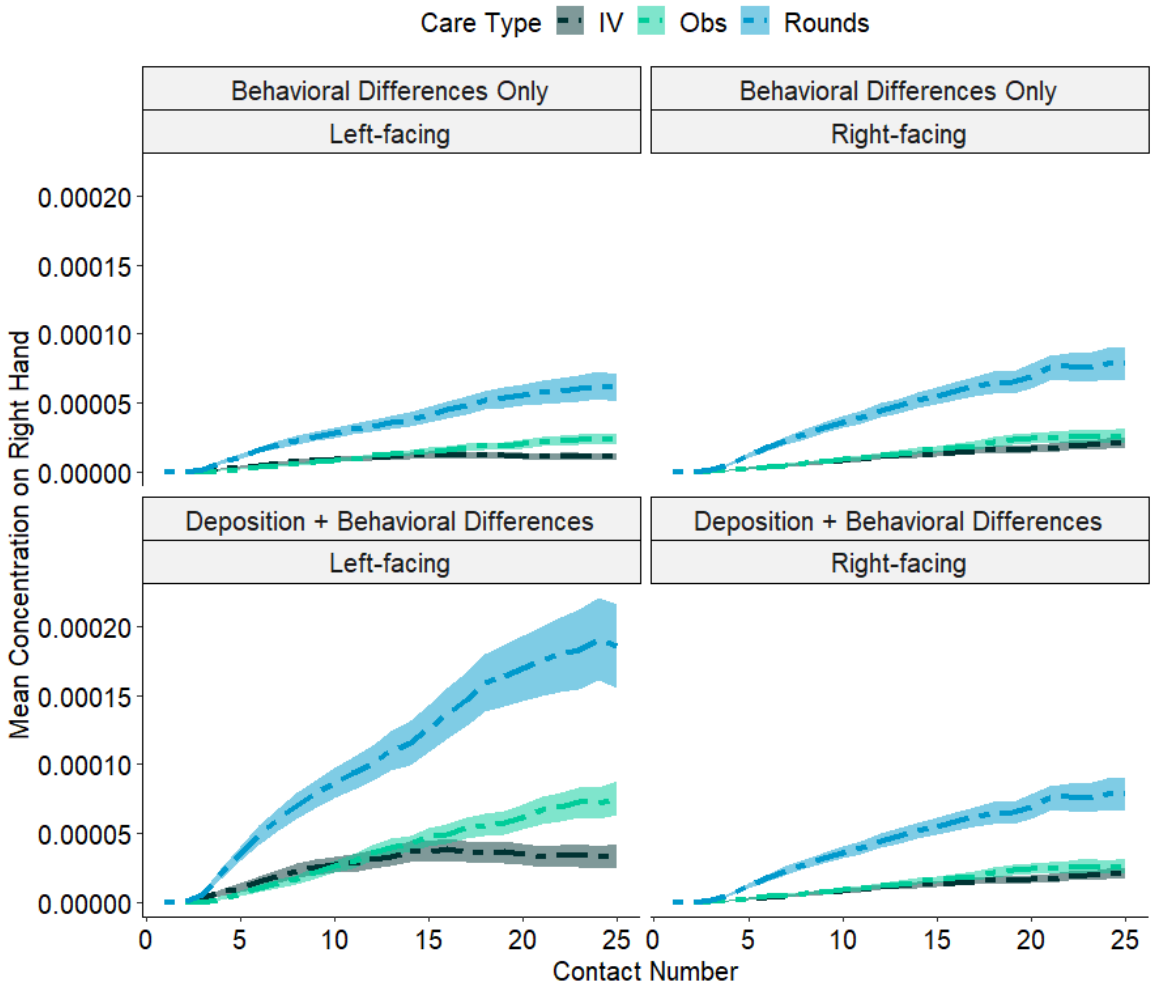


Figure S1. Mean ± SD concentration on the right hand over the number of contacts with 1,000 iterations per care type and room type combination

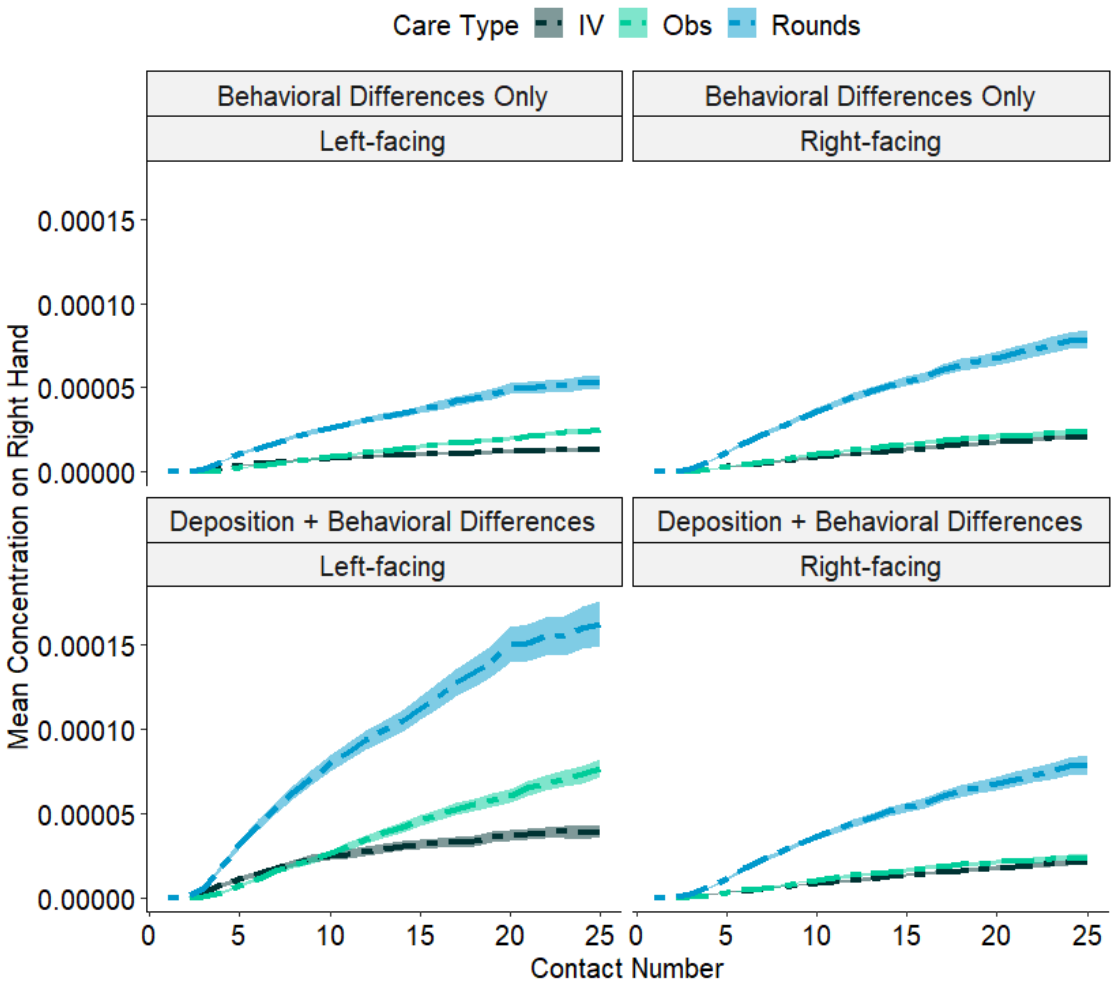


Figure S2. Mean ± SD concentration on the right hand over the number of contacts with 5,000 iterations per care type and room type combination

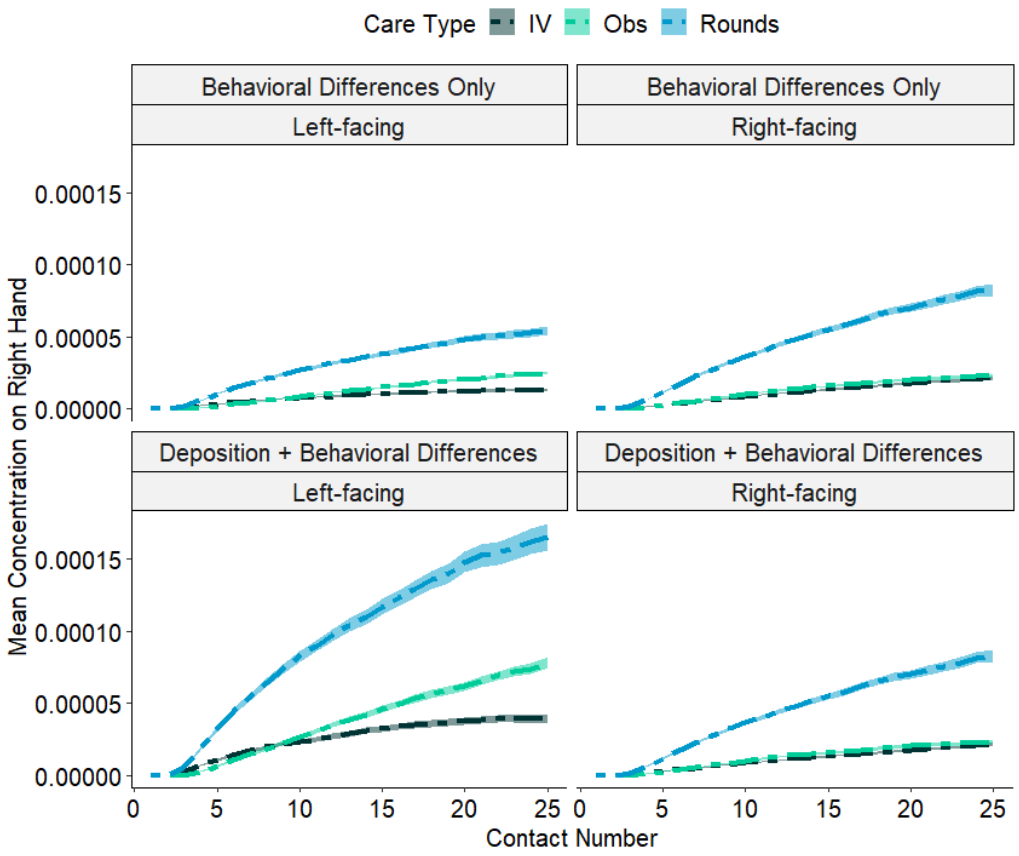


Figure S3. Mean ± SD concentration on the right hand over the number of contacts with 10,000 iterations per care type and room type combination

Surface Area of Surfaces

Table S1. Surface area (m^2) for surfaces or velocity inlet/pressure outlets

Object	**Surface Area (m^2)**
Chair	0.24
Side table	0.25
Desk	1.5
Floor	9.5
Door	1.9
Patient	0.44
Bed	0.50
Large Window	0.18
Small Windows	0.08

Iterations per Contact Number to Represent Mean Conc. on Hands

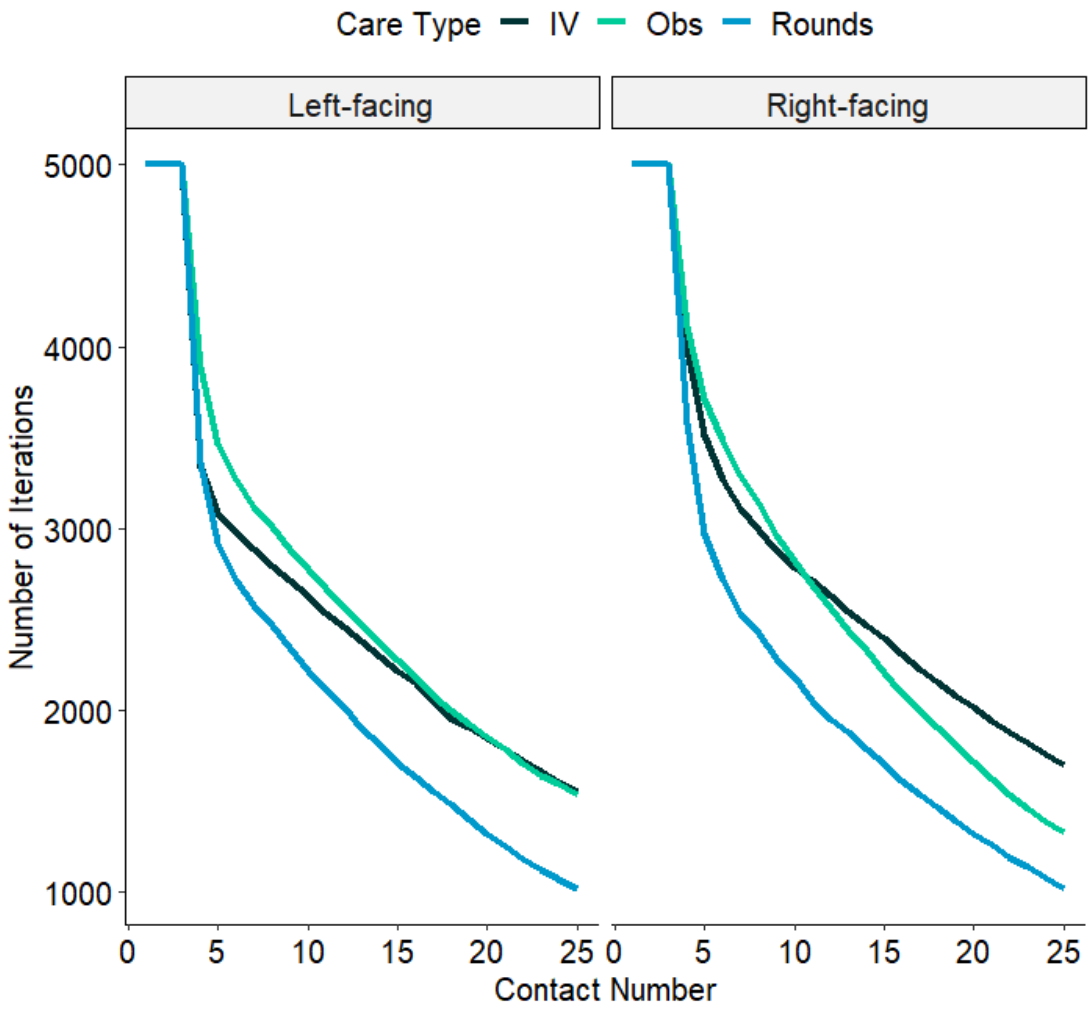


Figure S4. Number of iterations to inform mean concentration on hands per contact number*

*There is variability in length of simulations and number of contacts based on how quickly a transition to the "out" (exit from patient room) state occurs

Exposure Model Sensitivity Analysis

Figures S5-S22 reflect results from simulations for both deposition + behavior change and behavior change only model scenarios.

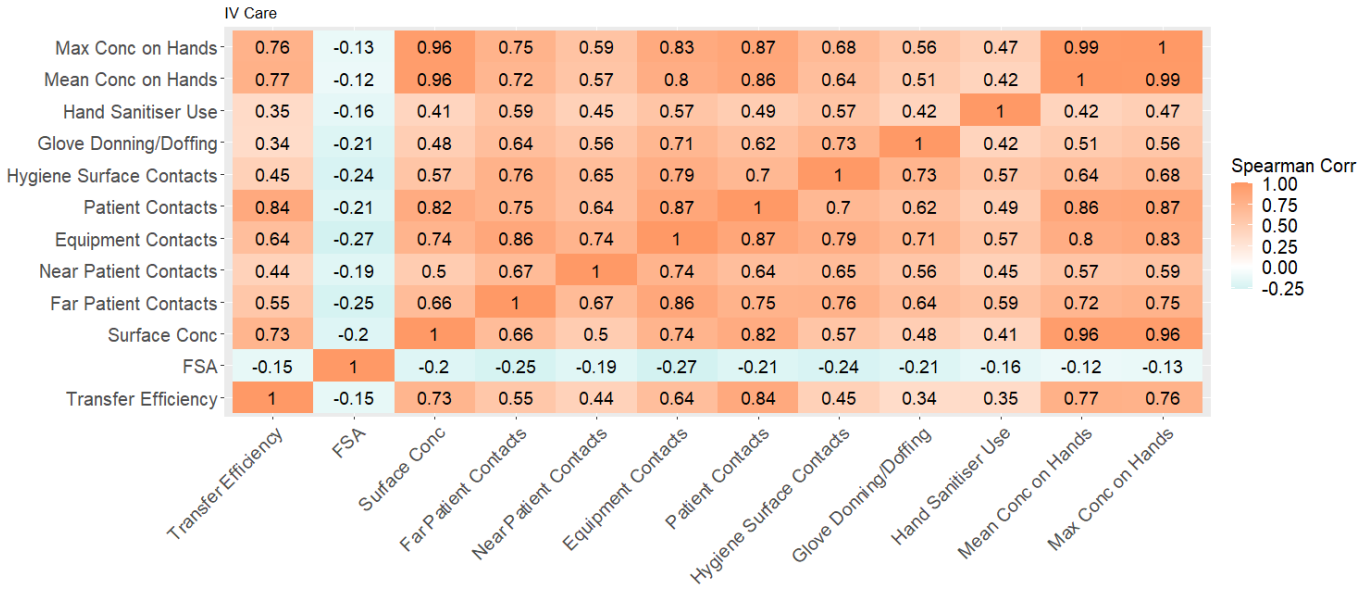


Figure S5. Spearman correlation coefficients for IV-care, left-facing

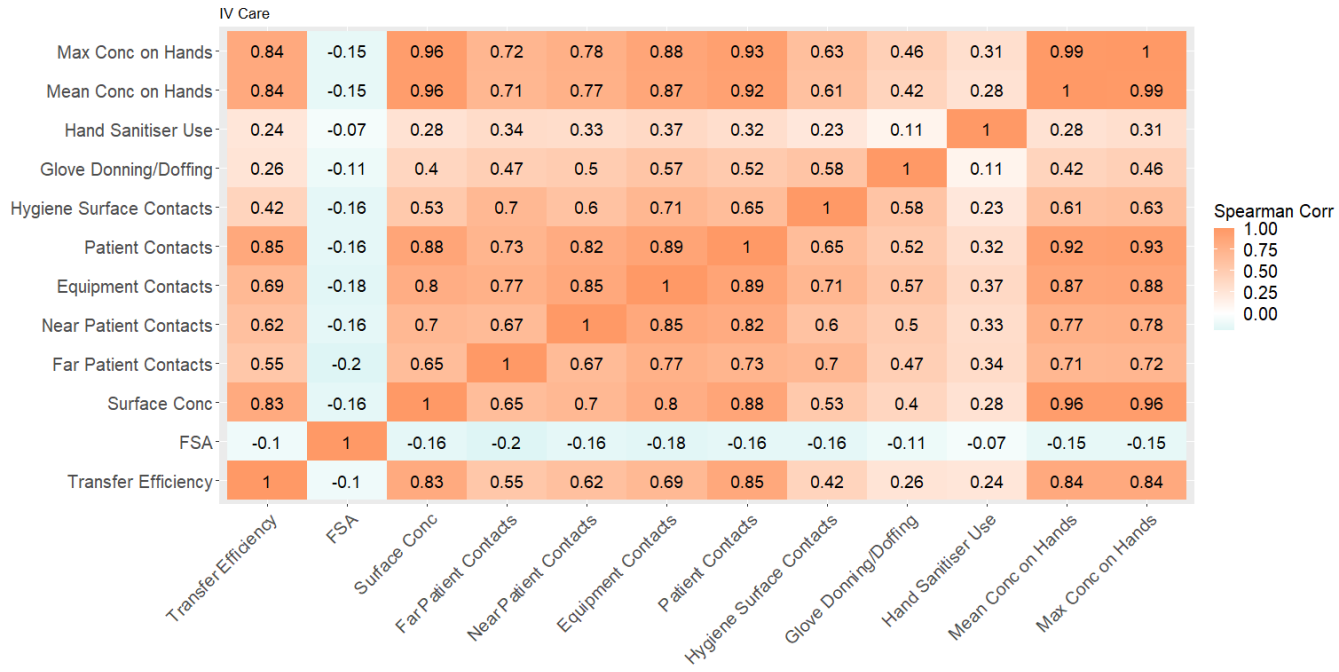


Figure S6. Spearman correlation coefficients for IV-care, right-facing

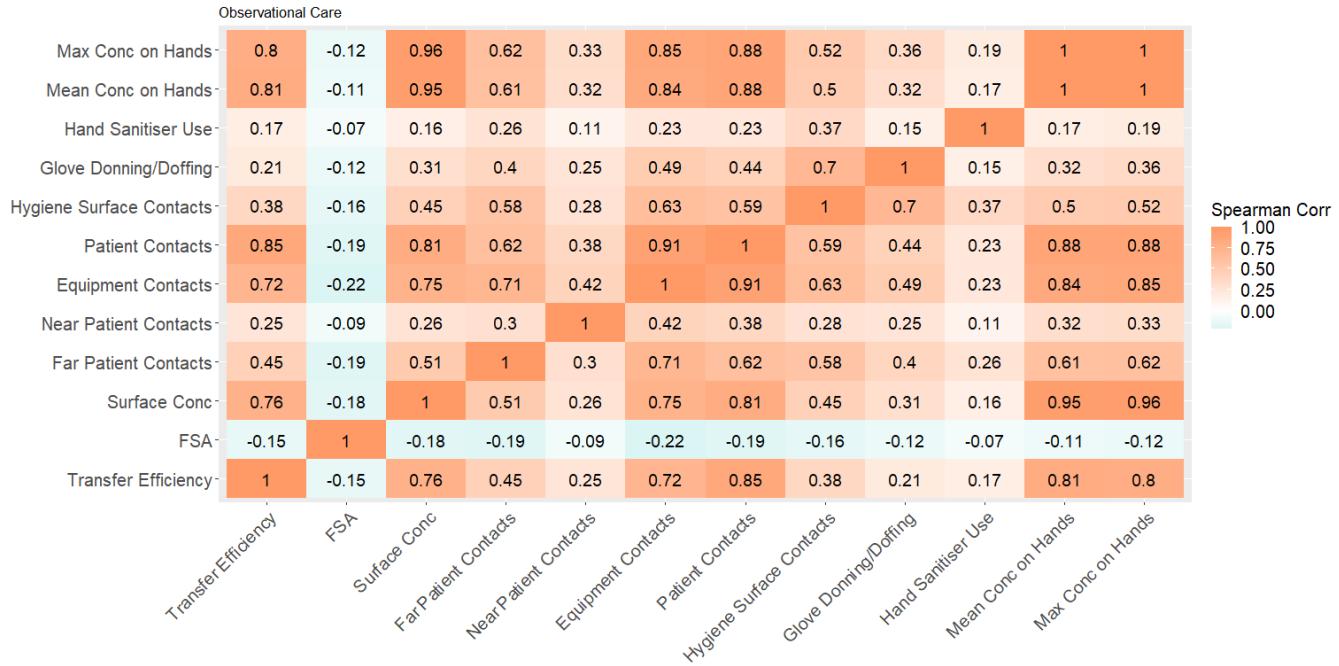


Figure S7. Spearman correlation coefficients for observational care, left-facing

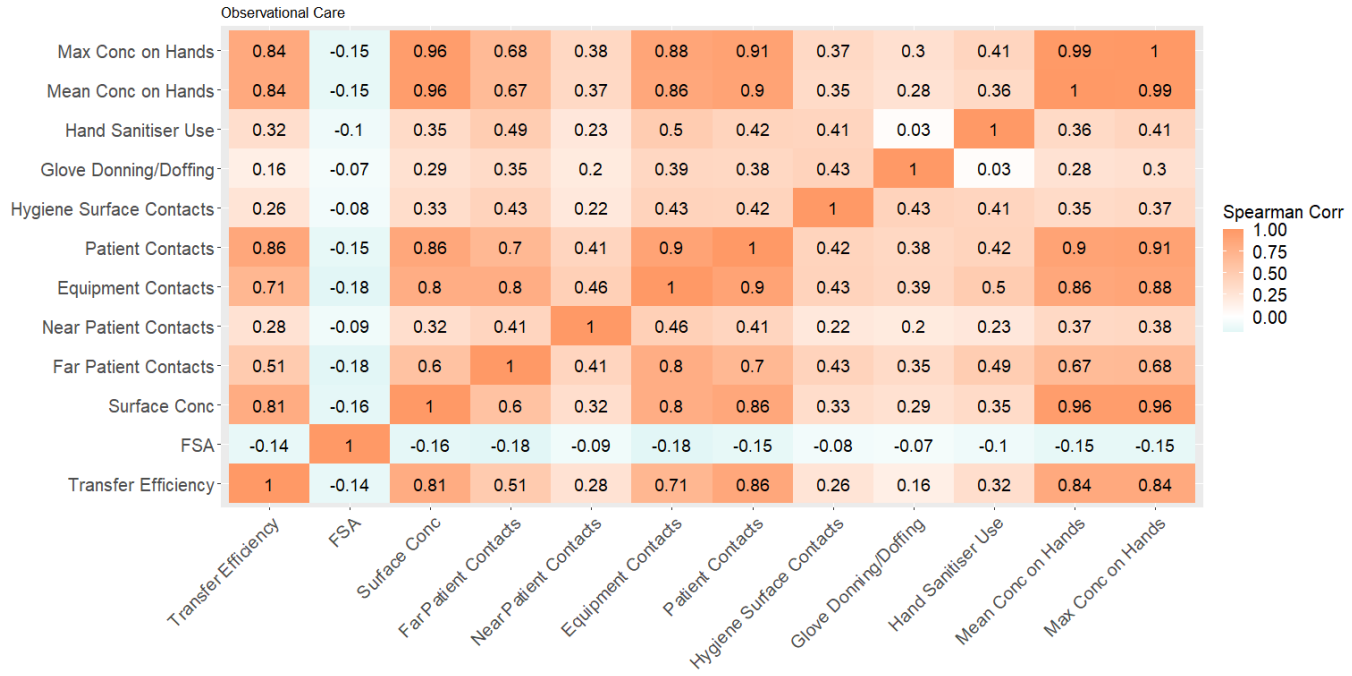


Figure S8. Spearman correlation coefficients for observational care, right-facing

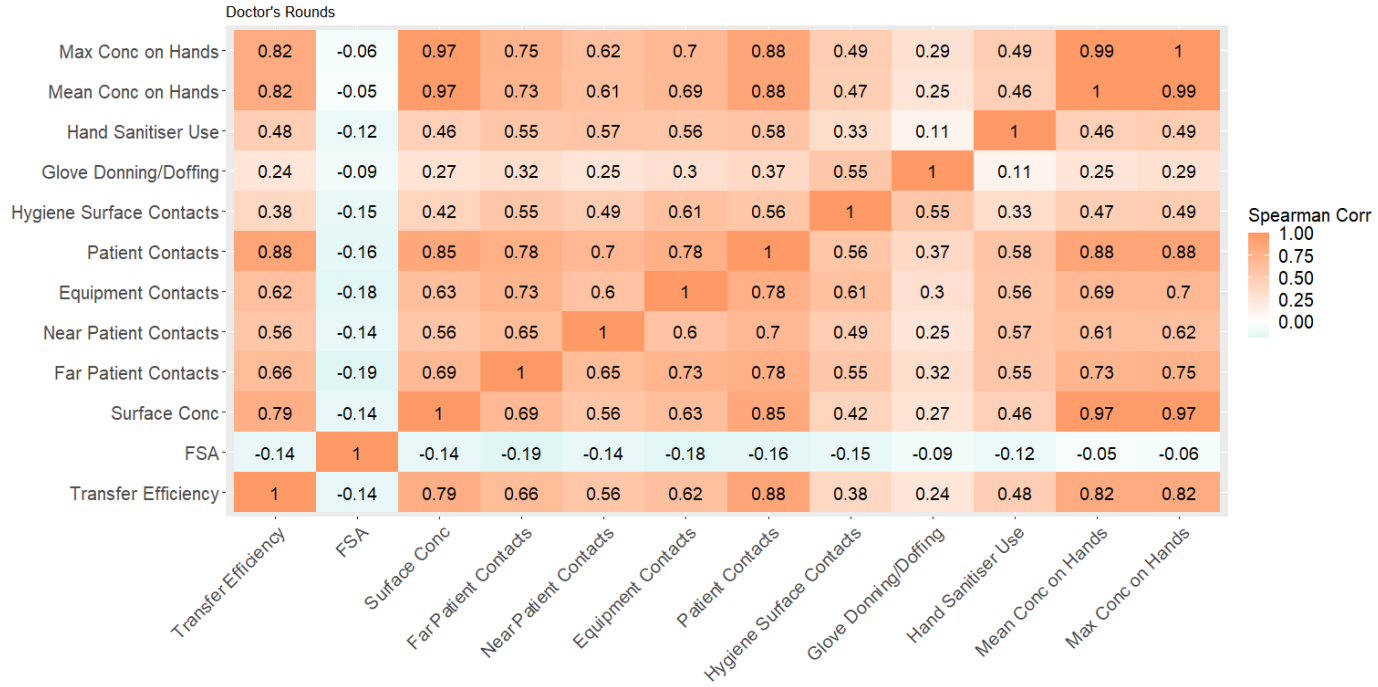


Figure S9. Spearman correlation coefficients for doctors' rounds, left-facing

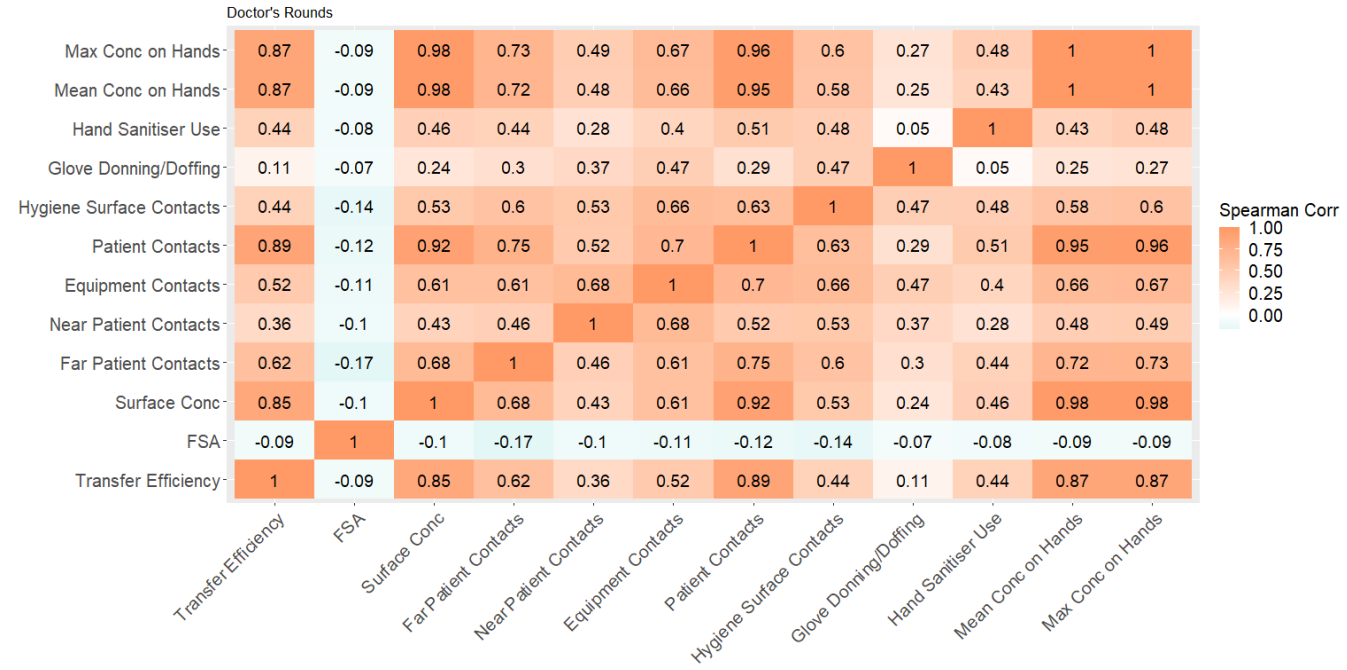


Figure S10. Spearman correlation coefficients for doctors' rounds, right-facing

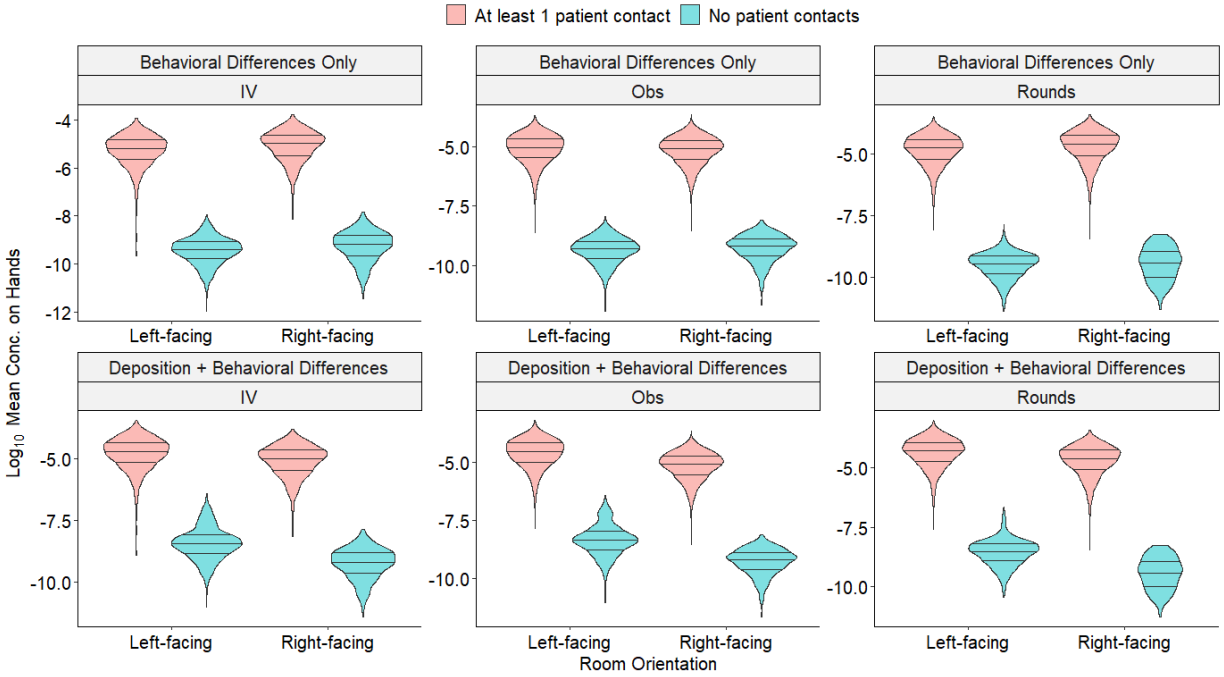


Figure S11. Distributions of Log_{10} Mean Concentrations on Hands for All Simulations

Scatter Plots

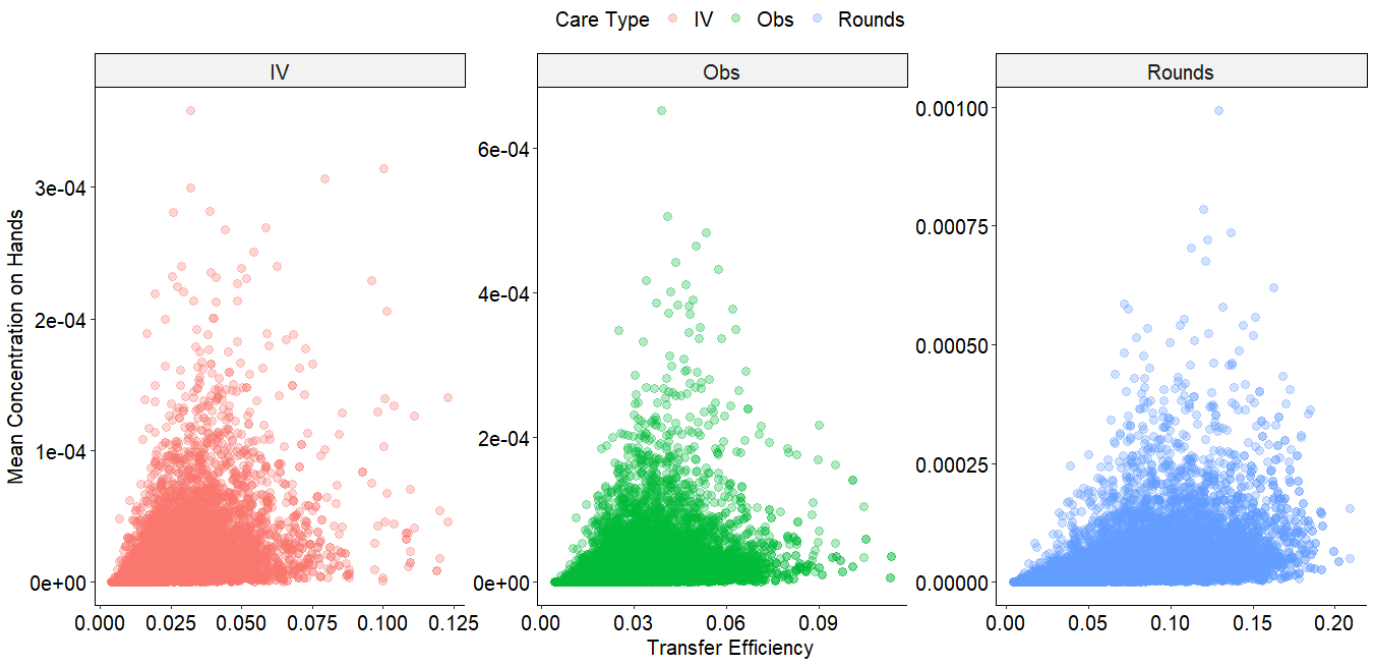


Figure S12. Scatter plots of mean concentration on hands vs. transfer efficiency

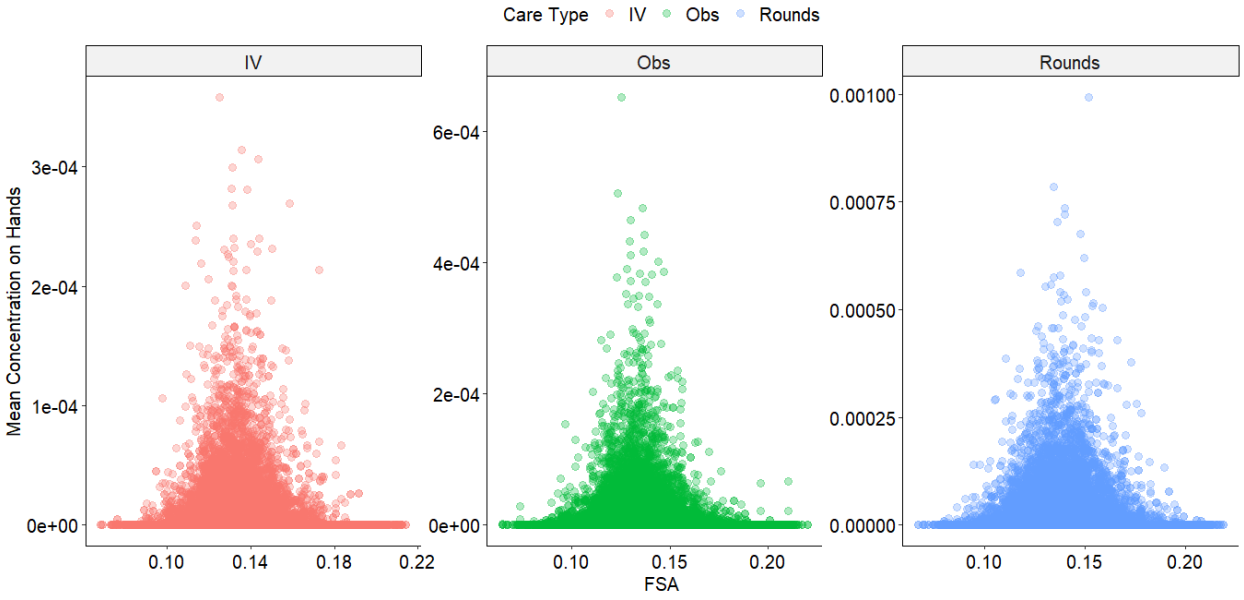


Figure S13. Scatter plots of mean concentration on hands vs. fractional hand surface area

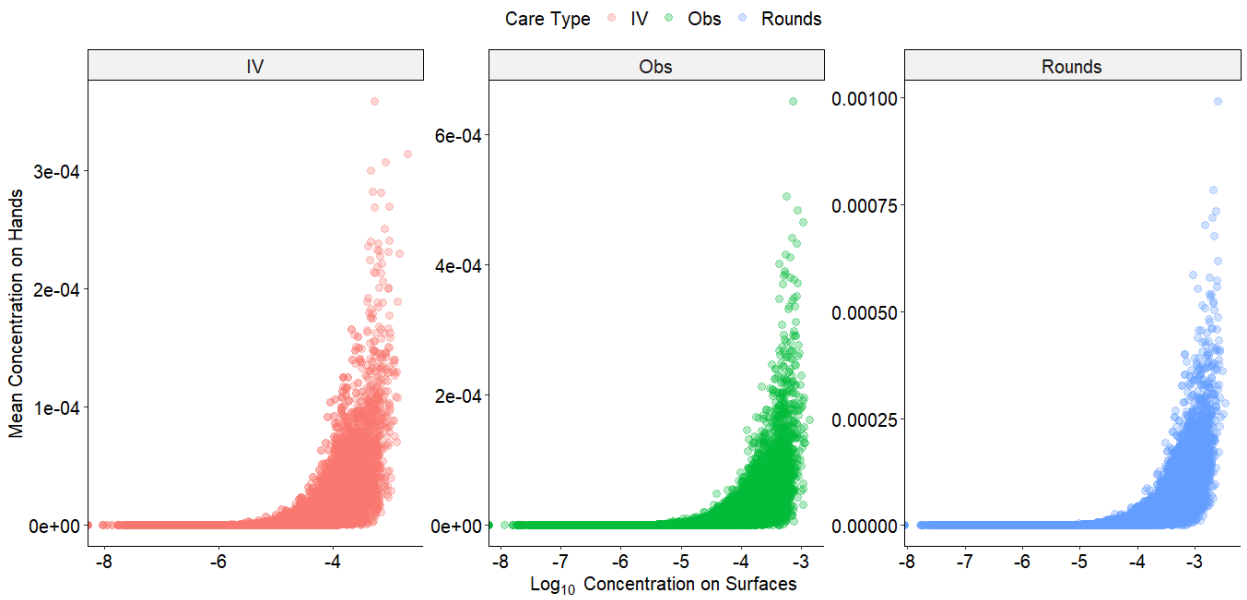


Figure S14. Scatter plots of mean concentration on hands vs. $\log_{10}$ concentration on surfaces

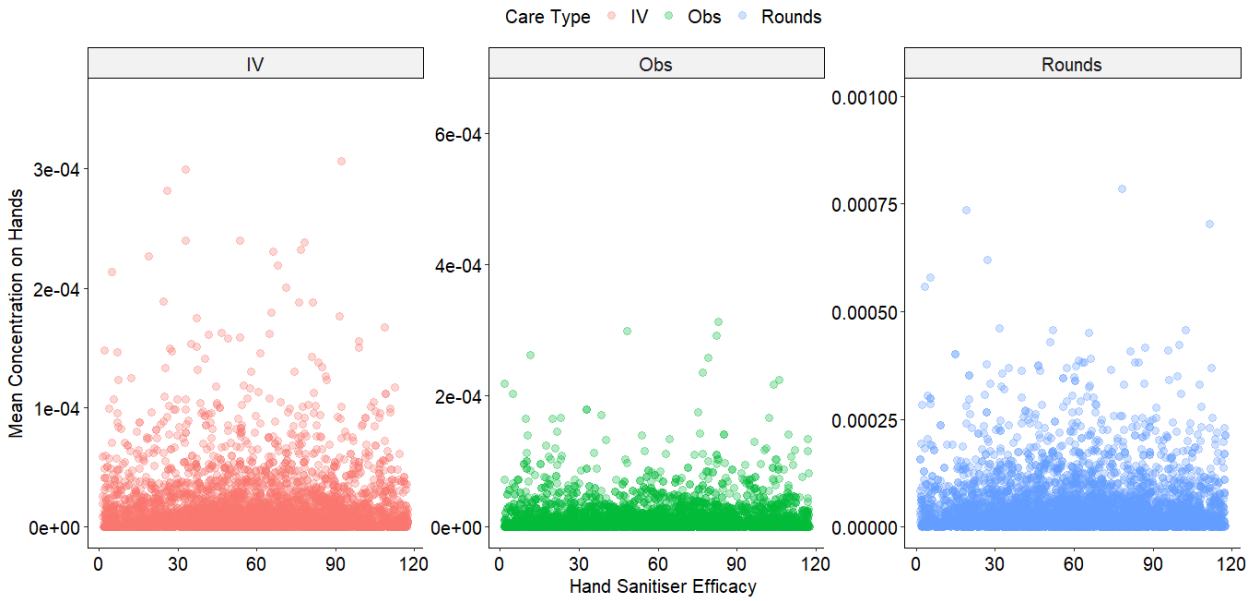


Figure S15. Scatter plots of mean concentration on hands vs. hand sanitizer efficacy

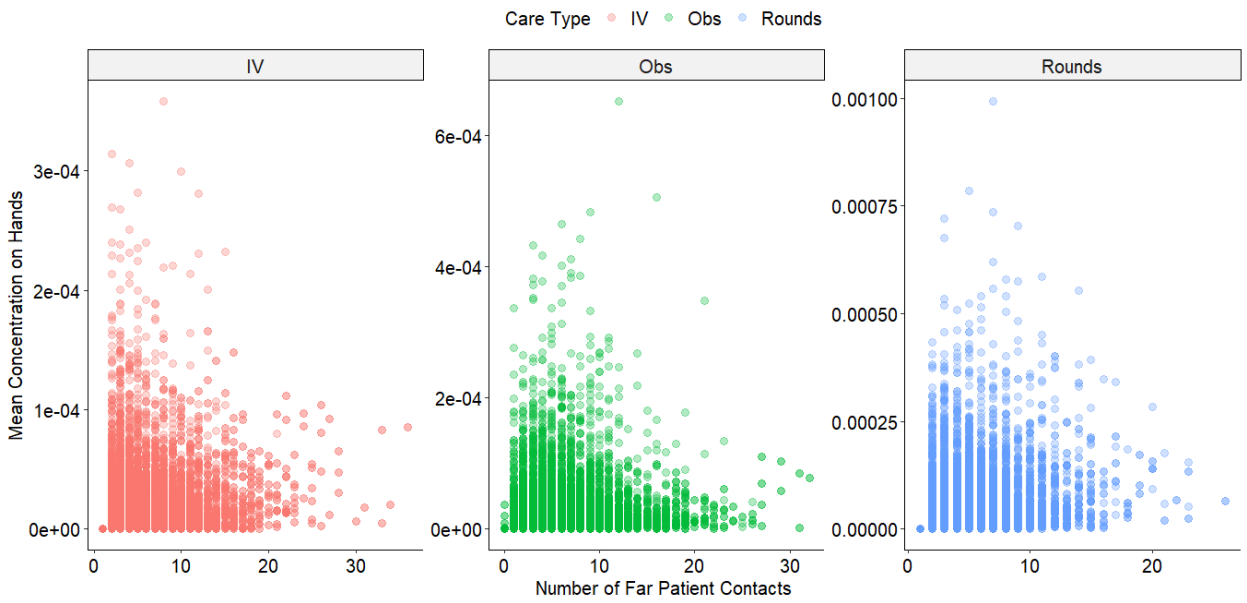


Figure S16. Scatter plots of mean concentration on hands vs. number of far patient surface contacts

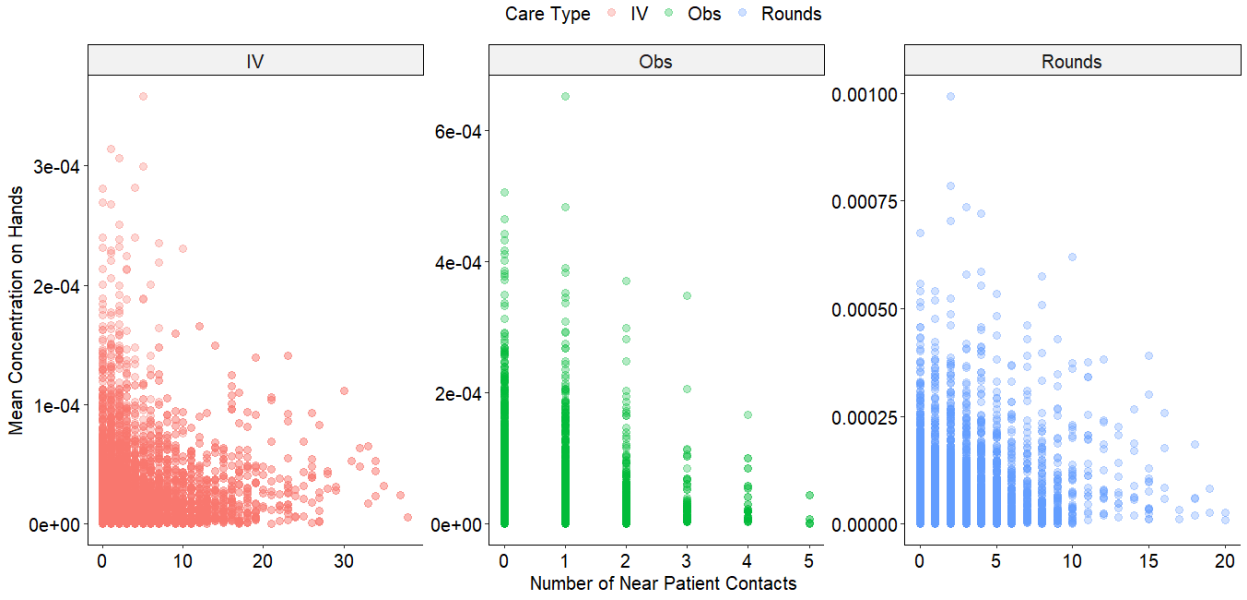


Figure S17. Scatter plots of mean concentration on hands vs. number of near patient surface contacts

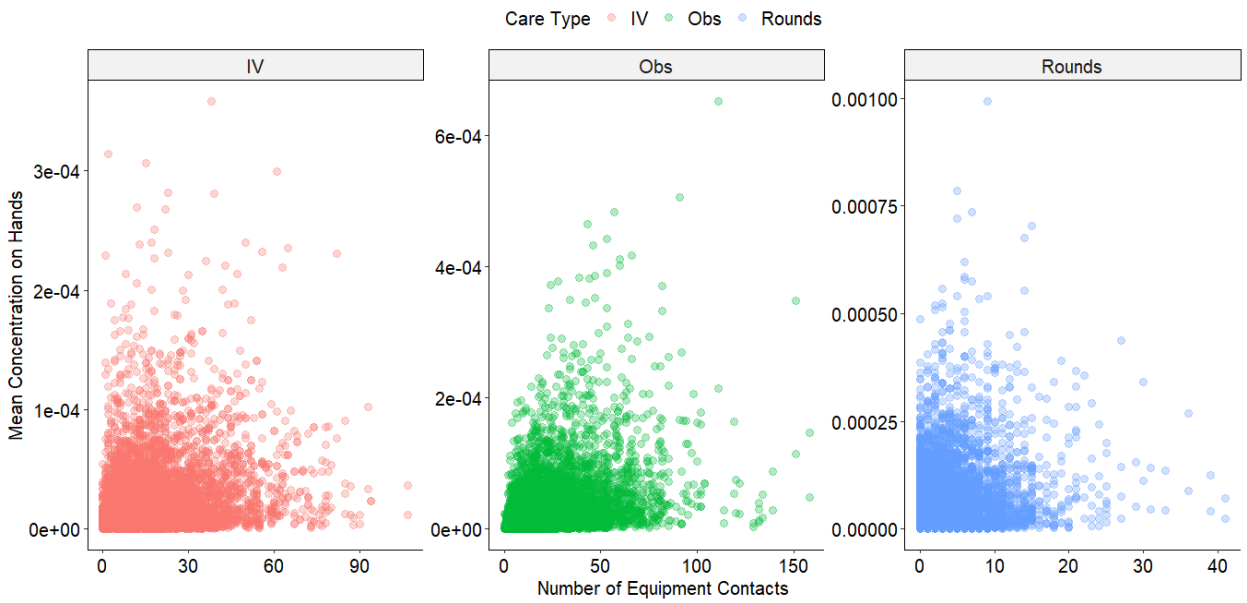


Figure S18. Scatter plots of mean concentration on hands vs. number of equipment contacts

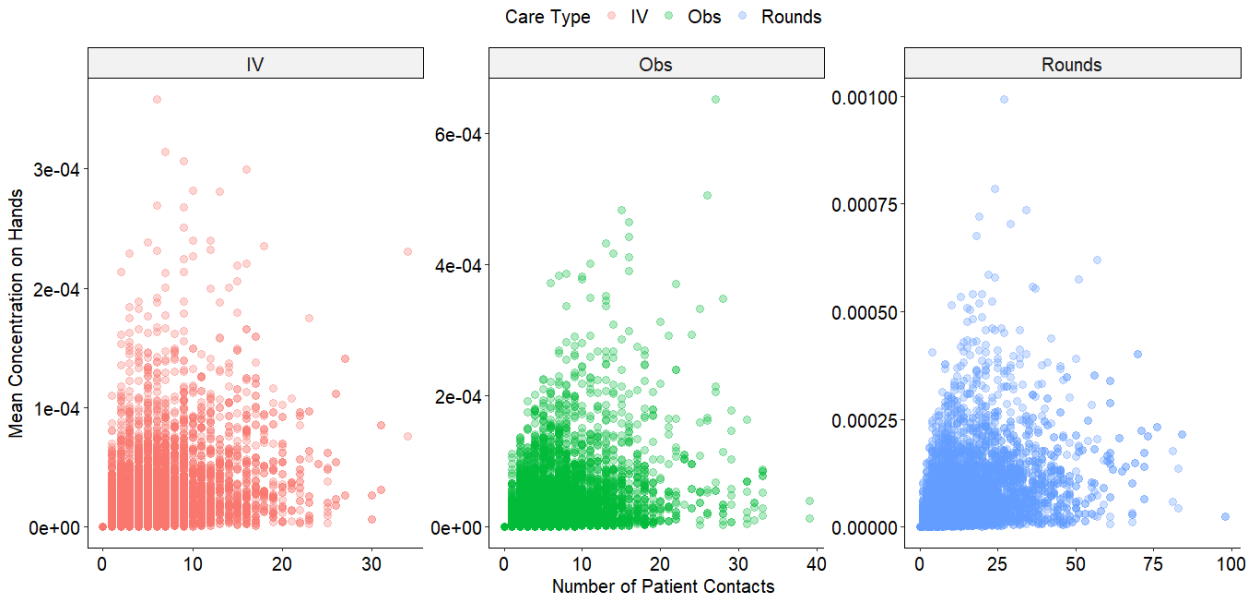


Figure S19. Scatter plots of mean concentration on hands vs. number of patient contacts

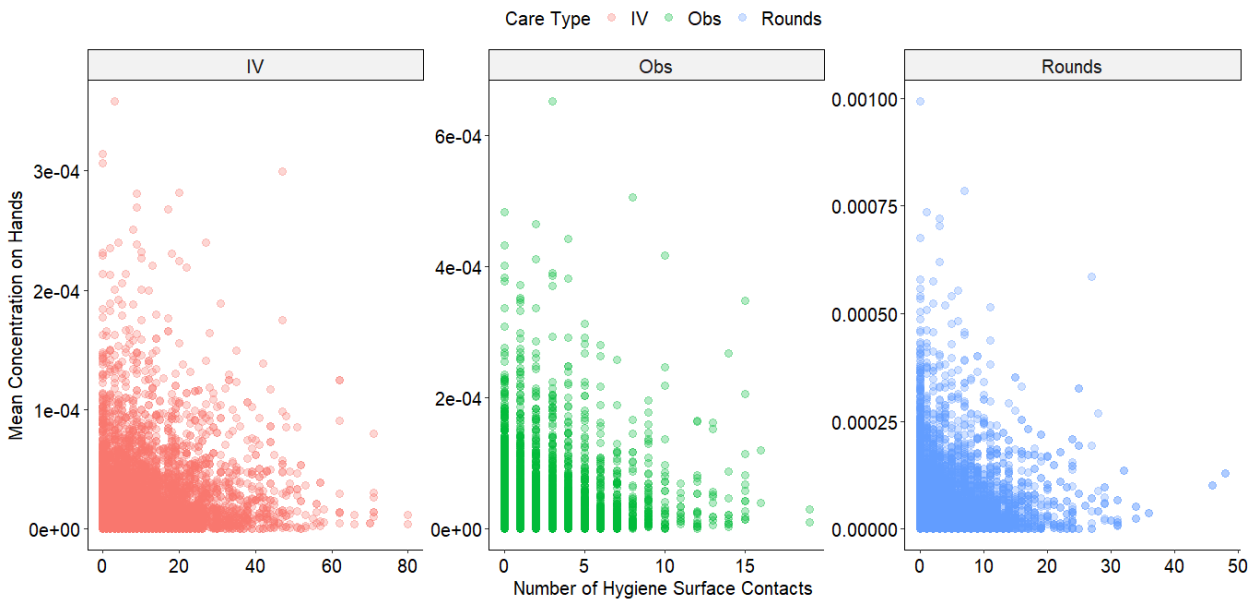


Figure S20. Scatter plots of mean concentration on hands vs. number of hygiene surface contacts

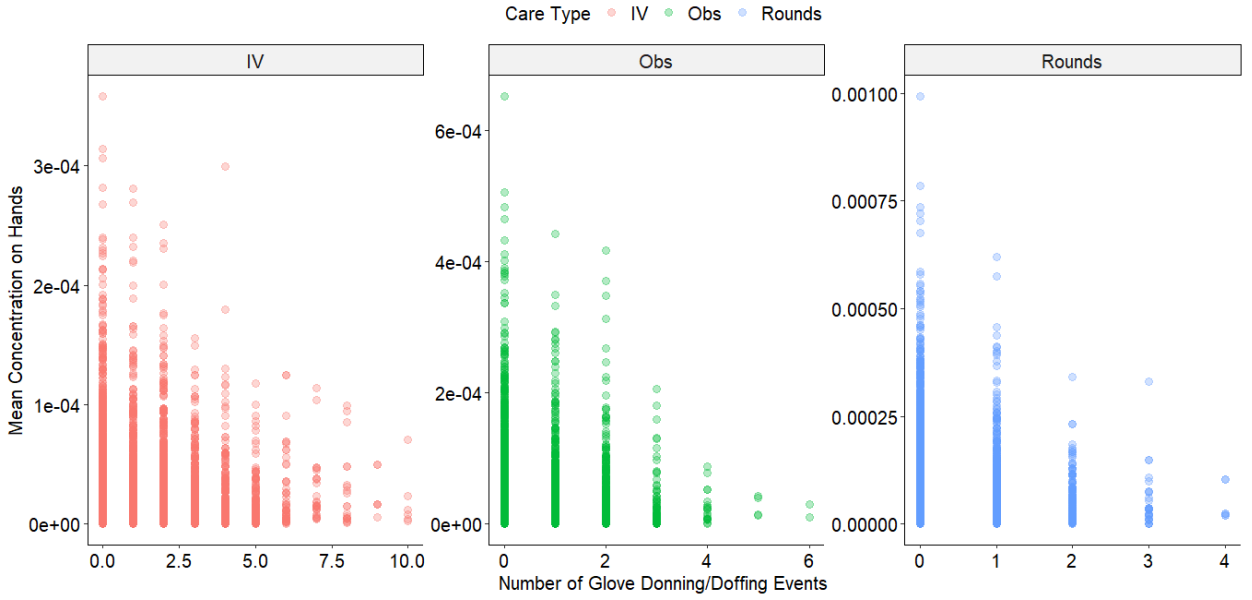


Figure S21. Scatter plots of mean concentration on hands vs. number of glove donning/doffing events

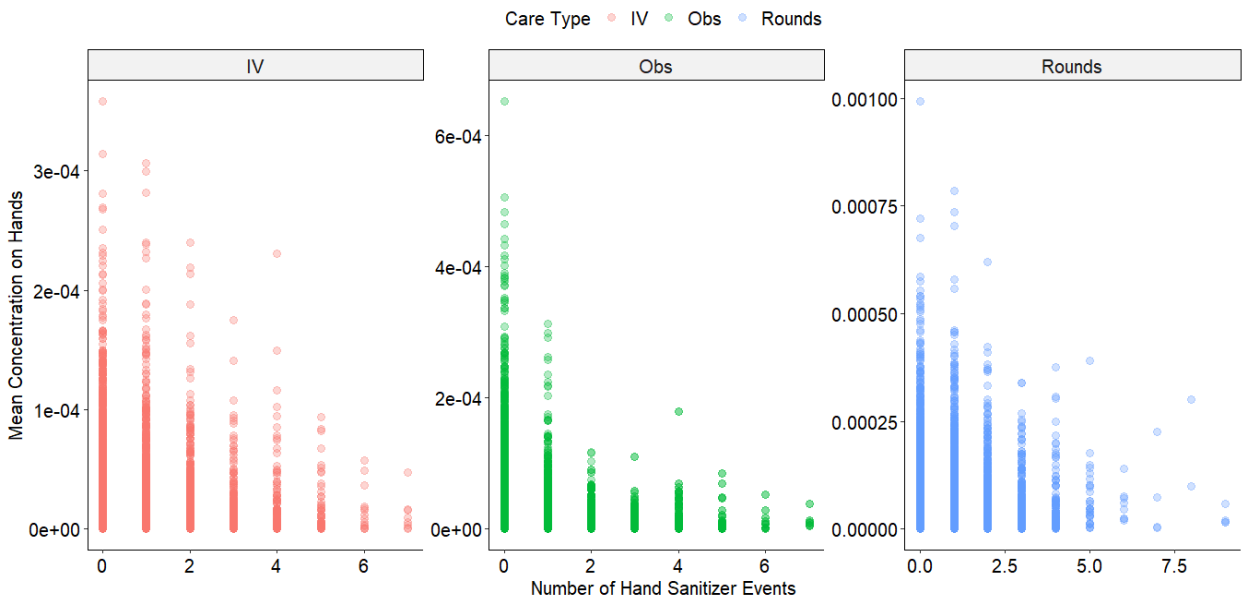


Figure S22. Scatter plots of mean concentration on hands vs. number of hand sanitizer events

Particle Deposition Sensitivity Analysis

In some cases, proportions will not sum to 1 due to some particles exiting out of the windows when windows acted as pressure outlets and due to loss of particles during the CFD simulation.

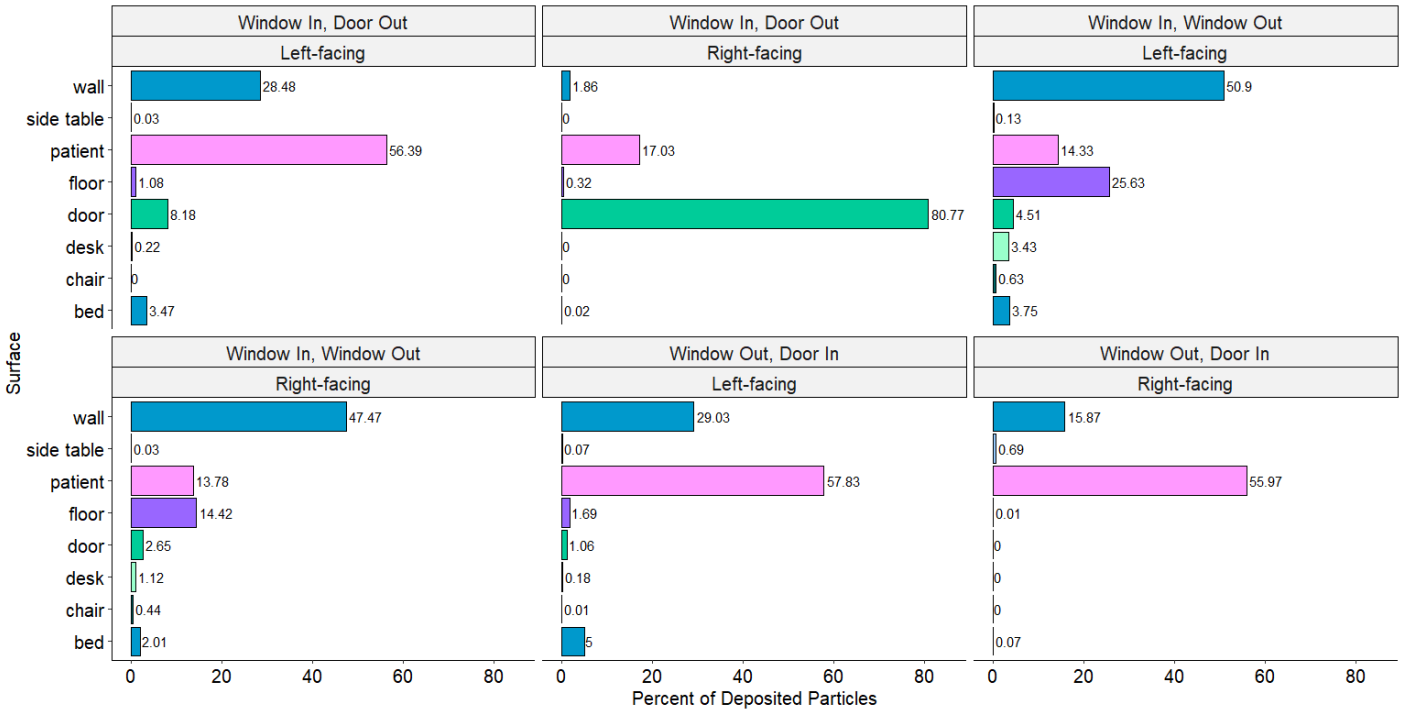


Figure S23. Particle deposition patterns for 10 ACH conditions

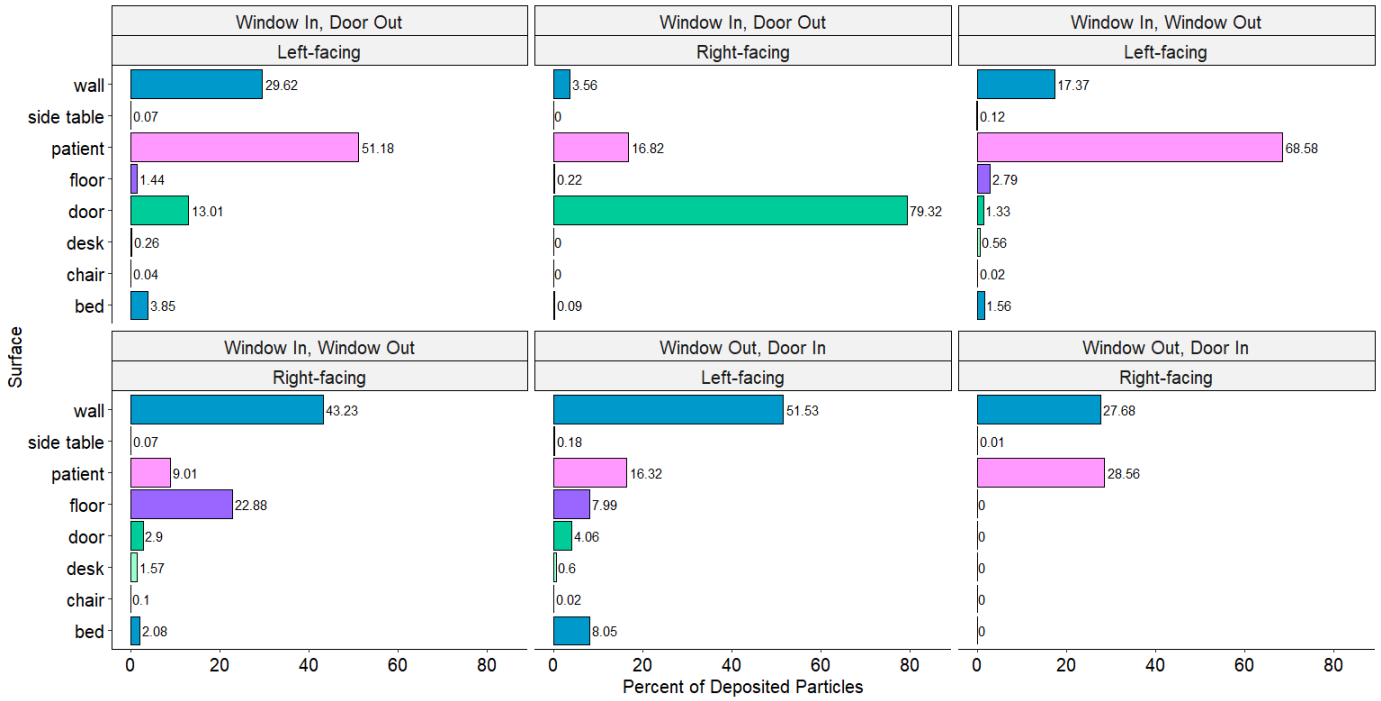


Figure S24. Particle deposition patterns for 6 ACH conditions

Figure S25. Particle deposition patterns for 2.5 ACH

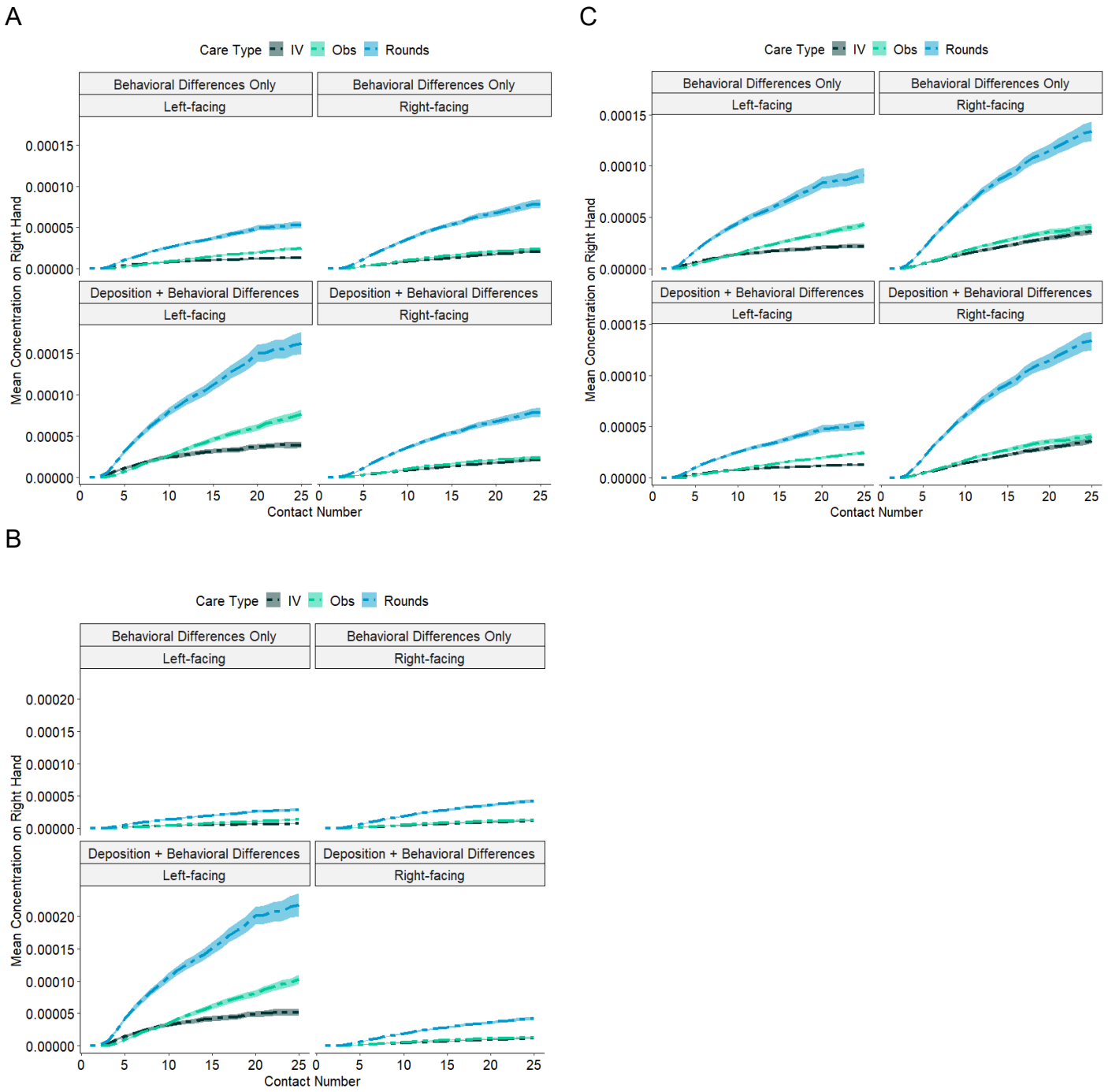
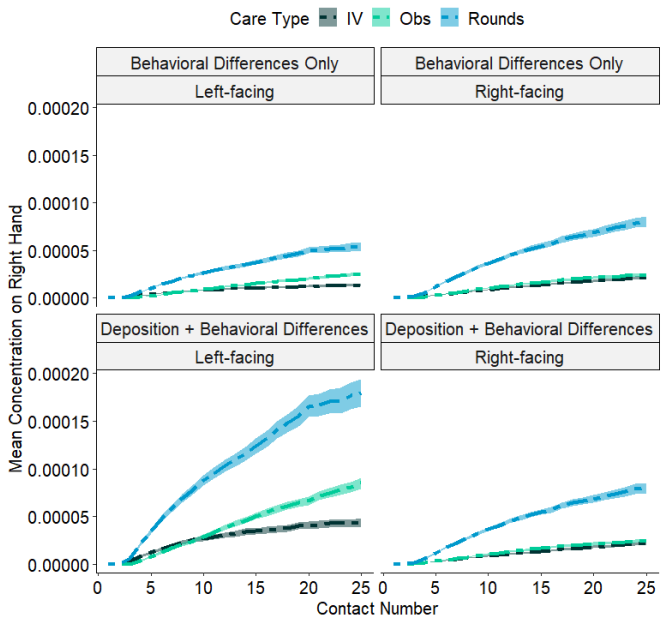
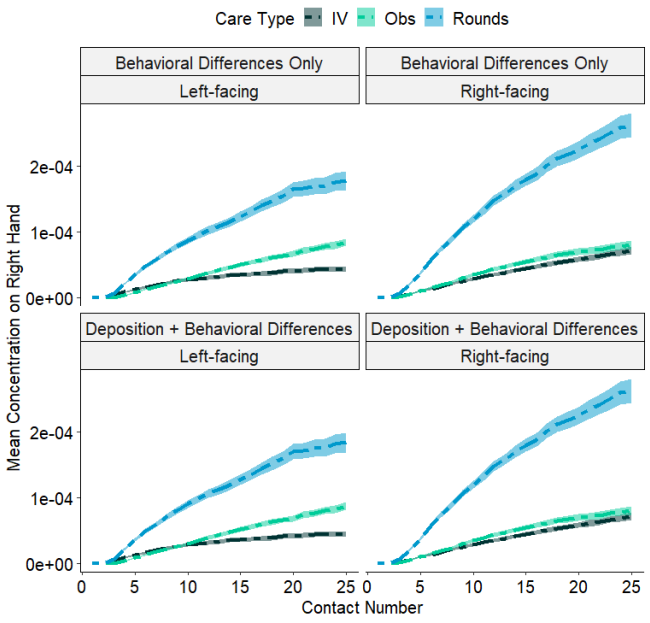


Figure S26. Mean ± SD concentration on the right hand over the number of contacts with 5,000 iterations per care type and room type combination for **6 ACH**, A.) Window In, Door Out, B.) Window In, Window Out, C.) Window Out, Door In

A



C



B

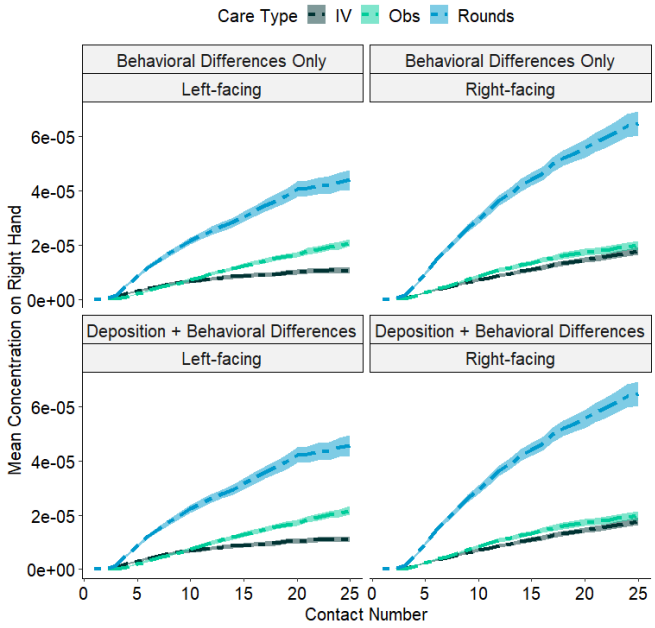


Figure S27. Mean ± SD concentration on the right hand over the number of contacts with 5,000 iterations per care type and room type combination for **10 ACH** A.) Window In, Door Out, B.) Window In, Window Out Scenario, C.) Window Out, Door In

A C

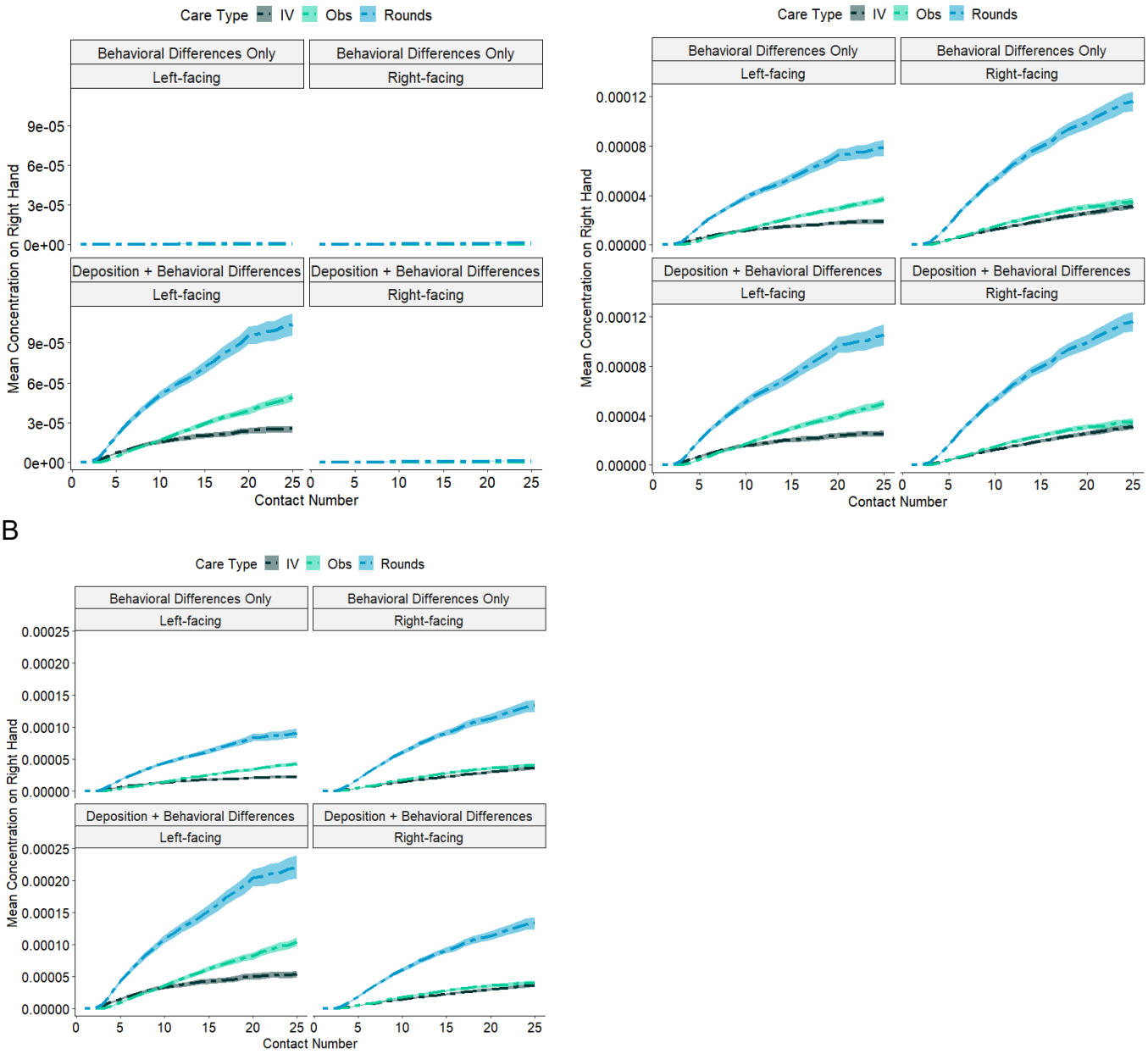


Figure S28. Mean ± SD concentration on the right hand over the number of contacts with 5,000 iterations per care type and room type combination for **2.5 ACH** A.) Window In, Door Out, B.) Window In, Window Out Scenario, C.) Window Out, Door In