Risk Analysis

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Applying a Risk-Risk Tradeoff Economics Approach to the Occupational Health of Nurses: Economic and Microbial Risk Analysis

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ABSTRACT

Public health challenges are increasingly complex, and interventions reducing the risk of one health outcome may increase the risk of another. We focus on the increased risk of occupational asthma (OA) for nurses and the decreased risk of occupational infections from contaminated surfaces from intensifying cleaning and disinfection protocols (i.e., during the COVID-19 pandemic). A risk–risk trade-off approach allows for the calculation of tolerable risks. We then determine, through a quantitative microbial risk assessment, critical concentrations of SARS-CoV-2 hygiene standards for surfaces that would achieve those tolerance levels. We find that, on average, in three out of our four scenarios, nurses prefer contracting a respiratory viral illness over OA around 80% of the time. Knowing another person who has contracted a respiratory viral infection (RVI) is negatively related to increasing respiratory viral infection risk. Critical concentrations were <0.01 viral particles/cm^2, implying frequent monitoring of viral concentrations on surfaces is needed to ensure risk targets are achieved. When applied to occupational health trade-offs for nurses engaging in cleaning and disinfection, we show that high environmental hygiene standards are needed.

1 | Introduction

The systems in which we live and work pose increasingly complex risks to manage, especially when public health interventions pose competing risks: An approach to decrease risk of an outcome increases risk of another. A competing risk situation gaining increased attention is that of asthma-related risks from increased cleaning and disinfection in the face of changed or intensified protocols due to COVID-19 (Gharpure et al. 2020; Wilson, Jung, et al. 2023). This is despite evidence of low COVID-19 risks from fomites (Centers for Disease Control and Prevention 2021; Wilson, Sleeth, et al. 2021) relative to other transmission routes (Jones 2020; Miller et al. 2021; Wilson et al. 2021, 2022). With years of research demonstrating risks for nurses from hygiene protocols in healthcare (Romero Starke et al. 2021; Wilson, O Ogunseye, et al. 2023) combined with a lack of standardization of microbial hygiene on surfaces in healthcare (Dancer 2004; Mulvey et al. 2011; Ryan et al. 2014; Smith et al. 2018; White

et al. 2008), there is an important competing risk scenario surrounding cleaning and disinfection. Although increased or intensified cleaning and disinfection in healthcare can increase work-related asthma risks for nurses depending upon protocol and product choices, decreased cleaning and disinfection could pose increased health risks, namely, increased occupational infection risks (Aw et al. 2017) from contaminated surfaces and increased risks of healthcare-associated infections for patients (Agency for Healthcare Research and Quality 2014).

There are multiple benefits to implementing policies in the healthcare sector to reduce the risk of individuals' infection and illness from contaminated surfaces. However, how individuals evaluate these benefits is an empirical question where individual responses depend on their own preferences, experience, and behavior (Mussio et al. 2024; Robinson and Hammitt 2011; Wilson, Mussio, et al. 2022). In risk assessment, the existence of a "context premium" for health risk changes related to surface cleaning and disinfection (which summarizes whether and how much more or less individuals' values risk changes across different morbidity contexts arising from such exposures) should also be empirically tested (Viscusi et al. 1991). This could inform resource allocation regarding investment in modernized hygiene technologies that may pose less occupational asthma (OA) risks, for example.

To estimate preferences for health risk changes arising from changing surface contamination procedures, we apply the risk–risk trade-off approach (RRTO). The RRTO approach was originally developed by Viscusi et al. (1991) and is a nonmonetary, relative valuation approach. RRTO has been applied in a wide range of contexts and has been used to analyze the trade-offs over fatal (mortality) and nonfatal risk (morbidity) changes, such as health related to climate change threats (Chilton et al. 2024; Mussio et al. 2024), chronic illnesses (Magat et al. 1996; McDonald et al. 2016; Van Houtven et al. 2008; Viscusi et al. 1991), mass shootings, and terrorist attacks (Dalafave and Viscusi 2023; Dalafave and Viscusi 2021; Viscusi 2009).

With a competing risk scenario that includes a microbial risk (i.e., infection risk from contaminated surfaces), a microbial risk assessment approach can also be taken to estimate what concentrations of pathogens in a given environment would yield a specific infection or illness risk (critical concentration (Hamilton et al. 2019)) given assumed behaviors in a scenario or environment. These critical concentrations provide context for what environmental quality standards or goals we should set in order to manage risk at specific thresholds, sometimes termed "benchmarks" (Gerrity et al. 2023). Using microbial risk assessment models in this way, however, requires a risk threshold for which to aim, and although this can be informed by experts, experts are prone to biases just like members of the public or communities who may be directly impacted by risk management choices (Shrader-Frechette 1995; Slovic 2000). There is an ethical argument for the involvement of communities in risk assessment processes from the beginning, with one outcome being to inform acceptable levels of risk (Shrader-Frechette 1995).

With greater attention given to how behavioral insights can inform the economic valuation of policy outcomes (Robinson and Hammitt 2011), we demonstrate an RRTO-QMRA framework in analyzing real nurse survey data regarding cleaning and disinfection and the competing outcomes related to changes in protocols, namely, increased OA risk for increased cleaning and disinfection use and the potential for increased occupational infections from contaminated surfaces if cleaning and disinfection protocols are relaxed. We used an RRTO QMRA approach to (1) measure the effects of different risk (probability) scenarios, experience, and socioeconomics on the likelihood of choosing an increased infection risk from contaminated surfaces (vs. an increased risk of OA from intensified cleaning/disinfection protocols), (2) quantify the value of the context premia for different risk trade-off scenarios, which tells us whether and how much more or less people value an increase in risk of OA versus an increase in the risk of a respiratory viral infection (RVI) (from intensified cleaning/disinfection protocols), (3) elicit summary statistics of acceptable risk levels for RVIs from contaminated surfaces in the workplace, and (4) incorporate acceptable risk levels (sample-level as opposed to individual-level) into a microbial risk assessment for calculating "critical concentrations."

Through this approach, we were able to examine acceptable risk levels for respiratory infection risks posed by fomites (focusing specifically on SARS-CoV-2, given the context of increased cleaning and disinfection protocols in the face of the COVID-19 pandemic). Although fomite-mediated risks from COVID-19 are low in comparison to other exposure pathways, such as inhalation of virus-laden aerosols (Jones 2020; Miller et al. 2021), the risks used in our survey were informed by a COVID-19 QMRA. Therefore, for consistency, we explore SARS-CoV-2 concentrations on surfaces that would yield specific risk thresholds.

This approach is novel in that we are translating the behavioral-based findings from the RRTO methodology into the scientific practice of microbial risk assessment. To our knowledge, this has never been done before, and it facilitates meaningful engagement of communities for input into risk assessment (e.g., elicitation of tolerable risk thresholds), which has long been a needed advancement in risk assessment (Shrader-Frechette 1985, 1995).

2 | Methods

2.1 | The Risk–Risk Trade-Off Framework

For the framework development, we follow the original model developed by Viscusi et al. (1991) and adapt it to this particular situation. In this context, we assumed a healthcare worker is faced with a choice between two risks, for example, the risk of contracting OA and the risk of contracting an RVI. The problem can be expressed in an expected utility framework. Consistent with the prior literature (Chilton et al. 2024; Magat et al. 1996; McDonald et al. 2016; Mussio et al. 2024; Van Houtven et al. 2008), we assume that nurses choose to maximize lifetime expected utility, $E(U)$:

$$E(U) = r_\alpha U(\alpha, m) + r_\gamma U(\gamma, m) + \left(1 - r_\alpha - r_\gamma\right) U(h, m) \quad (1)$$

with the model having the following mutually exclusive cases: contracting OA (α), contracting an RVI (γ) and full health (h). These have corresponding lifetime utilities depending on both the health outcome, α or γ, and wealth, m: $U(\alpha, m)$, $U(\gamma, m)$, and $U(h, m)$; and each of the probabilities r_α, r_γ and

$(1 - r_\alpha - r_\gamma)$. Without loss of generalization, the assumption of mutual exclusiveness is consistent with expected utility theory and is an approximation to the case of small probabilities (or risks, Viscusi et al. 1991).

In the healthcare context of this study, participants were asked to make a choice between moving to one of two healthcare environments in which to work (e.g., two hospitals or clinics), 1 or 2. In Healthcare Environment 1, the probabilities of contracting OA and RVI are represented by $r_{\alpha 1}$ and $r_{\gamma 1}$. In Healthcare Environment 2, the probabilities of contracting OA and RVI are represented by $r_{\alpha 2}$ and $r_{\gamma 2}$. Expected utilities of both healthcare environments are set out as follows:

$$E(U)_1 = r_{\alpha 1}\, U(\alpha, m) + r_{\gamma 1} U(\gamma, m) + \left(1 - r_{\alpha 1} - r_{\gamma 1}\right) U(h, m) \tag{2}$$

$$E(U)_2 = r_{\alpha 2}\, U(\alpha, m) + r_{\gamma 2} U(\gamma, m) + \left(1 - r_{\alpha 2} - r_{\gamma 2}\right) U(h, m) \tag{3}$$

If a healthcare worker is an expected utility maximizer and indicates indifference between Healthcare Environments 1 and 2, this would result in

$$E(U)_1 = E(U)_2 \tag{4}$$

Rearranging Equation (4) gives us the following utility-equivalent lottery, similar to the model framework setup in Jones-Lee (1976), where $r\, r_{\alpha\gamma} = \frac{r_{\gamma 2} - r_{\gamma 1}}{r_{\alpha 1} - r_{\alpha 2}}$ is defined as the ratio of the probability differences of each outcome under indifference between Healthcare Environments 1 and 2:

$$U(\alpha, m) = rr_{\alpha\gamma}\, U(\gamma, m) + \left(1 - rr_{\alpha\gamma}\right)\, U(h, m) \tag{5}$$

The utility of living with OA (asthma onset) can now be read as an equivalent lottery on life with good health and catching an RVI.

In practice, we do not directly observe utilities from applications of the RRTO method, but we do observe the relative sizes of risk changes that make participants indifferent between the two healthcare scenarios (Mussio et al. 2024). Therefore, the approach is to present scenario choices with different ratios of probability differences between the healthcare scenarios, $rr_{\alpha\gamma}$, as defined by Equation (5). By varying these ratios, the responses allow us to estimate the average value of the context premia ($\widehat{rr_{\alpha\gamma}}$, an empirical estimation of the ratio of probability differences for each scenario).

For example, if the participant is indifferent between Healthcare Environment 1 (with a probability of contracting OA of 30 in 1000 people and a probability of contracting an RVI of 120 in 1000 people) and Healthcare Environment 2 (with a probability of contracting OA of 120 in 1000 people and a probability of contracting an RVI of 80 in 1000 people), $rr_{\alpha\gamma}$ is calculated as $rr_{\alpha\gamma} = \frac{120-30}{120-80} = \frac{9}{4} = 2.25$, and Equation (5) would be rewritten as

$$U(\alpha, m) = 2.25\, U(\gamma, m) - 1.25\, U(h, m) \tag{6}$$

where $rr_{\alpha\gamma}$ is interpreted as follows: "Nurses value preventing contracting OA 2.25 times as highly as they do contracting a respiratory viral infection."

2.2 | Survey Design

The survey consisted of three sections: (1) Section 2.2.1, (2) Section 2.2.2, and (3) Section 2.2.3. Each section is described in detail below.

2.2.1 | Introduction and Priming

This first section included consent form and a series of validation questions (for the purposes of eligibility to take the survey), including whether the participant was a registered nurse (RN), had physician-diagnosed asthma, had worked in healthcare for over a year, and if the participant lived in the United States at the time of the survey. We also included a brief description of risk and risks in healthcare environments (including OA and RVI). In this case, risk was referred to as a concept of a chance of something negative happening.

A practice scenario was given to guide participants through and help them to understand the scenarios and to give them experience of answering the same type of preference elicitation question, that is, the RRTO that they would encounter in the main survey. A full description of this practice scenario is in the Supporting Information section.

2.2.2 | RRTO

After the practice scenario, participants were faced with four different RRTO scenarios, presented in random order, where risk was described as a number of people out of 1000 expected to have a negative health outcome in a given healthcare environment as a place of work. The four scenarios varied the baseline risk differences for OA and infection (I; in the next year) and differences in the severity of the outcome given infection (i.e., recovery [R] or death [D]): Scenario 1 (baseline risk: OA = infection and recovery (I&R), equal risk increase, OA, and I&R), Scenario 2 (baseline risk: OA = infection and death (I&D), equal risk increase, OA, and I&D), Scenario 3 (baseline risk: OA > I&R, increase in risk, OA > I&R), and Scenario 4 (baseline risk: OA > I&D, increase in risk: OA > I&D). These scenarios allowed us to compare the effect of baseline risk differences between the two outcomes and the effect of anticipated outcome of infection on the decision-making. Although we acknowledge that all infections run the risk of death, the framing of the scenarios with a specified outcome provided a level of control over how participant anticipated the infection would progress and how this assumption would influence their choice. We also bound the time in which OA would be anticipated to onset, and only those without diagnosed asthma could participate, increasing the likelihood that they would perceive the outcomes (infection or asthma) as mutually exclusive. This is addressed further in Section 4.3.

Table 1 summarizes the baseline risks for each scenario, the increase in risk in the next year for each healthcare environment and in each scenario, as well as the risk difference ratio

TABLE 1 | Risk–risk scenarios in terms of occupational asthma (OA), infection and recovery (I&R), infection and death (I&D) risks, and associated risk difference ratios (RDR).

1a. Scenario 1 (baseline risk: OA = I&R, equal risk increase, OA, and I&R, RDR = 1)		
Healthcare Environment 1 (baseline)		
Occupational asthma onset		60 in 1000
Respiratory viral infection and recovery		60 in 1000
Alternative healthcare environments		
	Healthcare Environment 2	***Healthcare Environment 3***
Occupational asthma onset	120 in 1000	60 in 1000
Respiratory viral infection and recovery	60 in 1000	120 in 1000
1b. Scenario 2 (baseline risk: OA = I&D, equal risk increase, OA, and I&D, RDR = 1)		
Healthcare Environment 1 (baseline)		
Occupational asthma onset		60 in 1000
Respiratory viral infection and death		60 in 1000
Alternative healthcare environments		
	Healthcare Environment 2	***Healthcare Environment 3***
Occupational asthma onset	120 in 1000	60 in 1000
Respiratory viral infection and death	60 in 1000	120 in 1000
1c. Scenario 3 (baseline risk: OA > I&R, increase in risk, OA > I&R, RDR = 0.142)		
Healthcare environment 1 (baseline)		
Occupational asthma onset		60 in 1000
Respiratory viral infection and recover		0.08 in 1000
Alternative healthcare environments		
	Healthcare Environment 2	***Healthcare Environment 3***
Occupational asthma onset	120 in 1000	60 in 1000
Respiratory viral infection and recover	0.08 in 1000	8.6 in 1000
1d. Scenario 4 (baseline risk: OA > I&D, increase in risk: OA > I&D, RDR = 0.0005)		
Healthcare Environment 1 (baseline)		
Occupational asthma onset		60 in 1000
Respiratory viral infection and death		0.0003 in 1000
Alternative healthcare environments		
	Healthcare Environment 2	***Healthcare Environment 3***
Occupational asthma onset	120 in 1000	60 in 1000
Respiratory viral infection and death	0.0003 in 1000	0.03 in 1000

Abbreviations: I&R, infection and recovery; OA, occupational asthma; RDR, risk difference ratio.

(RDR) which is the hypothetical $rr_{\alpha\gamma}$ for each scenario (each risk comparison). For scenarios in which baseline risks were equal (Scenarios 1 and 2), these probabilities were chosen based on literature informing baseline probabilities of asthma among nurses (Wilson, Mussio, et al. 2022). This survey advances the work from Wilson et al. (2022) in that we explore additional scenarios, described below, and recruited from a larger sample of RNs (Section 2.4).

We defined OA onset in the next year as a lifelong condition which will require management (medication, inhalers, etc.) and which could be exacerbated by the participant's job. In the case of I&R, RVI in the next year included a 60% chance of experiencing symptoms if infected, informed by roughly 40%–45% of individuals infected with SARS-CoV-2 being asymptomatic according to (Oran and Topol 2020), and would resolve in 2 weeks or less without long-term effects. In the case of I&D, RVI in the next year included symptoms, painful and difficult breathing, and ultimately would be fatal.

Figure 1 shows a complete example of how the scenarios were presented to the participant. Participants were first introduced to the scenario, given baseline probabilities of OA and infection and the specified outcome (i.e., recovery or death), referred to as "Healthcare Environment 1." Following standard RRTO elicitation practice, they were then told they must choose to work at a new healthcare environment, where either the risk of OA increases or where the risk of infection increases, called "Healthcare Environment 2" or "Healthcare Environment 3." They could also indicate they were indifferent to the choice, that is, they did not mind which healthcare environment they moved to. After making their choice, participants were then given an open-ended question asking them why they chose that specific option. A second question was asked on the basis of the RRTO choice for the relevant scenario, in which the participants were asked to indicate the maximum risk (i.e., "tipping point risk") they were willing to accept for their chosen risk increase (healthcare environment) to keep their other risk unchanged at its baseline level. For example, if they chose to increase their OA risk to maintain their RVI risk, we asked how much OA risk they would be willing to take on to maintain their RVI risk before they revert back to their other risk. Although this does not capture the complexities likely to be associated with changes in cleaning and disinfection protocol changes (i.e., decreased OA risk with simultaneous increase in RVI or vice versa), the change of only one outcome at a time is a standard RRTO experimental design approach that allows the researcher to isolate the effect of one risk increase on decision-making.

2.2.3 | Sociodemographics and Controls

The last section of the survey included questions on prior experience with cleaning and disinfection at home and at work, work-related cleaning questions (including the experience of oneself or others contracting respiratory infections at work), and demographic questions. These questions were used as the experience, belief, and socioeconomic controls for the econometric analysis. Details on the qualitative analysis conducted for open-ended responses can be found in the Supporting Information section. We internally tested the survey for comprehension with those in our research and personal networks to get feedback on readability and visual design and to determine approximately how long it would take individuals to complete it. We then piloted the survey with 69 participants (Wilson, Mussio, et al. 2022) from an Arizona-based nurses association.

2.3 | Participant Recruitment

The University of Arizona Institutional Review Board approved our research protocol (STUDY00000188). Participants were recruited via email through the listserv containing 16,078 RNs, where the listserv was purchased from the Oregon State Board of Nursing. Participants were eligible to participate if they were 18 years or older, were an RN, had been in healthcare for at least 1 year, and did not have physician-diagnosed asthma. The email recruitment text was University of Arizona IRB approved and contained information about the purpose of the study, eligibility criteria, compensation information (a gift card), and a link to participate. Informed consent was provided at the beginning of the survey, and participants had to confirm consent and their eligibility before proceeding to the survey. The survey was developed in REDCap (Harris et al. 2009, 2019), and more details can be found in the Supporting Information section.

2.4 | Analytical Strategy

Following Mussio et al. (2024), and given that these are independent RRTO decisions, logit regression models were used to calculate the influence of demographic variables (gender [male as reference], minority status [non-white as a reference group], ethnicity [non-Hispanic/Latino as reference group]), experience variables (knowing anyone with asthma [Y/N], having had a respiratory infection from work [Y/N], knowing someone who had gotten a respiratory infection from work [Y/N], knowing someone who had been hospitalized [Y/N] or died [Y/N] from a respiratory infection, years in healthcare [6–10, 11–20, and 20+]), and scenarios on the likelihood of choosing to increase infection risk. Statistical analysis was conducted with STATA (version 19).

2.5 | Empirical Calculation of the Aggregate Context Premia

To estimate the aggregate context premia for each scenario, $\widehat{rr_{\alpha\gamma}}$, we followed the approach of Van Houtven et al. (2008) and Mussio et al. (2024). Van Houtven et al. (2008) adopted the approach outlined by Cameron and James (1987), applying a binary choice model to analyze responses to the RRTO choices and generate an aggregate estimate of the context premia analogous to a WTP calculation. For this, we assumed that $rr_{\alpha\gamma}$ for individual i can be expressed by the function $rr_{\alpha\gamma_i} = \beta X_i + \varepsilon_i$, where X_i is a vector of variables and $\varepsilon_i \sim N(0, \sigma^2)$. Within this approach, we estimated a binary choice model where the responses to the RRTO choices were our dependent variable (in our case, the four healthcare environment choice scenarios), and the different scenarios appeared as dummies in the econometric specification, which allowed us to calculate the context premia for the trade-offs in this sample of nurses.

Consider the following scenario. You work in a healthcare environment with the following risks associated with the use of cleaning and disinfection products and interaction with contaminated surfaces.

Your risk of **occupational asthma** is **6% (60 out of 1,000 people).**
Your risk of getting a **respiratory viral infection** from a contaminated surface is **6% (60 out of 1,000 people).**

Risks	Healthcare Environment 1
Asthma onset in the next year	**60 out of 1,000 people** In other words: • 6% chance you will develop asthma. • 94% chance you will not develop asthma.
Resiratory viral infection and subsequent recovery in the next year	**60 out of 1,000 people** In other words: • 6% chance you will get infected and recover. • 94% chance you will not get infected. • 0% chance you will get infected and die.

The information below specifies the expected symptoms and outcomes of these risks to provide further context.

Risks	Outcome Description
Asthma onset in the next year	• Lifelong condition • Will require management (medication, inhalers, etc.) • May be exacerbated by your job

You have to switch to Healthcare Environment 2 or Healthcare Environment 3, where a different cleaning and disinfection protocol is used. You cannot stay at Healthcare Environment 1.

At **Healthcare Environment 2**, your risk of **asthma onset** increases.

At **Healthcare Environment 3**, your risk of **respiratory viral infection** increases.

The current situation in each healthcare environment is as follows:

	Healthcare Environment 2	Healthcare Environment 3
Asthma onset in the next year	**120 out of 1,000 people** In other words: • 12% chance you will develop asthma. • 88% chance you will not develop asthma.	60 out of 1,000 people In other words: • 6% chance you will develop asthma. • 94% chance you will not develop asthma.
Respiratory viral infection and subsequent recovery in the next year	60 out of 1,000 people In other words: • 6% chance you will get infected and recover. • 94% chance you will not get infected. • 0% chance you will get infected and die.	**120 out of 1,000 people** In other words: • 12% chance you will get infected and recover. • 88% chance you will not get infected. • 0% chance you will get infected and die.

Which healthcare environment do you prefer?

* must provide value

- ○ Healthcare Environment 2 (increased asthma risk with respect to Healthcare Environment 1)
- ○ Healthcare Environment 3 (increased respiratory viral infection risk with respect to Healthcare Environment 1)
- ○ I am equally happy with either option.

reset

Please explain in your own words why you chose the option that you did.

* must provide value

Expand

FIGURE 1 | Example of scenario setup in survey (Scenario 1 (baseline risk: OA = I&R, equal risk increase, OA, and I&R)).

In addition, as the aim of this study was to understand the impact of cleaning and disinfection practices in health workplaces in risk trade-offs, we used, as dependent variable, the choice to move to the healthcare environment with the increased risk of contracting an RVI. As explanatory variables, our model included dummies for the choice scenario, as well as socioeconomic and experience with the relevant risks as controls. For the specification of the econometric model, we follow the prior literature (Masterman and Viscusi 2025; Chilton et al. 2024; Mussio et al. 2024; Van Houtven et al. 2008), which specifies how to model decisions, scenarios, and unobserved heterogeneity:

$$\text{HCE\_}RI_i = \beta_1 + \beta_2 S_{2i} + \beta_3 S3_i + \beta_4 S4_i + \beta_5 X_i + \varepsilon_i \quad (7)$$

where $\text{HCE\_}RI_i$ is equal to 1 if the participant chose the healthcare environment with the increase in RVI risk. S_{ji} ($j = 2,3,4$) are dummies for Scenarios 2, 3, and 4 (with Scenario 1 as the base), and X_i includes socioeconomic and experience variables.

Therefore, with this model specification and following the prior literature on willingness to pay optimal design principles (Alberini 2005), we were able to tease out the average effects of each scenario with respect to the omitted scenario, where the aggregate context premium for each scenario (compared to Scenario 1; Beesley 1965; Gaudry et al. 1989; Daly et al. 2012) was estimated as

$$\widehat{rr_{\alpha\gamma,j}} = -\beta_1/\beta_j, j = 2,3,4 \quad (8)$$

For the purposes of the estimation of these models and the context premia, we included three variations. The first model only included the scenarios (Van Houtven et al. 2008). The second specification added experience variables, including years working in healthcare, experience with cleaning and disinfection, OA, and respiratory infection of oneself and others. The third specification added demographic variables, including gender, ethnicity, and race. Because each participant answered four RRTO questions, we clustered our standard errors by individual. Table 2 describes and defines all the variables used in the calculation of the context premia. As a robustness test, we included specifications without the participants answering indifference between the two healthcare scenarios.[1]

2.6 | Critical Concentration Analysis

We used QMRA to calculate the critical concentrations of SARS-CoV-2 viral particles on fomites that would yield acceptable risks, informed by sample-level summary statistics of tipping points elicited from the RRTO survey. These critical concentrations are important for evaluating the needed performance of hygiene interventions (e.g., UV or chemical disinfection of surfaces) to protect nurses at acceptable levels of occupational RVI.

For the QMRA model, an approach described by Wilson et al. (2025) was conducted. This includes using summary statistics of individual tipping points to inform a sample-level threshold, consistent with approaches in current microbial risk assessments in which a single given tolerable risk level is used to evaluate whether current environmental conditions are appropriate or are in need in additional controls. In this study, risk thresholds were informed by the 1st, 5th, and 50th percentiles of tipping points chosen by individual participants for the scenarios with real-world risks (Scenarios 3 and 4) and the arithmetic mean of accepted infection risks for Scenarios 3 and 4, separately.

For those who indicated a preference for one of the two healthcare environments, risk thresholds were set equal to the highest infection risk that an individual said they would accept: Either the baseline infection risk if they chose to increase their asthma risk (healthcare environment B) or the increased infection risk if they chose to maintain their original (healthcare environment A) asthma risk (healthcare environment C). For those who indicated that the healthcare environments were equally good, three different approaches were compared for robustness, described in detail in the Supporting Information section.

Exposure and dose-response models and parameters and distributions described by Wilson et al. (2025) were used, where infection risks were estimated for a 12-h shift infection risk based off of a steady-state concentration of virus accumulating on the hand due to hand-to-fomite contacts and an anticipated amount of viral transfer to the face given the rate of hand-to-face contacts (Beamer et al. 2015). Wilson et al. (2025) present a framework for how to utilize RRTO survey data to inform QMRA with simulated data, whereas this study utilizes real-world data from RNs, informing realistic microbial concentrations on surfaces that would yield acceptable risks.

Parameters and their distributions and references can be found in Table S6. Doses were then inputted into an exponential dose-response curve to estimate infection risk for a 12-h shift. This was then used to inform an annual risk, to be consistent with the framing of the survey, assuming three shifts per week and 48 working weeks per year ($3 \times 48 = 144$ shifts) (Wilson, Mussio, et al. 2022). The adjustment was made using the following equation:

$$P_{\text{infection,annual}} = 1 - \left(1 - P_{\text{infection,shift}}\right)^{144 \text{ shifts}} \quad (9)$$

Subsequent risk of I&R and risk of I&D were calculated using conditional probabilities used by Wilson et al. (2022) (Wilson, Mussio, et al. 2022) and originally informed by proportions of nurses who died of COVID-19 infections and anticipated proportions of those who will have symptomatic illness:

$$P_{\text{infection, death}} = P_{\text{infection,annual}} \times P_{\text{symptomatic|infection}} \times P_{\text{death|symptomatic}} \quad (10)$$

where $P_{\text{symptomatic|infection}}$ was set at 0.6, informed by (Oran and Topol 2020). $P_{\text{death|symptomatic}}$ was set at 0.0064, informed by the proportion of deaths among COVID-19 cases among nurses (Hughes et al. 2020). This approach is described in more detail by Wilson et al. (2022) (Wilson, Mussio, et al. 2022) in the Supporting Information section. Risk of infection and subsequent recovery was calculated by multiplying the annual risk of infection by the complement of risk of symptomatic illness and subsequent death:

$$P_{\text{infection,recovery}} = P_{\text{infection,annual}} \times (1 - P_{\text{symptomatic|infection}} \times P_{\text{death|symptomatic}} \quad (11)$$

TABLE 2 | Description of variables used in the analysis.

Variable	Description	% of participants
S1	=1 if participant completed Scenario 1 (baseline risk: OA = I&R, equal risk increase, OA, and I&R)	0.25
S2	=1 if participant completed Scenario 2 (baseline risk: OA = I&D, equal risk increase, OA, and I&D)	0.25
S3	=1 if participant completed Scenario 3 (baseline risk: OA > I&R, increase in risk, OA > I&R)	0.25
S4	=1 if participant completed Scenario 4 (baseline risk: OA > I&D, increase in risk: OA > I&D)	0.25
Years healthcare 6–10	=1 if participant has worked in healthcare for 6–10 years	0.24
Years healthcare 11–20	=1 if participant has worked in healthcare for 11–20 years	0.27
Years healthcare 20+	=1 if participant has worked in healthcare for over 20 years	0.27
Work long shift	=1 if the participant works shifts of more than the median time (10 h)	0.65
Cleaning negative effects	=1 if the participant experienced negative health effects from cleaning and disinfection activities at work	0.13
Asthma know anyone	=1 if they know anyone with asthma at work or outside of work	0.74
Respiratory infection	=1 if participant has contracted a respiratory viral infection from work	0.51
Respiratory infection others	=1 if participant knows anyone who has contracted a respiratory viral infection from work	0.86
Respiratory infection others hospitalization	=1 if participant knows anyone who has been hospitalized for a respiratory viral infection due to an infection from work	0.36
Respiratory infection others death	=1 if participant knows anyone who has died from respiratory viral infection from work	0.14
Female	=1 if participant self-identifies as female	0.82
Minority	= 1 if participant's race is not white	0.10
Hispanic	=1 if participant is Latin/Hispanic	0.10
N	Number of participants (responses to scenarios across all participants)	453 (1812)

Abbreviations: I&R, infection and recovery; OA, occupational asthma.

For each run of the models, 10,000 concentrations of viral particles on surfaces were randomly sampled from a wide distribution (uniform, min = −5, max = 5 $\log_{10}$ viral particles/cm^2) (Wilson et al. 2025), and the minimum concentration that yielded a risk (I&R or I&D, depending upon the scenario) at the threshold (i.e., the critical concentration) was identified. This was done 10,000 times, and summary statistics of the critical concentrations across these runs were calculated to inform overall critical concentrations that corresponded to each risk threshold.

3 | Results

3.1 | Survey Participants

Four hundred fifty-three participants recruited through the Oregon State Board of Nursing listserv completed an online REDCap RRTO, experiences, and demographics survey developed by the research team based on the target population and prior literature (Mussio et al. 2024; Chilton et al. 2024). The survey yielded a 2.8% response rate (453/16,078). This is comparable to documented response rates for email recruitment methods of large target samples of nurses (e.g., 3.4% of 4540 nurse practitioners recruited by Grant et al. (2021); 2% of 3700 members of a nursing society recruited by Wilson, Mussio, et al. (2022) but lower than those reported in other studies, especially those with smaller target samples (L'Ecuyer et al. 2023). We address this further in Section 4.

The demographics of participants were roughly comparable to demographics of RNs in Oregon based on 2015–2016 data from the Oregon Health Authoirty (2016) and from 2020 data from the PhilipT R. Lee Institute for Health Policy Studies (Bates et al. 2022) (Table S5). Due to a lack of overlapping categories, descriptive comparisons as opposed to inferences were made. A large proportion of female participants were consistent with the RN Oregon population (82.1% in our study, 82%–88% reported for state data) (Table 3). The age ranges of our participants included higher proportions of those between 26 and 35 (35.8%) relative to approximately 19%–20% reported between 25 and 34 years of age in state data, and a lower proportion of those 55–65 (11.7% in our study, roughly 20%–22% reported in state data). This may be in part due to our recruitment strategy using email, where older participants may have less technology access/comfort with participating virtually. Our participants had a higher proportion of Hispanic/Latino individuals (7.2% in our study vs. 3%–4% reported in state data) and a higher proportion of those reporting being Black/African American (2.9% in our study, <2% reported in state data). In comparing years of experience among our participants to years of RN registration reported by the state board, distribution of years of experience and RN registration appeared roughly comparable. With limited overlap of type of primary position and primary setting, there are limited direct comparisons, but of those available, the participants in our study were comparable in terms of a high proportion of those in direct patient care (81.2% in our study, 67.8% in 2015–2016 data) and a majority working in hospital environments (66.0% in our study, 56%–58% reported in state data).

Thirteen percent of participants indicated that they experience negative health effects (e.g., skin issues, allergic reactions, occasional cough, headache, throat and nasal irritation, watering eyes, and nausea) from cleaning and disinfection activities at work. Seventy-four percent reported knowing someone with asthma (Table 2). Eighty-six percent reported knowing someone who has contracted an RVI from work, and 51% reported acquiring a viral infection themselves. Thirty-six percent reported knowing someone who had been hospitalized for this, and 14% reported knowing someone who has died from this (Table 2). These are important factors considering healthcare workers, and nurses who provide direct patient care, specifically, face generally high risks for occupational respiratory infections (De Perio et al. 2020; Peytremann et al. 2020).

3.2 | Qualitative Analysis

Nineteen percent (n = 84) of nurses report that they tried to change cleaning/disinfection product choices or protocols in the workplace (Table 4). From those, almost half of those efforts were taken into account and were successful (N = 46), but a third (N = 31) stated that they were not (Table 4). We received 30 responses to the protocol change open question. Half of these responses were directly related to negative experiences with management and administration (N = 15), whereas a third (N = 10) included statements related to costs. More details on qualitative analysis findings can be found in the Supporting Information section.

3.3 | RRTO Results and Context Premia Calculation

In Scenario 1 (baseline risk: OA = I&R, equal risk increase, OA, and I&R), a majority of nurses (85.7%) indicated a preference of contracting an RVI over OA (in the next year) (Figure 2). When the risk of RVI specified an outcome of death (Scenario 2, baseline risk: OA = I&D, equal risk increase, OA, and I&D), the proportion of participants choosing the risk of contracting an RVI was reduced to 32% (Figure 2). In both scenarios where the risk of OA onset was larger than contracting an RVI and recovering (Scenario 3, baseline risk: OA > I&R, increase in risk, OA > I&R) or dying (Scenario 4, baseline risk: OA > I&D, increase in risk: OA > I&D), the majority of nurses preferred contracting the RVI (88.3% and 77.3%, respectively) (Figure 2). In the latter scenarios, when the risks of RVI were very small compared to those of OA (Table 1), a majority of people preferred the RVI, which was specified to pose short-term effects, resolving in 2 weeks or less, compared to the lifelong impact of OA (Figure 1).

The summary results of our logit specifications are found in Table 5. Consistent with the distribution of responses in Figure 2, all specifications show that there are significant differences in the responses between Scenario 1 (baseline risk: OA = I&R, equal risk increase, OA, and I&R) and Scenario 2 (baseline risk: OA = I&D, equal risk increase, OA, and I&D), as well as between Scenario 1 (baseline risk: OA = I&R, equal risk increase, OA, and I&R) and Scenario 4 (baseline risk: OA > I&D, increase in risk: OA > I&D). There are no significant differences in the choices between Scenario 1 (*increase in risk of OA = increase in risk of infect and recover)* and Scenario 3 (*increase in risk of OA > increase in risk of infect and recover)*. Using Specification (1), our logit results translate in a significant average probability of choosing healthcare Scenario 3, with the increase in risk of contracting an RVI of 86% for Scenario 1 (baseline risk: OA = I&R, equal risk increase, OA, and I&R), of 32% for Scenario 2 (baseline risk: OA = I&D, equal risk increase, OA, and I&D), and of 77% for Scenario 4 (baseline risk: OA > I&D, increase in risk: OA > I&D; see Figure 3, the probability of Scenario 3 is 88% but it is not significantly different from Scenario 1, as found in the distribution of responses).

TABLE 3 | Demfographics of participants in comparison to those of Oregon registered nurses (RNs).

Demographic variable		% (*n*)
Gender	Male	16.3% (74)
	Female	82.1% (372)
	Non-binary	1.1% (5)
	Other	0.2% (1)
	Choose not to respond	0.2% (1)
Age (year)[a]	18–25	5.7% (26)
	26–30	18.1% (82)
	31–35	17.7% (80)
	36–40	14.1% (64)
	41–45	11.0% (50)
	46–55	17% (77)
	56–65	11.7% (53)
	65+	4.4% (20)
	Choose not to respond	0.2% (1)
Ethnicity[b]	Latinx/Hispanic	7.2% (33)
	Non-Latinx/Hispanic	83.4% (378)
	Choose not to respond	9.3% (42)
Race[b]	American Indian/Alaska Native	0.7% (3)
	Asian	4.0% (18)
	Native Hawaiian or Other Pacific Islander	0.2% (1)
	Black or African American	2.9% (13)
	White	88.1% (399)
	Multiple races	2.2% (10)
	Other	0.4% (2)
	Don't know/Prefer not to answer	1.5% (7)
Years of experience[c]	1–5	21.4% (97)
	6–10	24.1% (109)
	11–20	27.4% (124)
	20+	27.2% (123)
	Choose not to respond	0% (0)
Primary position	Direct patient care	81.2% (368)
	Administrative/Leadership	11.0% (50)
	Education	2.4% (11)
	Other	5.3% (24)
Primary work setting for direct patient care	Hospital	66.0% (243)
	Outpatient clinic	24.5% (79)
	Home healthcare	3.8% (14)
	Long-term care	2.4% (9)
	Military	0.3% (1)
	School	0.5% (2)
	Other	5.4% (20)

(Continues)

TABLE 3 | (Continued)

[a]Age categories for state board of nursing data are roughly comparable to those in our study. Categories that were compared are stated above percentages in the state board of nursing data column. State board of nursing percentages for age were visually estimated from Figure 2 2016 data in the Characteristics of the Nursing Workforce in Oregon 2016 report.

>[b]Race and ethnicity were combined categories in reported state board of nursing data. We assumed that the percent of non-Hispanic/Latino individuals was equal to the complement of the percent of Hispanic/Latino individuals reported. The percentages for racial groups do not sum to 100% for state board of nursing because of the combination of race and ethnicity categories in the state board of nursing data.

[c]State board of nursing data are of years registered.

TABLE 4 | Cleaning and disinfection protocol responses.

	Have you ever tried to change cleaning/disinfection product choices or protocols in the workplace? % (*N*)	**Were your suggestions or concerns taken into account? % (*N*)**
Yes	18.5 (84)	55 (46)
No	79 (359)	37 (31)
I don't know	2 (8)	7 (6)
Choose not to respond	0.5 (2)	1 (1)
N	*453*	*84*

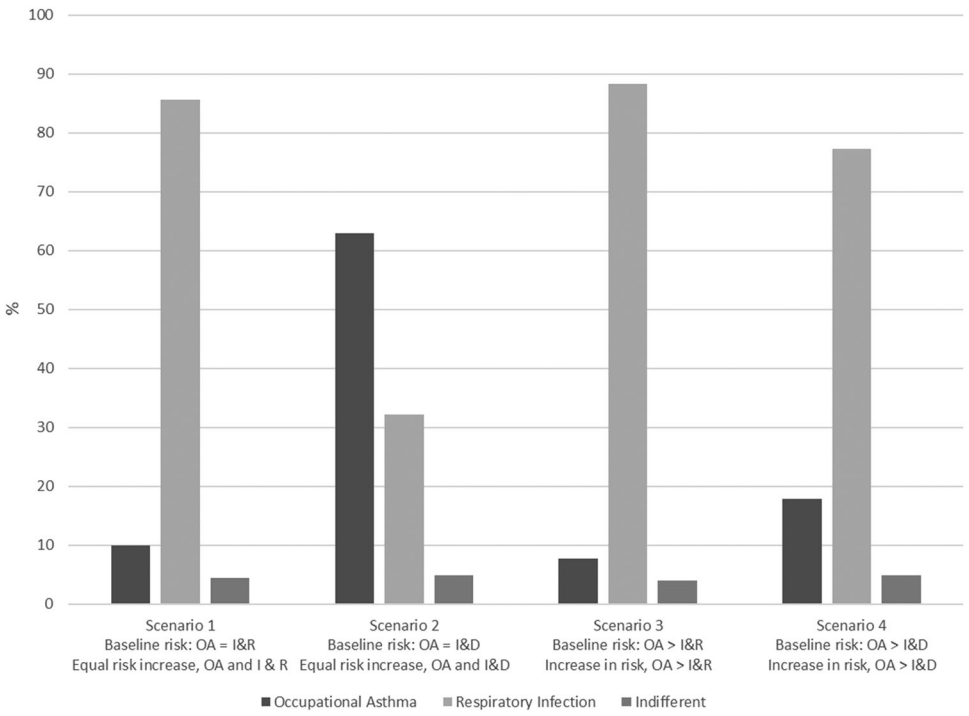

FIGURE 2 | Distribution of the healthcare environment choices, by scenario and chosen risk increase (%).I&R, infection and recovery; OA, occupational asthma.

In terms of systematic heterogeneity, knowing another person who has contracted an RVI is negatively related to the choice of Healthcare Environment 3, where the risk of contracting the RVI increases (compared to the baseline risks). Other experience variables are either not significant or marginally significant.

For examining the decisions with respect to the baseline Healthcare Scenario 1 (60 in 1000 people in the next year for both risks), we focus on the no constant specification in Table 5. We can infer that in the cases where there is an option to *infect and recover* (Scenarios 1 and 3), respondents are more likely to move from Healthcare Environment 1 to Healthcare Environment 3, which has an increase in the risk of RVI rather than move to Healthcare Scenario 2 (with an increase in the risk of OA). In the case of Scenario 2 (Baseline risk: OA = I&D, equal risk increase, OA, and I&D), participants are less likely to move to Healthcare Environment 3 and prefer to move to Healthcare Environment 2, which has an increase in OA risk.

TABLE 5 | Summary results of the logit specifications (coefficients).

d.v. Choice is healthcare environment with increase in risk of RVI	Scenarios only	Scenarios + experience	Scenarios + experience + demographics
S2	−2.53***	−2.56***	−2.58***
	(0.16)	(0.16)	(0.16)
S3	0.23	0.24	0.24
	(0.15)	(0.15)	(0.15)
S4	−0.56***	−0.57***	−0.57***
	(0.15)	(0.15)	(0.15)
Cleaning negative effects		−0.01	0.03
		(0.23)	(0.24)
Asthma know anyone?		0.15	0.14
		(0.19)	(0.19)
Respiratory infection		−0.07	−0.07
		(0.16)	(0.17)
Respiratory infection others		0.55**	0.54**
		(0.26)	(0.26)
Respiratory infection others hospitalization		−0.36*	−0.37*
		(0.19)	(0.20)
Respiratory infection others death		0.16	0.22
		(0.26)	(0.25)
Constant	1.79***	1.42***	1.40***
	(0.13)	(0.29)	(0.34)
Cluster by participant	*Yes*	*Yes*	*Yes*
Controls			
Experience in healthcare	*No*	*Yes*	*Yes*
Socioeconomic	*No*	*No*	*Yes*
Observations	1812	1812	1812

Note: Dependent variable is 1 for the participant choosing the Healthcare environment with the respiratory infection risk increase, 0 otherwise. Standard deviation between parentheses, clustered by participant. As a reminder, dummies for all scenarios are defined as follows: S1–S4 as follows (from Table 2): Scenario 1 (baseline risk and base comparison: OA = I&R, equal risk increase, OA, and I&R), Scenario 2 (baseline risk: OA = I&D, equal risk increase, OA, and I&D), Scenario 3 (baseline risk: OA > I&R, increase in risk, OA > I&R), Scenario 4 (baseline risk: OA > I&D, increase in risk: OA > I&D).

Abbreviation: RVI, respiratory viral infection

*$p = 0.10$.

**$p = 0.05$.

***$p = 0.01$.

Using the econometric specifications in Table 5, we estimate the context premia for each scenario. As a reminder, if the context premium is 1, this means that the participant values preventing contracting OA and RVI in both scenarios equally in comparison with the baseline scenario. If the premium is more than 1, the participant weighs the risk of contracting an RVI, more than the risk of contracting OA in comparison with the baseline scenario, and if it is less than 1, the participant weighs the risk of contracting OA, more than the risk of contracting an RVI in comparison with the baseline scenario.

Table 6 shows the context premia for our three model specifications. If we take Specification (1) in Table 5, Equation (8) translates into a context premia value of 0.71 against Scenario 2 (Baseline risk: OA = I&D, equal risk increase, OA, and I&D). This means that on average, our sample weighs the risk of contracting OA at 0.71 times that of the risk of contracting an RVI compared to the case where the increase in risk of OA is equal to the increase in risk of infect and recover. For Scenario 4, where the *increase in risk of OA > increase in risk of infect and death*, the context premium is 3.17. This means that on average, our sample weighs the risk of contracting OA at 3.17 times that of the risk of contracting an RVI compared to Scenario 1 (baseline risk: OA = I&R, equal risk increase, OA, and I&R). Similar but slightly lower values are found when systematic heterogeneity (controls) is included in the model estimations (Specifications 2 and 3 in Table 5).

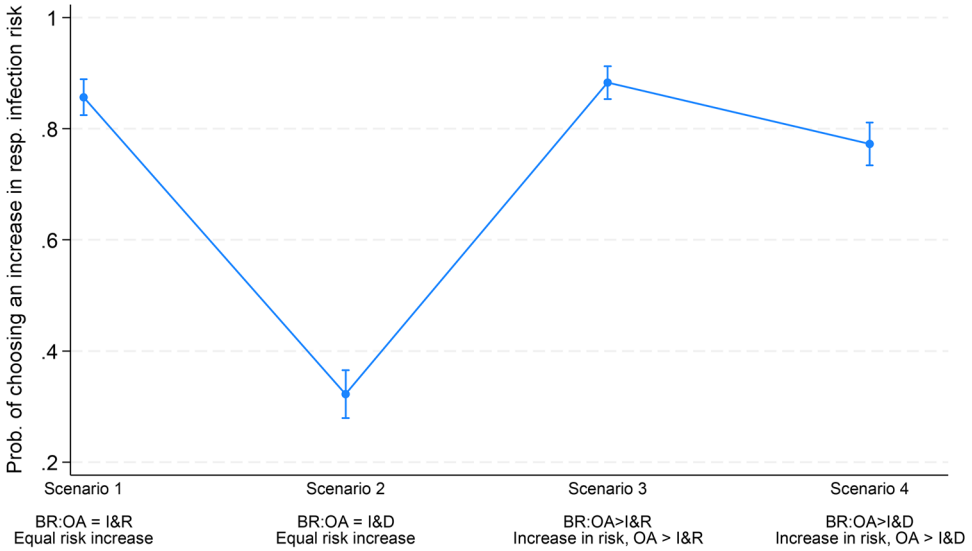

FIGURE 3 | Probability of choosing an increase in respiratory infection risk (instead of an increase in occupational asthma), by scenario. Probabilities calculated based on specification (1) of Table 5. I&R, infection and recovery; OA, occupational asthma.

TABLE 6 | Context premia calculation results by scenario.

Comparator scenario is Scenario 1	Scenarios only	Scenarios + experience	Scenarios + experience + demographics
Scenario 2	0.71***	0.58***	0.54***
	(0.03)	(0.11)	(0.13)
Scenario 3	−7.62	−6.13	−5.89
	(5.13)	(4.40)	(4.22)
Scenario 4	3.17***	2.62***	2.44***
	(0.68)	(0.70)	(0.72)

Note: Context premia are calculated based on Equation (8), using the results from Table 5. Following Mussio et al. (2024), the premia using a logit specification is calculated as (−constant/scenario dummy). This means that a negative coefficient in the logit regressions increases the premia. Scenario 1 (baseline risk: OA = I&R, equal risk increase, OA, and I&R), Scenario 2 (baseline risk: OA = I&D, equal risk increase, OA, and I&D), Scenario 3 (baseline risk: OA > I&R, Increase in risk, OA > I&R), Scenario 4 (baseline risk: OA > I&D, Increase in risk: OA > I&D), where * indicates signifiance at level p = 0.10, ** indicates signifiance at level p = 0.05, and *** indicates significance at p = 0.01 level.

*$p = 0.10$.

**$p = 0.05$.

***$p = 0.01$.

3.4 | Risk Thresholds

As described below, we used the tipping points from the surveys to inform RVI risk thresholds for fomite hygiene and used a variety of summary statistics to demonstrate how varying acceptable risks would yield different risk thresholds at a sample level, as opposed to individual-level thresholds, for informing risk analysis. This is consistent with current microbial risk assessment practices where a single risk threshold is typically used as representative of tolerable risk across an entire population.

For Scenario 3 (baseline risk: OA > I&R, increase in risk, OA > I&R), the acceptable infection and subsequent recovery risks ranged from 8.0×10^{-5} to 6.5×10^{-1}, with a mean of 1.3×10^{-1} (SD = 2.1×10^{-1}). For Scenario 4 (baseline risk: OA > I&D, increase in risk: OA > I&D), the acceptable infection and subsequent death risks ranged from 3.0×10^{-7} to 6.5×10^{-1}, with a mean of 2.7×10^{-2} (SD = 8.6×10^{-2}). The summary statistics used to inform risk thresholds for reverse QMRA modeling can be seen in Table 7, and histograms of tipping points can be seen in Figure S3. The first and fifth percentiles for both scenarios were equal to the lowest possible acceptable infection risks in both scenarios. The median acceptable infection risks were roughly three orders of magnitude apart (similar to the 2.4 $\log_{10}$ difference between baseline I&R and I&D risks in these scenarios), with greater risk acceptance for I&R than infection and subsequent death. There was roughly one order of magnitude difference in the arithmetic mean of acceptance risks.

When indifferent individuals (i.e., those who said they were equally happy with healthcare environment B or C) were assumed to accept the higher infection risk, calculated tipping points based on quantiles or arithmetic means were nearly identical to those calculated with the removal of those who indicated

TABLE 7 | Tipping point calculations per scenario and approach with those indicating indifference.

Approach with indifferent responses	Scenario	Tipping point quantile or summary statistic			
		0.01	0.05	0.5	Mean
Removal	Scenario 3	8.0×10^{-5}	8.0×10^{-5}	1.0×10^{-2}	1.3×10^{-1}
	Scenario 4	3.0×10^{-7}	3.0×10^{-7}	3.0×10^{-5}	2.7×10^{-2}
Assume higher infection risk is acceptable	Scenario 3	8.0×10^{-5}	8.0×10^{-5}	1.0×10^{-2}	1.2×10^{-1}
	Scenario 4	3.0×10^{-7}	3.0×10^{-7}	3.0×10^{-5}	3.1×10^{-2}
Assume lower infection risk is acceptable	Scenario 3	8.0×10^{-5}	8.6×10^{-3}	1.0×10^{-2}	1.2×10^{-1}
	Scenario 4	3.0×10^{-7}	3.0×10^{-5}	3.0×10^{-5}	2.6×10^{-2}

Note: Scenario 1 (baseline risk: OA = I&R, equal risk increase, OA, and I&R), Scenario 2 (baseline risk: OA = I&D, equal risk increase, OA, and I&D), Scenario 3 (baseline risk: OA > I&R, increase in risk, OA > I&R), Scenario 4 (baseline risk: OA > I&D, increase in risk: OA > I&D).

indifference (Table 7). When instead, indifferent individuals were assumed to accept the lower infection risk, the 0.05 quantile was two orders of magnitude larger when the lower infection risk was assumed for indifferent responses relative to when they were removed (e.g., 3.0×10^{-5} vs. 3.0×10^{-7} for Scenario 4) (Table 7).

3.5 | QMRA Results and Critical Concentrations

Regardless of the approach used to inform a tipping point for those who indicated indifference in healthcare environment choice, critical concentrations were nearly identical between Scenario 3 (baseline risk: OA > I&R, increase in risk, OA > I&R) and Scenario 4 (baseline risk: OA > I&D, increase in risk: OA > I&D; Table 8). For example, the critical concentrations for a risk threshold set to the 1st quartile of tipping points were 2.8×10^{-7} viral particles/cm^2 for Scenario 3 and 2.7×10^{-7} viral particles/cm^2 for Scenario 4. Critical concentrations were identical between risk thresholds set to the 0.01 and 0.05 quantiles of the tipping points. However, when the risk thresholds were set to the medians of tipping points, the critical concentrations were increased by roughly 2 $\log_{10}$.

In the case of critical concentrations for risks set to the mean of tipping points, critical concentrations were only calculated for Scenario 3 (baseline risk: OA > I&R, increase in risk, OA > I&R). This is because the maximum infection risk that can be calculated with the assumed probability of symptoms given infection and the probability of death given symptoms is below the risk thresholds from means of tipping points. Even with a risk of nearly 1, the highest infection risk that can be calculated is 0.00384 (1 probability of infection × 0.6 probability of symptoms given infection × 0.0064 probability of death given symptoms, described in Section 2), and the lowest infection risk from mean tipping points is 0.026 (Table 7). This was not an issue in Scenario 3, because the maximum risk of I&R that could be estimated was 0.996 (1 probability of infection × (1 − 0.6 probability of symptoms given infection × 0.0064 probability of death given symptoms), described in Section 2), and the smallest risk threshold based on mean tipping points was 0.12 (Table 7). Critical concentrations for Scenario 3 ranged from 4.5×10^{-4} to 4.7×10^{-4} viral particles/cm^2, with variation depending upon how the tipping points were treated for those who expressed indifference in choosing one healthcare environment over another (Table 8).

4 | Discussion

4.1 | Key Findings From RRTO Analysis

The majority of nurses indicated a preference of contracting an RVI over OA in the next year, except when the risk of RVI and subsequent death was equal to that of OA (Figure 1). Choices were, in part, influenced by whether someone knew another person who had contracted an RVI, where knowing someone who had contracted an RVI was negatively related to choosing an increase in RVI. Without controlling for experiences and demographics, context premia varied widely among the scenarios, where a context premium of 1 means participants equally valued the prevention of OA and RVI, and a context premium greater than 1 means a higher value is placed on preventing RVI than OA. Relative to Scenario 1 (baseline risk: OA = I&R, equal risk increase, OA, and I&R), participants weighed the prevention of contracting OA less than the prevention of infection in Scenario 2 (baseline risk: OA = I&D, equal risk increase, OA, and I&D) and Scenario 3 (baseline risk: OA > I&R, increase in risk, OA > I&R) on average. When infection was specified to be a much smaller risk than OA (Scenario 4, baseline risk: OA > I&D, increase in risk: OA > I&D), the prevention of OA was valued over three times greater than the prevention of RVI (Table 6). When experiences and demographics were accounted for, the context premia still had a consistent sign (i.e., positive or negative; Table 6). Still, these differences in context premia across scenarios imply that relative valuations can change depending upon the expected circumstances of the outcome (e.g., recovery vs. death) and the differences in the risk magnitudes.

4.2 | Key Findings on Critical Concentrations and Acceptable Risk Thresholds

In our study, nurses were inclined to take on increased RVI risk to maintain OA risks in all scenarios except Scenario 2 (baseline risk: OA = I&D, equal risk increase, OA, and I&D), but the amount of

TABLE 8 | Summaries of concentrations (infectious viral particles/cm^2) yielding risk thresholds presented by risk threshold and approach for tipping points for those indicating indifference.[a]

Approach with indifferent responses	Scenario	Critical concentrations (viral particles/cm^2), mean (SD)			
		0.01	0.05	0.5	Mean
Removal	Scenario 3	2.8×10^{-7}	2.8×10^{-7}	3.5×10^{-5}	4.7×10^{-4}
		(8.4×10^{-8})	(8.4×10^{-8})	(1.1×10^{-5})	(1.4×10^{-4})
	Scenario 4	2.7×10^{-7}	2.7×10^{-7}	2.7×10^{-5}	b
		(8.2×10^{-8})	(8.2×10^{-8})	(8.1×10^{-6})	
Assume higher infection risk is acceptable	Scenario 3	2.8×10^{-7}	2.8×10^{-7}	3.5×10^{-5}	4.5×10^{-4}
		(8.4×10^{-8})	(8.4×10^{-8})	(1.1×10^{-5})	(1.4×10^{-4})
	Scenario 4	2.7×10^{-7}	2.7×10^{-7}	2.7×10^{-5}	b
		(8.1×10^{-8})	(8.1×10^{-8})	(8.2×10^{-6})	
Assume lower infection risk is acceptable	Scenario 3	2.7×10^{-7}	2.8×10^{-7}	3.5×10^{-5}	4.5×10^{-4}
		(8.5×10^{-8})	(8.5×10^{-8})	(1.1×10^{-5})	(1.3×10^{-4})
	Scenario 4	2.7×10^{-7}	2.7×10^{-7}	2.7×10^{-5}	b
		(8.0×10^{-8})	(8.1×10^{-8})	(8.3×10^{-6})	

[a]Risk is a probability of infection and subsequent recovery or infection and subsequent death in a year, depending upon the scenario.

[b]It was not possible to estimate risk of infection and death greater than 0.0038, equal to a probability of nearly 1 multiplied by the proportion expected to be symptomatic (0.6) and the proportion of those who are symptomatic who will die (0.0064). The threshold for Scenario 4 informed by the mean of tipping points is greater than 0.0038, meaning that no concentration can generate a lack of compliance. This is addressed in more detail in the Section 4. Scenario 1 (baseline risk: OA = I&R, equal risk increase, OA, and I&R), Scenario 2 (baseline risk: OA = I&D, equal risk increase, OA, and I&D), Scenario 3 (baseline risk: OA > I&R, increase in risk, OA > I&R), Scenario 4 (baseline risk: OA > I&D, increase in risk: OA > I&D).

risk they were willing to take on differed by whether they were considering risk of I&R or risk of I&D. This difference in tolerable risks translated to nearly equal critical concentrations between the two scenarios; that is, concentrations that yielded acceptable risks of infection and subsequent recovery and acceptable risks of infection and subsequent death were nearly equal.

The use of different summary statistics of tipping points to inform risk thresholds had notable impacts on critical concentrations. Although 1st and 5th quantiles generated similar risk thresholds and critical concentrations, a nearly 2-$\log_{10}$ increase in critical concentrations was seen from 5th to 50th quantile risk thresholds. There were challenges in using mean tipping points, because the tolerable risk for Scenario 4 (baseline risk: OA > I&D, increase in risk: OA > I&D), in this case, was greater than what was assumed possible in the model, given a very low probability of death for those who would have symptomatic illness. Despite this numerical limitation, it is likely that a more appropriate threshold for real-world implementation would be the 1st or 5th quantile, because these would protect 99% or 95% of the population, respectively, at or below a risk deemed acceptable, if (1) tipping points are reflective of acceptable risks and (2) the tipping points from survey data reflect risk acceptability for the population, at large.

Assuming these thresholds indicate acceptable risk to nurses, comparisons of these risk thresholds to those used in fomite-specific and other QMRAs can provide insights into whether current risk assessments are likely protecting nurses at acceptable levels. Microbial risk assessments, however, often use an infection risk without specifying an outcome (recovery or death). If we adjust the acceptable infection and subsequent recovery probabilities to estimate a probability of infection (divide by 1—probability of symptoms given infection × probability of death given symptoms), these range from 8×10^{-5} (based on 0.01 of tipping points with removal of indifferent individual data) to 1.3×10^{-2} (based on the mean of tipping points with removal of indifferent individual data). The more conservative end of this range is comparable to an annual risk threshold of 1×10^{-4} within drinking water contexts. In the context of fomites, infection risk from a single fomite contact directly followed by a hand-to-face contact is typically compared to 1×10^{-4} and 1×10^{-6} risk threshold (Centers for Disease Control and Prevention 2021; Ryan et al. 2014; Wilson et al. 2021). Relating our RVI risk thresholds to a single fomite touch, single face touch scenario can be challenging due to lack of data regarding how many fomite contacts are directly followed by hand-to-face contacts, especially in occupational contexts in healthcare environments where nurses are likely engaging in hand hygiene behavior. Future work is needed to determine how the temporal framing of the risk (e.g., a single fomite touch, a shift, and a year) influences the acceptable risk levels informed by tipping points and what this may mean for differences in critical concentrations.

In the case of our framing (i.e., annual risk of infection and subsequent recovery or of infection and subsequent death), critical concentrations were nearly identical for both scenarios, implying that the framing of the scenario (I&R vs. I&D) affected the acceptable risk thresholds but in a way in which they were seemingly

adjusted for the difference in risk of infection leading to recovery versus death. These choices started with much smaller risk values for Scenario 4 (baseline risk: OA > I&D, increase in risk: OA > I&D), because of the very small baseline risks of infection and subsequent death to begin with. It is possible that participants are anchoring on these small baseline risks, where tipping point differences are more reflective of the baseline risk differences as opposed to preference differences. This would explain why critical concentrations are nearly equal across these scenarios.

However, it may also be reflective of individuals' true preferences given the options, because people tend to be risk averse (Bougherara et al. 2021) and likely would prefer risks to be as low as possible (i.e., as close to baseline as possible). In our survey, participants were not able to indicate they would prefer risks below any of the provided options, which could be evidence of "stickiness" or unwillingness to take any risk increase whatsoever in a less favored outcome, such as getting an illness (Nielsen et al. 2019).

Exploring how acceptable risks translated to critical concentrations simply from an environmental monitoring feasibility lens, critical concentrations that protected the most people at an acceptable risk level (i.e., using the 0.01 quartile of the tipping points to set the risk threshold) were extremely small: a maximum concentration of roughly 3 viral particles for every 10,000,000 cm^2 (3×10^{-7} viral particles/cm^2), or, another potential interpretation, 3 out of 100,000 samples of 100 cm^2 (a typical environmental monitoring area for contaminants on fomites (Connor et al. 2016; Nourmoradi et al. 2021; Verhougstraete et al. 2024)) barely above the limit of detection (1 viral particle/100 cm^2). However, this is assuming a 1:1 ratio of infectious virus to detectable virus. If we assume a 1:1000 ratio, used in some risk assessments (Pitol and Julian 2021; Wilson et al. 2021), critical concentrations increase by 3 $\log_{10}$. In the example above, this would be 3 out of every 100 samples as opposed to 100,000. More research is needed to determine the feasibility of evaluating such small critical concentrations or if perhaps another approach could be to determine how many $\log_{10}$ of concentration reduction would be needed for anticipated levels of viral bioburden to reduce to acceptable levels, as is done in drinking water and direct potable reuse. QMRAs in which "log reduction targets" (Gerrity et al. 2023) are used to inform interventions that, in tandem, could theoretically reduce concentrations well below detection limits, satisfying robust risk thresholds.

In highlighting how the RRTO method can significantly enhance risk assessment, our study demonstrates how potential improvements can be made in how cleaning and disinfection protocols are chosen. Although our study focuses on respiratory viral pathogens for which fomite transmission is not as arguably important as other routes, fomites are crucial in the transmission of many healthcare-associated infections (Gideskog and Melhus 2019; Kanamori et al. 2017). Future work is needed to address how specific pathogens and health outcomes impact premia within the context of work-related asthma outcomes associated with surface hygiene.

4.3 | Limitations

The real-world scenario in our study involves a trade-off in which one risk likely increases, whereas the other simultaneously decreases: Cleaning and disinfection are de-intensified, and OA risk decreases and occupational infection risk increases. It is also possible that cleaning and disinfection, done properly with the right occupational controls, could reduce risks for both outcomes. In our RRTO scenarios, however, following standard practice, we change only one risk at a time. It should be noted that the outcomes are mutually exclusive in our scenario in the sense that participants were only eligible to participate if not diagnosed with asthma (meaning they cannot already have asthma and take on an infection risk), and we bound asthma onset to within 1 year, limiting its ability to co-occur with infection. This is an area that requires further exploration.

Additionally, we framed infection risk as having a specified outcome, recovery or death, so as to limit the number of assumptions participants may make about their expected outcome. In reality, all infections pose a risk of death. Although this means that the scenarios do not fully capture the true complexities of the nurses' choices, they allow for preliminary estimates of how nurses may value one risk over another framed in an overall RRTO scenario and with information about how anticipation of the outcome of the infection impacts their valuations. More data are needed across many scenario versions to isolate the effects of simultaneous and dependent changes in risk versus independent changes in risk and how this influences premia and QMRA outputs. This study is a first step in using real-world data in an RRTO-QMRA framework for quantitatively incorporating people's values into QMRA for informing environmental microbial concentration controls.

Although our study involves a novel approach on an understudied topic and our response rate was comparable to similar studies in which a large number of nurses were recruited via email (Grant et al. 2021), we had a low response rate in comparison to other nursing studies with differing recruitment methods, which could impact the external validity of the results (L'Ecuyer et al. 2023). Other factors that could have influenced our response rate include the length of the survey (a practice scenario + four scenarios + experience and demographic questions) and the complexity of the tasks (L'Ecuyer et al. 2023). Although RRTO approaches tend to reduce the cognitive burden on participants in comparison to willingness-to-pay approaches (Mussio et al. 2024; Nielsen et al. 2019), our scenarios still required interpretation of populations and evaluation of how one's choice may change as the outcomes change (i.e., I&R vs. I&D) and as baseline risks change. It should also be noted that at the time of recruitment (Spring 2023), nurse shortages and burnout were occurring nationwide in the United States, and nurses were heavily recruited during the COVID-19 pandemic, possibly explaining lower response rates than expected. Future approaches could include mailed surveys (besides an online approach), which have yielded higher response rates than emailed surveys in other studies across different populations (Leece et al. 2004).

Another challenge in this study included accurately representing very low risks, such as infection and subsequent death from surfaces contaminated with SARS-CoV-2, while hoping to capture acceptable risks. Overweighting of small probabilities, and specifically of rare side effects, is a known challenge in behavioral research (Tversky and Kahneman 1974) and could lead to systematic biases in decision-making. This could also

explain why participants might choose Scenario 4 over Scenario 1 (baseline risk: OA > I&D, increase in risk: OA > I&D vs. baseline risk: OA = I&R, equal risk increase, OA, and I&R), where low probability choices are seen as highly risky and therefore avoided (Lichtenstein et al. 1978; Slovic et al. 1977).

Lastly, the model presented in this article is grounded in expected utility theory, which assumes that individuals make objective choices based on the given probabilities of death and recovery. However, if we were to adopt an alternative behavioral framework that incorporates subjective probabilities, additional assumptions would be necessary. For instance, we would need to specify a probability weighting function to distinguish whether differences in context premia arise from differences in respondents' subjective beliefs or from variations in utility. Future research should explore alternative utility theories, such as Rank-Dependent Utility and investigate how these frameworks can be effectively applied to analyze individual decision-making in the context of cleaning and disinfection-associated risks. We also acknowledge that variations to the original Viscusi et al. (1991) design, such as the one laid out in this study, are necessary to understand consistency in decision-making and potential behavioral biases, such as loss aversion and diminishing sensitivity to gains and losses.

4.4 | Conclusions

We demonstrate the multidisciplinary application of an RRTO approach to (1) studying risk perceptions of nurses, and more specifically risk trade-offs regarding OA risks and RVI risks from intensified cleaning and disinfection practices, and (2) explaining critical concentrations that would achieve acceptable (or perhaps, more appropriately named "tolerable") risks of RVI considering competing risks. This case study shows how RRTO behavioral economic surveys can inform the setting of environmental concentration thresholds for specific pathogens of concern and sheds light on how nurses value RVI versus OA, in relative terms, within the context of cleaning and disinfection of fomites and fomite-mediated disease. This can be used in exploring how the cost of cleaning and disinfection protocol changes may be weighed against health benefits.

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Conflicts of Interest

Amanda M. Wilson has contributed to research funded by companies that make hygiene products, including SC Johnson and Reckitt Benckiser. The other authors have nothing to disclose.

Data Availability Statement

Anonymized data are included as a Supporting Information file.

Endnotes

[1] Although the derivation of monetary values for these outcomes is not the purpose of this paper (as explained above), it might be useful for some readers to consider the Value of a Statistical Respiratory Case (VSRC) which would serve as a common monetary measure for both morbidity and mortality impacts. This is based on the concept of a Value of a Statistical Case (VSC)—which itself is built on the concept of the Value of a Statistical Cancer Case (Alberini and Ščasný 2018). It represents the total amount that society would be willing to pay to reduce the risk of a certain negative health outcome, such as asthma or respiratory infection by one case. Arguably, this is more flexible than the Value per Statistical Life (VSL) because it monetarizes the value of preventing a case of such illnesses, even if it does not always lead to a fatal outcome. It would allow the analyst to determine how much people value reducing their risk of getting, for example, a respiratory infection compared to the value of avoiding a respiratory death. Alberini and Ščasný (2018) show how, in the context of cancer, it can be converted to a VSL for a respiratory disease by dividing the VSRC by the conditional probability of dying from cancer.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Supporting File 1: risa70122-sup-0001-SuppMat.docx