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Modeling Flight Attendants' Exposures to Pesticide in Disinsected Aircraft Cabins

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ABSTRACT

Aircraft cabin disinsection is required by some countries to kill insects that may pose risks to public health and native ecological systems. A probabilistic model has been developed by considering the microenvironmental dynamics of the pesticide in conjunction with the activity patterns of flight attendants, to assess their exposures and risks to pesticide in disinsected aircraft cabins under three scenarios of pesticide application. Main processes considered in the model are microenvironmental transport and deposition, volatilization, and transfer of pesticide when passengers and flight attendants come in contact with the cabin surfaces. The simulated pesticide airborne mass concentration and surface mass loadings captured measured ranges reported in the literature. The medians (means±standard devitions) of daily total exposures intakes were 0.24 (3.8±10.0), 1.4 (4.2±5.7) and 0.15 (2.1±3.2) μg/(day kg BW) for scenarios of Residual Application, Preflight and Top-of-Descent spraying, respectively. Exposure estimates were sensitive to parameters corresponding to pesticide deposition, body surface area and weight, surface-to-body transfer efficiencies, and efficiency of adherence to skin. Preflight spray posed 2.0 and 3.1 times higher pesticide exposure risk levels for flight attendants in disinsected aircraft cabins than Top-of-Descent spray and Residual Application, respectively.

INTRODUCTION

Spraying of aircraft cabin is currently required for all international flights by 23 countries to kill insects that may pose risks to public health and to native ecological systems[1]. This process is known as disinsection, and is currently accomplished with synthetic pyrethroids which are effective not only against insects but also against arthropods. Although approved by WHO for aircraft disinsection, certain adverse health effects on cabin crew and flight attendants, such as dizziness, nausea, fatigue and mild disturbance of consciousness, have been reported by various researchers[2-4]. Recent toxicological studies have also identified adverse neurological effects[5], age-related disease[6] and abnormal development of fetal brain[7] in rats and mice resulting from exposures to pyrethroids.

Classifications and procedures of pesticide application methods are different among different organizations and countries[8-10]. Generally, there are two ways to conduct disinsection: active pesticide spraying while crew and passengers are in the cabin, and Residual Application performed as part of maintenance while the aircraft is empty. Pesticide spraying can be conducted by flight attendants before passenger board (Preflight Spray) or when a flight begins its descent with passengers in the aircraft cabins (Top-of-Descent Spray). Residual Application needs to be effective for at least 8 weeks with recommended initial loadings of 50 μg/cm^2 on rugs and 20 μg/cm^2 on other surfaces including seats and walls[9, 11].

Exposures of cabin crew and passengers to pesticides sprayed in aircraft cabins can occur via inhalation, dermal contact, and unintentional ingestion. The concentrations of airborne pesticide in disinsected aircraft cabins were around 5 times higher than those in public, private and industrial buildings where permethrin was applied as an hygiene insecticide[12]. Exposure levels can be highly dependent upon the pesticide spraying method and upon the time since the last application. Only limited number of studies has reported measurements or modeling of exposures to pesticide in disinsected aircraft cabins. One estimate of the inhaled dose of *d*-phenothrin during aircraft disinsection is 30-235 μg per 100 g applied spray based on measurements made in unoccupied aircraft cabins sprayed while on the ground[13, 14]. In another study, urinary permethrin metabolite levels of flight attendants flying predominantly to Australia, which requires residual aircraft disinsection, were higher than those of the general US population[15]. These results suggest that the pesticides loadings on aircraft cabin surfaces contributed to the pesticide body burden of flight attendants flying on disinsected planes. To date, modeling studies have been focused on simulating the airborne mass concentrations and surface mass loadings of pesticides in the short term, e.g. minutes or a few hours, after a single spray event in disinsected aircraft cabins[10, 16, 17].

In the current study, a modeling system was developed, based on mass balance, to simulate airborne mass concentrations and surface mass loadings of pesticide in disinsected aircraft cabins under three scenarios of pesticide application: Preflight spray, Top-of-Descent spray, and Residual Application. The mass intake exposures to pesticide were then simulated by combining profiles of pesticide concentrations and loadings with activity data for flight attendants. Sensitivity and risk analysis were incorporated into the modeling process, to assess the sensitivity of the calculated pesticide exposures and associated risks for different inputs and parameters.

METHODS

Pyrethroid pesticide was treated as an inertial species[16] because of its long half life time (7-110 days)[18, 19]. The current exposure modeling system relied on probabilistic distributions of parameters describing the flight routes and flight attendants (Table S1). Different "virtual aircraft cabins" were simulated based on different routes flown with distinct flight times. To track the concentrations and surface loadings of pesticide in a given virtual aircraft cabin, a fixed during-flight time was assigned for this cabin, and it always traveled on the same route. Different "virtual flight attendants" were simulated by assigning different genders and body weights. The exposure of a given "virtual flight attendant" to pesticides was tracked over repeated travels in the same cabin on the same route.

The pesticide application scenarios are schematically depicted in Figure 1: each daily one-way trip of the aircraft flying between location A and B were divided into four stages: (1) before flight, T1, (2) during flight, T2, (3) deplane, T3, and (4) remaining time within the 24 hour day, T4. Details about these spray scenarios can be found in standard disinsection procedure guidance[9].

Time Activity Profile of Flight Attendants. A "virtual aircraft cabin" was generated for a specific route by assigning different durations for T1, T2 and T3. The remaining time, T4, was obtained by deducting the total of T1, T2 and T3 from 24 hours to provide a daily time profile for each "virtual flight attendant". A total utilization time of 24 hours was employed in the current study because the mean during-flight time T2 for international flights is approximately 10 hours, and the total duty time including stages before-flight T1 and deplane T3 can be as high as 19 hours[20]. Thus, flight attendants are unlikely to conduct two flights in a single 24-hour period. International flight information, such as departure and arrival times, duration and seat occupancy were derived using data from the Bureau of Transportation Statistics [20]. The derived parameters of flight routes were mainly representative of international flights operated between U.S. and the rest of the world.

A virtual flight attendant was generated by assigning a gender type and a body weight; gender probability was equal for male and female. For each flight attendant, travel frequency P_D was used to decide how many trips he/she was on duty. Mean travel frequency was derived from the average duty days per week. The weekly duty days were obtained from data on both domestic and international flights[21]. The value of 3.9 duty days per week may be high for flight attendants working on international flights, but it was used in the current study to provide conservative risk estimates associated with pesticide exposures.

Pesticide Concentration and Surface Loading. Profiles of pesticide concentration and surface loading in an aircraft cabin were obtained by solving the mass balance equations (1) and (2):

$$\begin{cases} \dfrac{dC_{Si}(t)}{dt} = -k_V C_{Si}(t) + \dfrac{k_d V_C C_{Air}(t)}{\sum_i S_i} - k_{Ti} C_{Si}(t) + I_{T_S}(t) S_{Si}(t) - I_{T_R}(t) R_{Si}(t) \\ I_{T_S}(t) = \begin{cases} 1, & t \in T_S \\ 0, & t \notin T_S \end{cases}, \quad I_{T_R}(t) = \begin{cases} 1, & t \in T_R \\ 0, & t \notin T_R \end{cases} \end{cases} \tag{1}$$

$$\frac{dC_{Air}(t)}{dt} = -k_d C_{Air}(t) + \frac{\sum_i k_V C_{Si}(t) S_i}{V_C} - X_V C_{Air}(t) + I_{T_S}(t) S_{Air}(t) \tag{2}$$

Where C_{Si} is the loading on surface *i* (μg/cm^2), k_V the volatilization rate coefficient (1/h), k_d the deposition rate coefficient (1/h), V_C the volume of aircraft cabin (m^3), C_{Air} the air concentration inside a cabin (μg/m^3), S_i the area (cm^2) of surface *i*, k_{Ti} the touch transfer (removal) coefficient (1/h), and X_V the air exchange rate (1/h). $S_{Si}(t) / S_{Air}(t)$ and $R_{Si}(t)$ are source and sink terms to indicate the spray and cleaning event, respectively. $I_{T_S}(t)$ and $I_{T_R}(t)$ are the indicator functions. T_S or T_R is the set of time intervals when one spray or cleaning event happens, respectively. The pesticide volatilization from seat surface was adjusted by the percentage of seat occupancy P_O . It was assumed there would be no pesticide volatilization from the seat surfaces, which are occupied by passengers.

Eleven different surface zones were considered in an occupied cabin: aisle, ceiling, floor center, floor side, human body, human lap, seat back, seat, seat top, seat sides and wall. Surfaces such as the human lap and the whole human body, and top and back of seats were represented as separate surfaces so that the concentrations for each type of surface can be directly simulated without requiring interpolation in post processing. Positions and configurations of these surface zones inside the aircraft cabin and the cabin volume have been reported previously [16].

Source terms $S_{Si}(t)/S_{Air}(t)$ for scenarios of Preflight and Top-of-Descent Spray were calculated using Computational Fluid Dynamics (CFD) modeling[16]. The CFD model was designed based on the geometry of a cabin mockup to simulate the pesticide concentrations and surface loadings during spray and up to 20 mins after spray[16]. The source terms for the Residual Application scenario, were initial surface loadings of pyrethroid of 50 μg/cm^2 on the aisle, floor center and floor side surfaces and 20 μg/cm^2 on the ceiling, seat back, seat, seat top, seat sides and wall surfaces. The initial air concentration was assumed to be zero. The period between two sequential Residual Applications was uniformly distributed between 40 and 56 days. These loadings and application frequency are consistent with recommended disinsection procedures[9, 11]. The sink term $R_{Si}(t)$ from cleaning was parameterized using a bulk transfer efficiency TE_{Bi} in the form of $R_{Si}(t) = TE_{Bi}C_{Si}$.

The touch transfer (removal) coefficients k_{Ti} for the 11 different surfaces in aircraft cabins were lumped into two types, either 'Hard' or 'Soft' surface for equation (3). For soft surfaces (seat, seat top and back), K_{Ti} was related to the hand-to-surface touch number TN_{HSi} (1/h) and single touch removal efficiency TE_{SHi}(%). For hard surfaces, K_{Ti} was related to during-flight hour T_2 (h) and bulk transfer efficiency TE_{Bi}.

$$K_{Ti} = \begin{cases} -TN_{HSi}\log(1-TE_{SHi}), & \textit{Soft Surface} \\ -\log(1-TE_{Bi})/T_2, & \textit{Hard Surface} \end{cases} \qquad (3)$$

The air exchange rate was dependent upon the specific flight stage, as follows: 25 Air Changes per Hour (ACH) for stages T1, T2 and T3; 1 ACH for stage T4 (Figure 1); and 29 ACH and

1ACH for the short duration when spraying pesticide under the scenarios of Top-of-Descent and Preflight, respectively. These ACH values are the sum of the recirculated air and outside air. The pesticides were assumed to be removed from the recirculated air by a High-Efficiency Particulate Absorption (HEPA) filter on the aircraft.

The governing equations for pesticide concentrations and surface loading (i.e. equations (1) and (2)) can apply to different types of aircraft cabins, if the ratios of inside surface area to volume are similar as in the current study (3.78 m^2m^{-3})[16].

Exposure Model. Flight attendants' mass intake exposures to pesticide in an aircraft cabin were estimated based on simulated pesticide concentrations and loadings. The total, unintentional ingestion, inhalation and dermal exposures are described by equations (4), (5), (6) and (7), respectively,

$$E_T = E_{Inge} + E_{Inha} + E_{Derm} \qquad (4)$$

$$E_{Inge} = \frac{\int_t^{t+\Delta t_E} P_H(1-(1-TE_{HM})^{TN_{HM}})P_{OAR}C_H(t)S_H I(t)dt}{BW} \qquad (5)$$

$$E_{Inha} = \frac{\int_t^{t+\Delta t_E} InC_{Air}(t)I(t)dt}{BW} \qquad (6)$$

$$E_{Derm} = \frac{\int_t^{t+\Delta t_E} S_{Hum}TE_{DS}C_{Hum}(t)I(t)dt}{BW} \qquad (7)$$

where S_H is the surface area of hand (cm^2), P_H the proportion of hand area contacting the mouth for each touch event (%), TE_{HM} the transfer efficiency from hand to mouth for a single touch event (%), TN_{HM} the hand-to-mouth touch number (1/h), P_{OAR} the oral adsorption rate, BW the body weight, and TE_{DS} the adherence efficiency on skin (%). $I(t)$ is an identity variable which assumes an 1 or 0 value when a flight attendant is on or off duty, respectively.

The exposure duration Δt_E can be set to different values for assessing exposures associated with different time durations. It was assumed that exposures only occurred on the aircraft. Thus, the daily exposure durations was based on the flight attendants' duty time: 'before flight' T1, 'during flight' T2 and 'deplane' T3 (Figure 1) on days the flight attendant was on duty.

$C_H(t)$ is the surface loading of pesticide on the hands, which is calculated using the surface loading on the human body $C_{Hum}(t)$ from equation (8),

$$C_H(t) = fC_{Hum}(t) \qquad (8)$$

where f is a scale factor. Since multiple contacts occur with different surfaces and objects, $C_H(t)$ is expected to be higher than $C_{Hum}(t)$ and f was assumed to be uniformly distributed from 1.5 to 3. This assumption was made based on comparisons between transfer efficiencies of chlorpyrifos and allethrin from a hand to a shirt [22].

S_{Hum}, derived from equation (9), is the exposed human surface area,

$$S_{Hum} = BW \times F_{BS} P_{EX} \qquad (9)$$

where F_{BS} is the ratio of surface area to weight (m^2/kg) of human body, and P_{EX} is the percentage of exposed surface area (%)[23].

Sensitivity Analyses. Mean daily mass intake exposure to pesticide was selected as a metric for testing the system's sensitivity to multiple inputs and parameters. Global sensitivity analyses were performed based on Morris's design [24]. This design estimates the main effect of a parameter by computing a number of local sensitivities at random points of the parameter space. The mean of these randomized local sensitivities indicates the overall influence of a given parameter on the output metric, while the corresponding standard deviation indicates the effects of interaction and nonlinearity [25].

In the current study, each of the 21 parameters (Table S1) was sampled 11,000 times according to Morris's method from 500 random trajectories (each has 22 steps) in the parameter space [24, 25]. Each of the parameters was perturbed between 50% and 150% of its base value or distribution while keeping other parameters unchanged.

The mean daily exposure for sensitivity analyses was generated using one "virtual flight attendant" and one "virtual aircraft cabin" flying 20 round trips. Equation (10) was used to calculate the Normalized Sensitivity Coefficients (NSC) at a local point:

$$NSC_{i,j} = \left(\frac{\Delta r_{i,j}}{r_{i,j}}\right) \bigg/ \left(\frac{\Delta p}{p}\right) \quad (10)$$

$NSC_{i,j}$ is the NSC for exposure route j under scenario i, p the input parameter value, $r_{i,j}$ the corresponding output mean daily exposure, Δp the perturbation in p, and $\Delta r_{i,j}$ the corresponding change in $r_{i,j}$. The global *NSC* of a parameter, *NSCg*, is defined as the mean of the corresponding local sensitivities. The average absolute global *NSC*, $\overline{|NSCg|}$, for each parameter, exposure path and spraying scenario can be derived based on means of the absolute *NSCg*. Similarly, the standard deviations averaged over each exposure path and spraying scenario ($\overline{STD}$) can be obtained to evaluate the interaction and nonlinearity effect of input parameters on modeling output.

Risk Analyses. A risk quotient (RQ), as defined in equation (11) was used for assessing risks associated with pesticide exposures:

$$RQ_{i,j} = \frac{E_{i,j}}{ADI} \qquad (11)$$

The $RQ_{i,j}$ for exposure route j under scenario i was calculated by dividing the corresponding daily exposure $E_{i,j}$ by an Acceptable Daily Intake (*ADI*). A No Observed Adverse Effect level (NOAEL) of 0.5 mg/(kg BW day) was established for permethrin, based on a 2-year study of hepatotoxicity in rats [26, 27]. An ADI of 0.01mg/(kg BW day) was suggested by the European Medicines Agency by applying a safety factor of 500 to the above mentioned NOAEL [28]. In the current study, an ADI of 0.01mg/(kg BW day) was adopted to calculate RQ. Estimated RQs were compared to a risk Level of Concern (LOC) to determine if regulation should be recommended. The RQ LOC used in this study was 1.0.

Statistics of Concentrations, Exposures and RQs. To generate statistics for concentrations, surface loadings, exposures and risk quotients, simulations were conducted using 100 "virtual flight attendants" in 100 "virtual aircraft cabins". Each virtual attendant flew 70 round trips inside the same virtual aircraft cabin under each of three scenarios of pesticide application.

RESULTS AND DISCUSSION

Pesticide Concentration and Surface Loading. Figure 2 summarizes the statistics of simulated pesticide air concentrations and surface loadings. The percentiles of boxplots were calculated based on simulated surface loadings and concentrations averaged over 70 round trips for each of the 100 "virtual aircraft cabins". Residual Application tended to cause a higher pesticide surface loading on the floor; its median was 2.1 and 9.5 times higher than those under scenarios of Preflight spray and Top-of-Descent spray, respectively. This resulted partly from the assumption that pyrethroid was an inertial species, which did not decompose on surfaces inside aircraft cabins. Preflight spray tended to have a higher air concentration with its median being

2.1 and 6.4×10^5 times higher than those under scenarios of Top-of-Descent spray and Residual Application, respectively. Top-of-Descent spray appeared to cause higher surface loadings on seat top and exposed surface of human body with its median loading on seat top (human body) being 1.1 (5.3) and 1.8 (5.3) times higher than those under scenarios of Residual Application and Preflight spray, respectively. Low variability in simulated air concentrations for scenarios of Preflight spray and Top-of-Descent spray was the results of the application amount of pesticide being the same for each spraying event. The air concentration inside a cabin under a given spraying scenario was dominated by the air exchange rate during and up to 20 mins after spraying. Since the air exchange rate parameter during spraying or normal operations under a given scenario was same across aircraft cabins, the air concentration variability across cabins was low and probably underestimated.

Few measurements of the pesticide concentrations and surface loadings in aircraft cabins have been reported. Berger-Preiß et al. measured pesticide concentrations and loadings after releasing 107-204 grams of aerosols containing 0.32% pyrethrin in a parked A310 aircraft cabin with air ventilation system operating [13]. The pyrethrin concentrations and loadings in the studied cabin were reported to be 11-65 $\mu g/m^3$ and 0.002-0.056 $\mu g/cm^2$, respectively, in integrated 40 minute samples collected during and following the in-flight spraying application. In their follow up study, 91-202 grams aerosol containing 2% d-phenothrin were sprayed using “pre-embarkation” method in parked aircrafts [14]. The measured d-phenothrin concentrations and loadings were 1-1753 $\mu g/m^3$ and 0.1-1.16 $\mu g/cm^2$, respectively. Isukapalli et al. determined the pesticide concentrations and loadings by spraying aerosol containing 2% permethrin or 2% d-phenothrin using four canisters (each 9.7±0.5 g) inside a section of a twin aisle aircraft cabin mockup under a high ventilation scenario and a low ventilation scenario [16]. The samples were collected from the start of spraying up to a period of 20-40 min after a single spraying event. Measured surface loadings varied from 0.33 to 1.22 μg/cm^2 for the low-ventilation case from 0.05 to 0.20 μg/cm^2 for the high-ventilation case. Mohan and Weisel [29] measured the surface loadings of pesticide residue on an economy row of three airline seats and a section of a carpet from an aircraft in a laboratory setting. The initial surface loadings applied to seat and carpet were around 0.48 and 0.81 μg/cm^2, respectively. The residue pesticide varied from 0.05 to 0.8 μg/cm^2 depending on the number of days since the application, which ranged from 0 to 180 days.

While the time frame and ranges of the measured surface loadings and air concentrations in the above studies can be captured by our simulations, fully equivalent simulation-to-measurement comparisons could not be done. Differences between the measurements and simulations include: measurements were made after a single spraying event without passengers on board, while the simulation considered multiple spraying events on multiple trips of a given "virtual aircraft cabin"; except for the Isukapalli et al. [16] study, the initial application amount of pesticide, spraying time and ventilation rate were widely different from that of our modeling; and the measurements did not incorporate the influence of multiple removal processes.

Therefore only qualitative comparisons were carried out between our simulations and the measurements from Isukapalli et al.[16], which has the closest source term to our simulation. The high ventilation case (29 ACH) was assumed to represent a Top-of-Descent spraying, while the low ventilation case (1 ACH) was assumed to represent a Preflight spraying. To match the time duration over which the measurements were made[16], the percentiles were calculated from simulated pesticide loadings generated for the initial 10 min (for Top-of-Descent spray) and 20 min (for Preflight spray) time periods after the first spray event for 100 'virtual aircraft cabins'.

Percentiles of simulated air concentrations were calculated using average simulation results during and up to 40 min after that spray event.

The simulated median of pesticide loading (0.65 μg/cm^2) on seat top for the Preflight spray scenario was in good agreement with the median of measurements (0.64 μg/cm^2) which had pesticides sprayed during low ventilation conditions. However, the measured surface loadings for the Top-of-Descent spray scenario and air concentrations for both the Preflight and Top-of-Descent scenarios were generally distributed at the low ends of simulated percentiles. The simulated median seat top surface loading was 0.39 μg/cm^2 during the Top-of-Descent spray, and the simulated median cabin air concentrations were 6.8×10^2 and 3.1×10^2 μg/m^3 during the Preflight spray and Top-of-Descent spray, respectively. These simulated medians were 3.6 and 4.8-10.5 times higher than the measured medians of pesticide loadings and air concentrations, respectively. The overestimation of pesticide loadings and concentrations were mainly due to the higher values of the source terms $S_{Si}(t)$ and $S_{Air}(t)$ in equations (1) and (2) than those associated with the measurements. These source terms were provided by the CFD modeling, which was reported to systematically overestimate the surface loadings for the high ventilation case [16]. Additional sources for the overestimations can be attributed to imperfect matches of scenarios between experimental setup and simulations.

Exposures to Pesticide. While female and male flight attendants' distributions of body weight, inhalation rate and hand surface area are different, no significant differences in simulated exposures between female and male flight attendants were identified based on a Student T test. Thus data from all flight attendants were combined. Figure 3 shows the simulated cumulative probability of flight attendants' daily exposures to pesticide. For Residual Application, the medians of the daily ingestion, inhalation, dermal and total exposures were 2.3×10^{-3}, 1.2×10^{-8},

2.4×10^{-1} and 2.4×10^{-1} μg/(day kg BW) with the ranges being 0.0-1.2, 0.0-3.5×10^{-6}, 0.0-1.1×10^{2} and 0.0-1.2×10^{2}, respectively. For Preflight spray, the medians of the daily ingestion, inhalation, dermal and total exposures were 1.1×10^{-2}, 8.5×10^{-8}, 1.3, and 1.4 μg/(day kg BW) with the ranges being 0.0-1.2×10^{-1}, 0.0-1.7×10^{1}, 0.0-9.9, and 0.0-2.1×10^{1}, respectively. For Top-of-Descent spray, the medians of the daily ingestion, inhalation, dermal and total exposures were 1.3×10^{-3}, 4.2×10^{-8}, 1.5×10^{-1}, and 1.5×10^{-1} μg/(day kg BW) with the ranges being 0.0-5.1×10^{-2}, 0.0-8.2, 0.0-3.3, and 0.0-1.1×10^{1}, respectively.

For Preflight and Top-of-Descent sprays, the dermal exposure was the most important contributor to the median total exposures of flight attendants resulting in daily exposures of <2 μg/(day kg BW). However for the 10% highest exposed flight attendants, inhalation exposure contributed the most resulting in daily exposures exceeded 6 μg/(day kg BW) (Figure 3). For Residual Application, dermal contact was the dominant route with median daily exposures of <1 μg/(day kg BW) and the 10% highest exposures exceeded 18 μg/(day kg BW). The bimodal cumulative probabilities of exposures in Figure 3 are due to half of the trips taking place without spraying events. Overall, the total daily pesticide exposure distributes over a wider range under the Residual Application scenario than under Preflight and Top-of-Descent spray scenarios.

Sensitivity Analyses. The global sensitivity of the simulated exposures to different parameters is illustrated in Figure 4. Overall, the global *NSC* of all parameters varied between -0.5 and 0.5, indicating the robustness of the modeling approach. Ingestion and dermal exposures were more sensitive to parameter perturbations, with average absolute global *NSC*, $\overline{|NSCg|}$, being 0.15 and 0.11, respectively. Sensitive parameters included: single-touch transfer efficiency (TE_{SHi}), deposition rate coefficient (k_d), body weight (BW), portion of hand surface touching mouth (P_H), ratio of body surface to weight (F_{BS}) and skin adhere efficiency (TE_{DS}). Inhalation exposure was less sensitive to modeling parameters. Total exposures were sensitive to: transfer efficiency, body weight, body surface to weight ratio and hand-mouth touch number (TN_{HM}).

High interaction and nonlinearity effects among parameters were found for pesticide exposures under the scenarios of Preflight Spray and Residual Application with average interaction effects $\overline{STD}$ being 2.2 and 2.4, respectively. Parameters with high interaction and nonlinearity effects included the scale factor from human body to hand (f), travel frequency (P_D), hand-to-mouth touch number (TN_{HM}) and body surface to weight ratio (F_{BS}). Except for TN_{HM}, low interaction effects were found for exposure parameters under the scenario of Top-of-Descent Spray. This resulted from the fact that flight attendants deplaned and left the cabin soon after pesticide application in the case of Top-of-Descent Spray.

Uncertainties in sensitive and interactive input parameters result in large deviations of model predictions. Parameters derived from large population studies, such as distribution of body weight (BW, $\overline{|NSCg|}$=0.15), inhalation rate, hand surface area and the ratio of body weight to surface area (F_{BS}, $\overline{|NSCg|}$=0.15), are believed to bear lower uncertainties. High uncertainties are expected for sensitive parameters: k_d, $\overline{|NSCg|}$=0.12; TE_{SHi}, $\overline{|NSCg|}$=0.10; TE_{DS}, $\overline{|NSCg|}$=0.11; and interactive parameters: f, $\overline{STD}$=2.1; P_D, $\overline{STD}$=2.1; TN_{HM}, $\overline{STD}$=3.5.

Volatilization (resuspension) and deposition rate coefficients depend on surface characteristics, temperatures and pesticide physicochemical properties such as fugacity[30]. Data on these dependencies are extremely limited for pesticide deposition and resuspension in aircraft cabins. The values of k_v and k_d used in the current study were derived from references on pesticide-containing particles [17, 30]. Widely different pesticide transfer efficiencies due to hand touch have been reported in the literature[31, 32]. Distribution of single-touch transfer efficiency (TE_{SHi}) in the current study was taken from Beamer, et al. (2008) who considered multiple studies of pesticide transfer efficiency[31]. Data of skin adherence efficiency (TE_{DS}) are either not available or very limited for passengers and flight attendants. Further investigations to reduce the uncertainties in k_d, TE_{SHi}, TE_{DS}, f, P_D and TN_{HM} are crucial for accurate assessments of flight attendants and passengers' exposures to pesticides in disinsected aircraft cabins.

Risk Analyses. Potential risks due to flight attendant's pesticide exposures in disinsected aircraft cabins are displayed in Figure 5, which summarizes the statistics of estimated RQs. Statistically, for Residual Application, RQs did not exceed LOC at any percentiles through any exposure route. For Preflight spray, RQs did not reach the LOC at any percentiles through either ingestion or dermal exposures; RQs did not exceed the LOC up to the 75th percentile through inhalation exposures. RQs reached the LOC around the 75th percentile for total exposures. For Top-of-Descent spray, RQs did not exceed the LOC for exposures through ingestion, inhalation or dermal contact. They reached LOC for total exposure at percentiles greater than 75th.

Overall, Preflight spray posed a higher potential pesticide exposure risk for flight attendants in disinsected aircraft cabins than either Top-of-Descent spray or Residual Application. The maximum RQ for flight attendants due to total pesticide exposure under the scenario of Preflight spray is 2.0 and 3.1 times higher than the Top-of-Descent spray and the Residual Application, respectively. It should be noted that results from the current study are only applicable to flight attendants, although the modeling approach can be straightforwardly customized to simulate passengers' pesticide exposure risks.

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SUPPORTING INFORMATION

Additional information regarding the model parameters, schematic diagram and typical simulated profiles of pesticide concentrations, loadings, exposures and risks. This information is available free of charge via the Internet at http://pubs.acs.org/.

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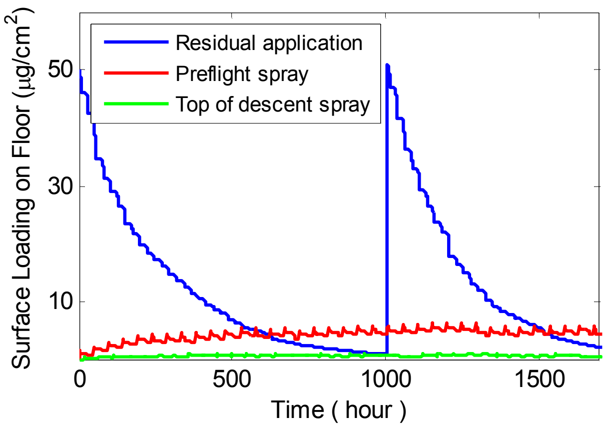
FIGURES



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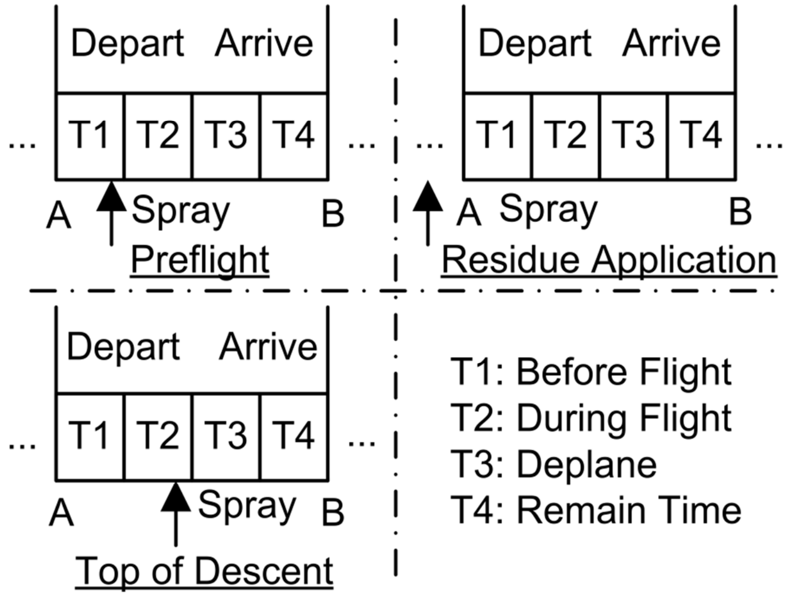

Figure 1 Schematic diagram of three disinsection scenarios and sequence of spraying events for simulated aircraft cabins. Each daily one-way trip of the aircraft flying between location A and B was divided into four stages: (1) before flight, T1, (2) during the flight, T2, (3) deplane, T3, and (4) remaining time within the 24 hour day, T4. For Preflight scenario, spray events were conducted in stage T1 whenever the aircraft flew to destination B. For Top-of-Descent scenario, spray events were carried out in stage T2 when the aircraft started to descent to destination B. For Residual Application scenario, the spray events were carried out by maintenance workers in stage T4; the period between two sequential Residual Applications was uniformly distributed between 40 and 56 days.

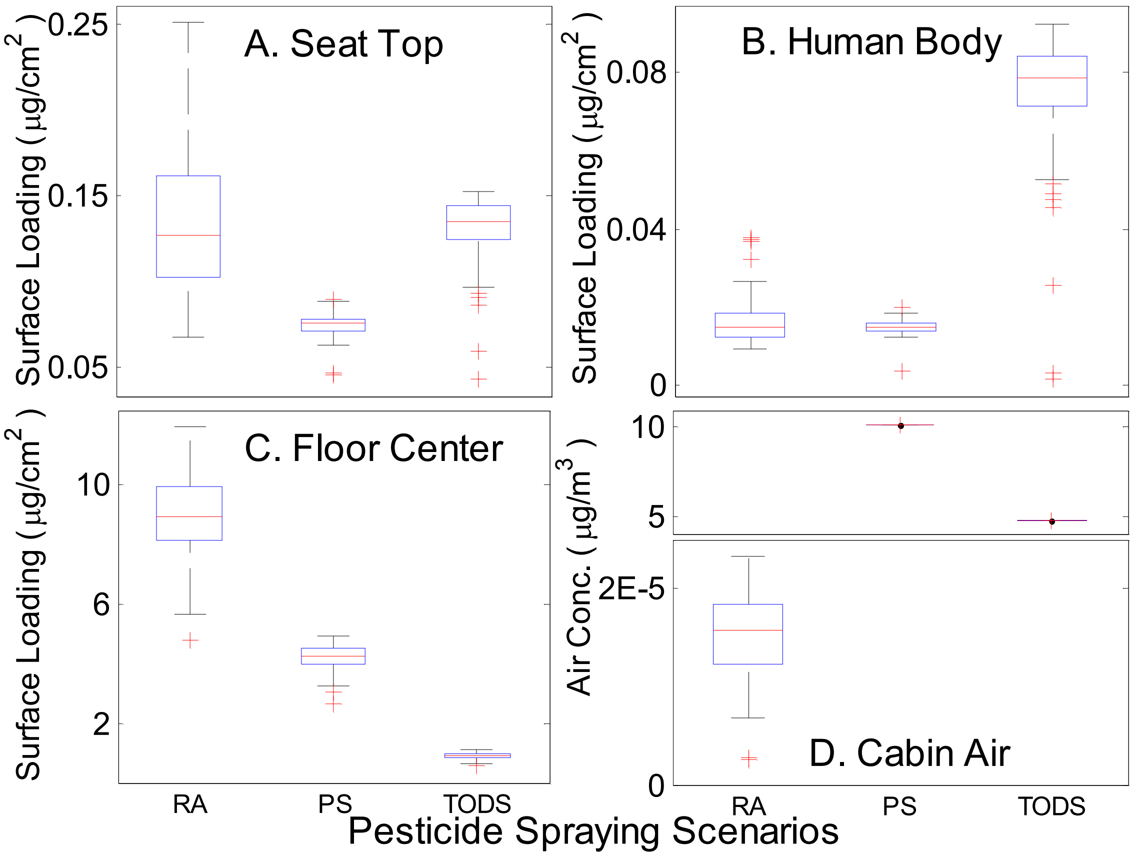

Figure 2. Simulated pesticide concentrations and surface loadings averaged over 70 round trips (140 days) for each 'virtual aircraft cabin' under scenarios of Residual Application (RA), Preflight Spray (PS) and Top-of-Descent Spray (TODS): (A) on seat top, (B) on human body, (C) on floor, and (D) inside the cabin air. Boxplots were generated from simulation results of 100 disinsected aircraft cabins. On each box, the central red line is the median; the edges are the 25th (q_1) and 75th (q_3) percentiles; the whiskers represent $q_3 + 1.5(q_3 - q_1)$ and $q_3 - 1.5(q_3 - q_1)$, respectively. The "outliers" of simulation results were plotted as red plus.

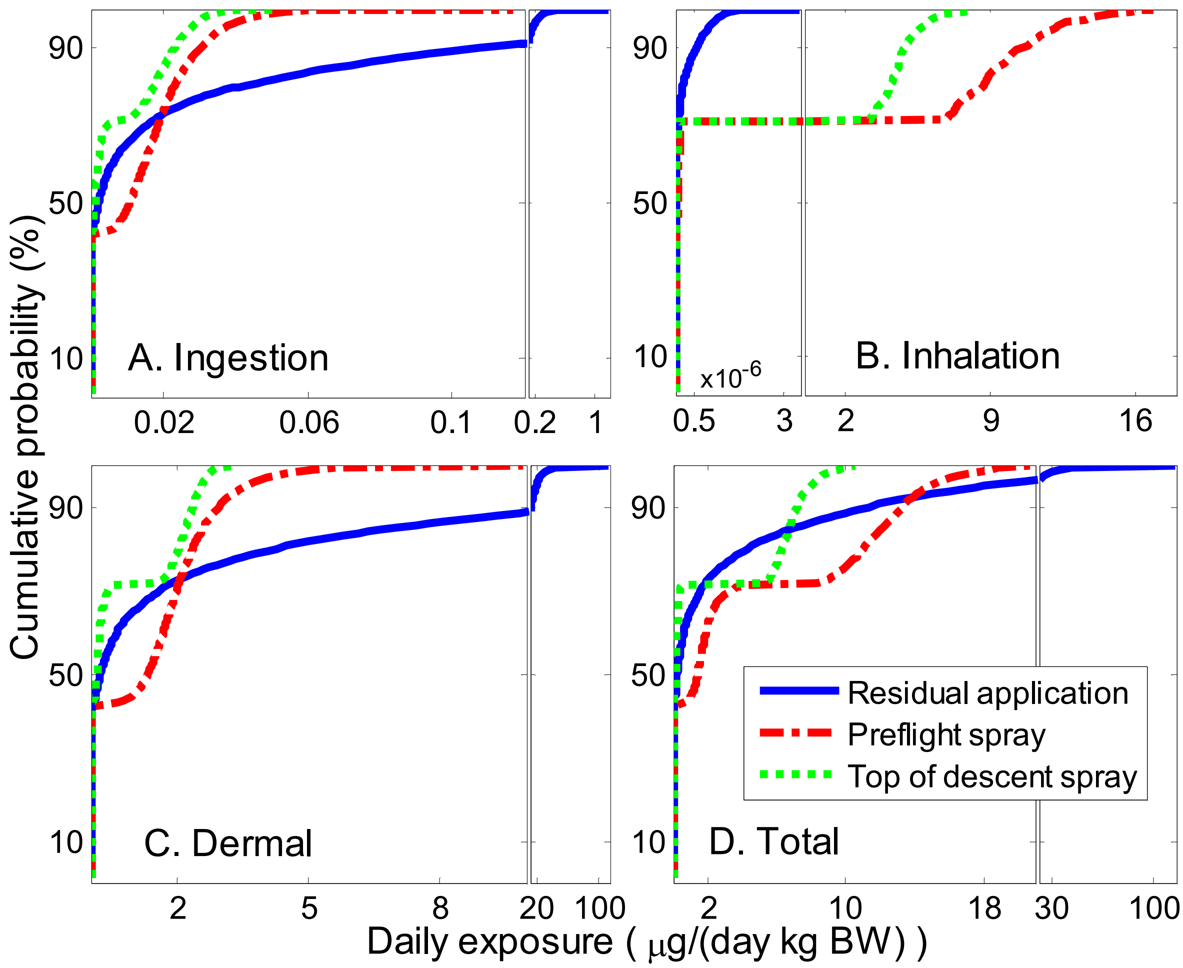

Figure 3. Simulated cumulative probability distributions of daily exposures of flight attendants to pesticide in disinsected aircraft cabins: (A) unintentional ingestion, (B) inhalation, (C) dermal, and (D) total. Data were from simulation results of 100 virtual flight attendants and 100 virtual disinsected aircraft cabins under three different disinsection scenarios.

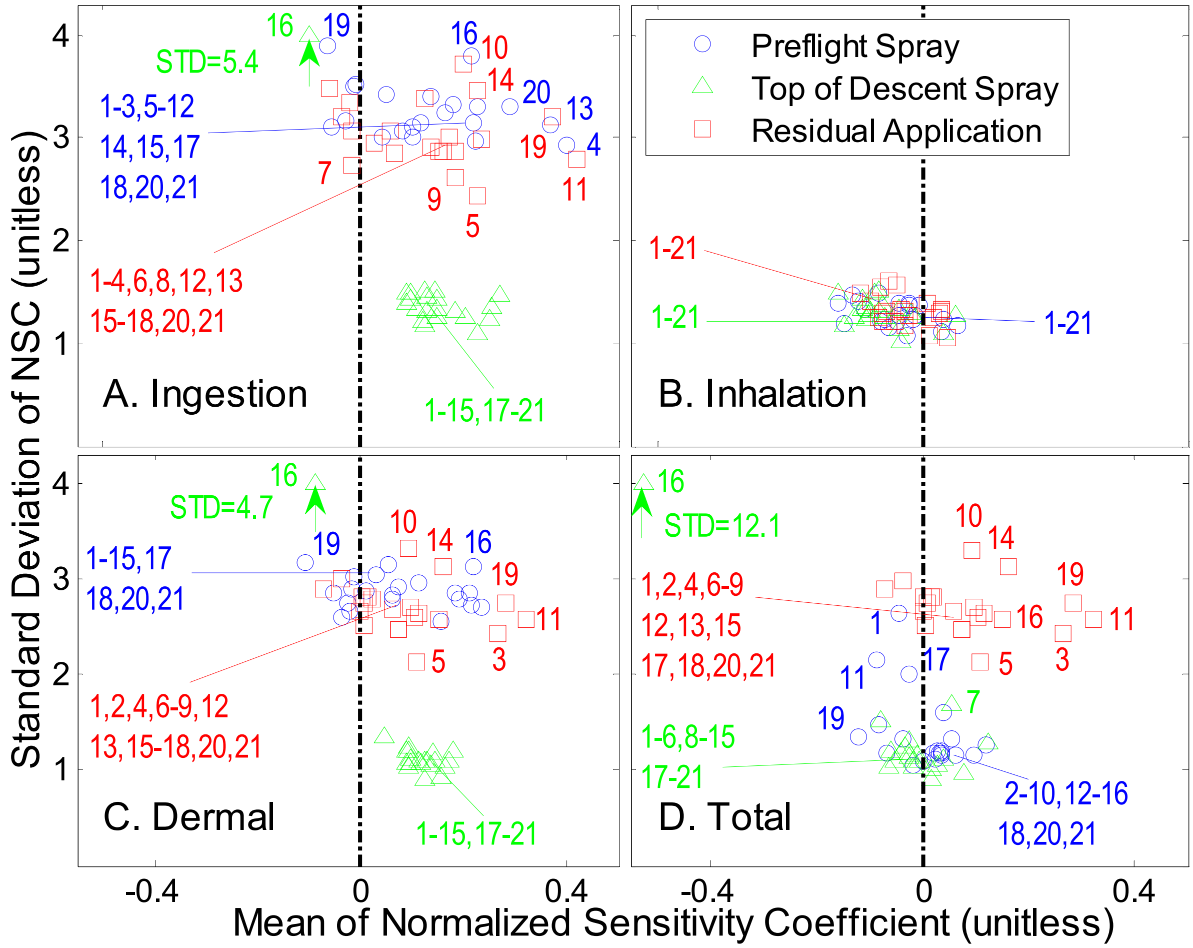

Figure 4. Mean and standard deviation of Normalized Sensitivity Coefficient (NSC) for flight attendants' daily (A) unintentional ingestion, (B) inhalation, (C) dermal, and (D) total exposures to pesticide in a disinsected aircraft cabin under three different disinsection scenarios. The vertical dashed lines represent the NSC values of 0. Numbers in the figure are parameter IDs: 1 TN_{HSi}, 2 TE_{Bi}, 3 TE_{SHi}, 4 k_d, 5 k_V, 6 $T2$, 7 $T1$, 8 $T3$, 9 P_O, 10 f, 11 BW, 12 S_H, 13 P_H, 14 P_D, 15 TE_{HM}, 16 TN_{HM}, 17 P_{OAR}, 18 In, 19 F_{BS}, 20 TE_{DS} and 21 P_{EX}.

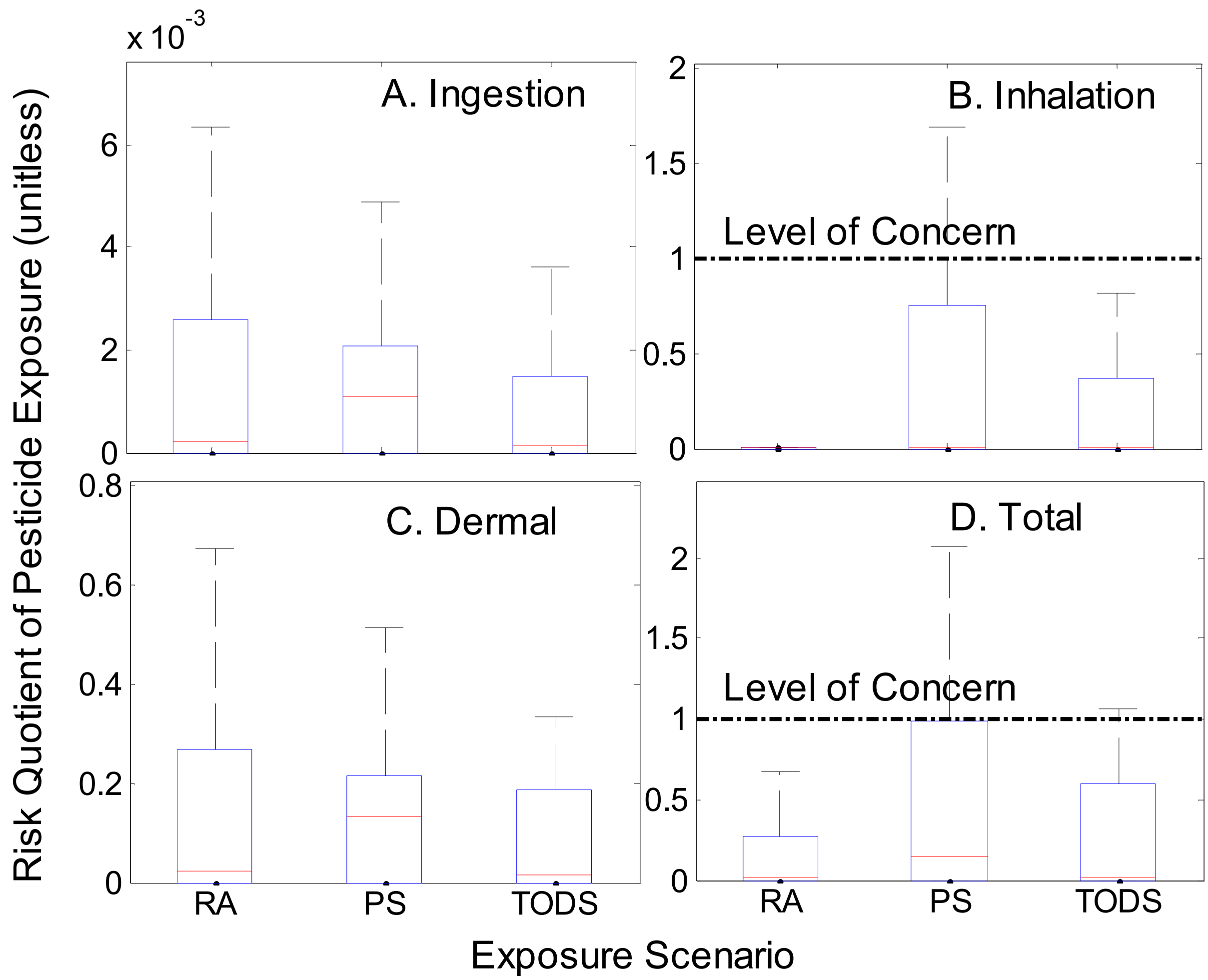

Figure 5. Simulated risk quotients of flight attendants based on their (a) unintentional ingestion, (b) inhalation, (c) dermal, and (d) total daily exposures to pesticide in disinsected aircraft cabins under scenarios of Residual Application (RA), Preflight Spray (PS) and Top-of-Descent Spray (TODS). Estimates were from simulation results of 100 disinsected aircraft cabins. On each box, the central red line is the median; the edges are the 25th (q_1) and 75th (q_3) percentiles; the whiskers represent $q_3+1.5(q_3-q_1)$ and $q_3-1.5(q_3-q_1)$, respectively. The horizontal dashed line represents the threshold level of concern.