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EFFECT OF VACCINATION ON RISK OF EXPOSURE TO AIRBORNE INFECTIOUS DISEASE DURING THE BOARDING PROCESS IN A COMMERCIAL AIRCRAFT USING AGENT-BASED SIMULATION

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ABSTRACT

As increasing proportions of the world's population have received at least one dose of the vaccine against COVID-19, everyday activities start to be resumed, including travels. The present study investigates the impact of immunization on the risk of exposure to an infectious disease such as COVID-19, during the boarding process in a commercial airplane. An agent-based simulation model considers different vaccine types and vaccination rates among passengers. The results show significant decrease in the median exposure risk, when the vaccination rate increases from 0% to 100%, but also that people in seats adjacent to an infectious passenger are in much higher risk, for a similar vaccination coverage. Such results provide quantitative evidence of the importance of mass immunization, and also that, when full vaccination is not guaranteed for 100% of passengers, it may be recommendable to avoid full occupancy of the aircraft, by implementing physical distancing when assigning seats.

1 INTRODUCTION

The COVID-19 pandemic has caused about 475 million cases and 6 million deaths, as of March 2022 (World Health Organization 2022). Two years into the pandemic, the scientific community has learned much about the SARS-CoV-2 virus, such as how the transmission occurs and which are the best safety measures; thus, good hygiene, physical distancing, lower occupancy in closed spaces and mandatory use of masks are some of the measures since then implemented.

As people and organizations worldwide set about resuming normal activities, an increase in air travel numbers is also observed. While the month of April 2020 was the worst for the air transport industry, with Domestic Revenue Passenger-Kilometers (RPK) decreasing about 80% in comparison to 2019 (IATA 2021), in January 2022, domestic RPK was only 26.5% lower than the same month in 2019 (IATA 2022), which indicates an improvement in the air travel market since the onset of the pandemic. Although the appearance of new highly transmissible virus variants, such as Omicron, may curb the tendency for increasing demand on air transportation, at the same time, people seem now to be more prepared to take more risks.

Air travel is comprised of several stages, such as arriving at the departure airport, checking-in, dropping luggage, going through security, walking to the gate, boarding, traveling, disembarking, claiming luggage and leaving the destination airport. All these stages are characterized by the circulation of large groups of people, which contributes to an augmented risk of disease transmission. The boarding process, specifically, involves passengers in close proximity in a confined environment. Previous research has engaged in the discussion of the safety of the boarding for passengers, without considering vaccination rates (Cotfas et al. 2020; Schultz and Fuchte 2020; Islam et al. 2021; Namilae et al. 2017; Fabrin and Ferrari 2022). Overall, the risk of exposure is small, although there may be cases of higher probability, for example when a person seats adjacent to an infectious passenger.

In order to board an airplane, most airline companies require that the passenger be fully vaccinated and/or show a negative test for COVID-19, as some countries do not demand immunization comprobation in order to allow international travelers to come (Centers for Disease Control and Prevention 2022; Xie 2022). However, through a systematic review, it was estimated that up to 58% of COVID-19 patients present a false negative RT-PCR result (Pecoraro et al. 2022). Thus, even though mandatory tests decrease the risk of infection on a plane, testing alone cannot guarantee that an infected passenger will not come on board, since the pre-flight test result may be a false negative, or a passenger may become newly infected between the time the test is taken and the flight takes place (Swadi et al. 2021).

In 2021, the first vaccines approved for general use began to be widely administered (Park 2020). As of March 2022, about 11 billion doses of vaccines were administered and 64% of the world's population have received at least one dose of vaccine (Our World in Data 2022). However, there is a great discrepancy between different regions in terms of access to vaccination. In Brazil, for example, in the state of Amazonas, only 60.5% of the total eligible population have received two doses (Governo do Estado do Amazonas 2022), whereas in the state of São Paulo, that rate is 84.1% (Governo do Estado de São Paulo 2022). In Chile, while about 90% of the population is fully vaccinated, in Mexico, that proportion amounts to only 61% (Our World in Data 2022). Such disparities may be even more evident if different geographic regions across the globe are compared.

Another aspect about the COVID-19 vaccines is that they have been primarily developed to prevent severe disease, and consequent hospitalization and death (Pavilonis 2022). It is expected, though, that the chances of transmission be decreased (Funke 2021), as observed in the results of a cohort study in which vaccinated passengers during flight were 74% less likely to be infected (Lv et al. 2021).

So far, simulation studies addressing vaccination include the investigation of strategies to contain an influenza outbreak in a city using a stochastic simulation model (Andradóttir et al. 2010); the spread of COVID-19 pandemic in several U.S.A. cities using agent-based model (Alagoz et al. 2021); and dengue disease transmission control using a compartmental model (Abidemi et al. 2020). As far as it is known to the authors, there is a lack of investigations that aim at modelling the influence of vaccination in transmission during air travel. Therefore, it is important to assess the consequences when the population is only partially vaccinated. The present study aims at assessing the risk of exposure to an airborne infectious disease such as COVID-19 during the boarding process in a commercial airplane, considering that only part of the population is fully vaccinated.

2 METHODOLOGY

This study builds upon previous research (Fabrin and Ferrari 2022), in which an agent-based model (ABM) was created, using the open source simulation environment NetLogo (Wilensky 1999). ABMs are useful when the system under investigation involves heterogeneous entities, each with its own characteristics and behavior, that may interact with each other and may evolve with time. This allows for the visualization of the emergence of behaviors and patterns and for the gathering of information of the real-word complex systems (Bonabeau 2002).

In the present effort, each passenger is modeled as an independent agent that can interact with other passengers and the environment, make decisions based on a basic set of rules, and adapt according to a given situation. The environment is modeled based on a Boeing 737 aircraft cabin, although it may be easily generalized to any other aircraft configuration. The airplane cabin has a single-aisle layout with 3-3 seat configuration, and maximum capacity of 186 passengers. In the model, the cabin is discretized as

0.5 x 0.5m nodes, and each node represents a type of structure (seat, aisle, structure), as shown in Figure 1. The time step in NetLogo is called "tick" and 1 second corresponds to 20 ticks.

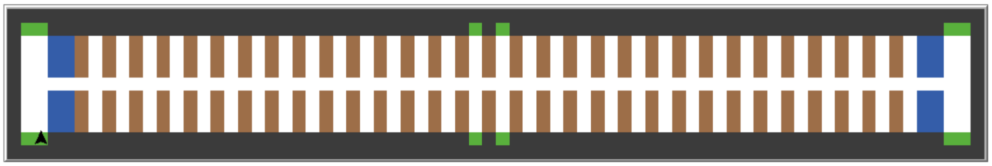

Figure 1: Example of boarding simulation for the Boeing 737 aircraft. Arrows correspond to passengers and their facing directions; white cells represent open spaces where passengers can walk freely, such as aisles and legroom; brown cells represent seats; blue cells represent aircraft internal structures; and green cells represent doors and emergency exits.

Some assumptions are made for the present model, described as follows:

1. Passengers travel alone, i.e., there are no groups and families traveling together;
2. There are no late comers, i.e., all passengers are ready to follow the boarding strategy setting;
3. Passengers cannot overtake one another, i.e. if there is a slower passenger ahead, the others must follow behind;
4. Passengers make no mistakes when moving towards their assigned seats (regarding either path or seat location);
5. Overhead bin is modeled so that it carries a limited number of bags per row;
6. All passenger's bags have the same format and size;
7. Passengers are allowed to carry at most one piece of luggage;
8. Only one infected passenger comes on board;
9. Vaccinated passengers are assumed to have completed the vaccination protocol and to have received the last dose at least 15 days prior to travel;
10. No vaccination loss of effectiveness due to time is considered;
11. All passengers must have presented a negative test for COVID-19 before boarding.

In summary, it is assumed that every passenger travels alone and follows the boarding rules imposed by the airline; even though it is expected that every individual presents a negative test for COVID-19 before boarding, it is also assumed that only one passenger has provided a false negative test, meaning that he or she is actually infectious. This is done in order to best evaluate the vaccine effectiveness and disease transmission during the boarding process.

2.1 Passenger's Characteristics

Each passenger is modeled as an unique agent, with the following characteristics: (i) age and, consequently, (ii) maximum walking speed, (iii) possession of a carry-on item, (iv) time needed to store luggage in the overhead bin, (v) seat shuffle time, (vi) seat ticket number, (vii) infection status, (viii) vaccination status, and (iv) vaccine type, if the passenger is fully vaccinated.

The age of each passenger is sampled from a distribution based on the Brazilian age pyramid (IBGE 2010), considering age groups within the ranges (i) 15-16, (ii) 17-25, (iii) 26-50, (iv) 51-64, and (v) 65-75 years old. For each age group, a maximum walking speed is attributed, based on an observational study on the free walking speed of individuals in a street (Willis et al. 2004), whose average walking speed corresponds to 1.47 m/s. Here, it is assumed that passengers walk in the airplane aisle with a slower speed than that observed in a street, as the space is narrower and they might be carrying luggage on board. Therefore, a average walking speed of 0.5 m/s is considered. For each age group, a correlation between the observational study measure and the assumed speed is made. For example, Willis et al. (2004) find that individuals older than 64 years old walk at 1.16 m/s; applying the correlation, the speed in the model is set as 0.39 m/s for this age group.

The possession of a carry-on item by each passenger is a modeled as a Bernoulli random variable with probability 80%, i.e., each passenger has a 80% chance of having a carry-on bag. The time needed to store a piece of luggage in the overhead bin is modeled as a random variable that follows a Weibull distribution (Schultz 2018) and is independent of the passenger's age. If an agent is flagged as an elder (65+ years old), this time is simply increased in 20%.

Seat shuffle time refers to the time needed to solve a seat interference. This occurs when, for example, a passenger walking in the aisle is assigned to a window seat ticket but, at that same row, there is another passenger already seating at the aisle seat. In such a real situation, the aisle passenger would have to stand up to let to window seat passenger enter the row and then return to the seat. The seat shuffle time corresponds to the interval needed to resolve the situation and it it modeled as a normal random variable with mean of 10s and standard deviation of 3s (Schultz 2018).

The seat ticket assignment to passengers is performed in a random fashion. All seats in the aircraft are available and their allocation is done before boarding, i.e., when the simulation starts, all passengers already have an appointed target seat. In real life, we would not know which individuals are infected on a plane and where they are seated; however, for research purposes, in this work, the infected passenger, or index patient, is always fixed at seat 14E. This means that, whoever gets assigned to that seat will become infectious in the simulation model. As the scope of this study is limited to the boarding process alone, the index patient can only expose others while within the airplane, i.e., no considerations about situations prior to boarding are made.

The vaccination status is modeled as a Bernoulli random variable, i.e., each passenger has a certain probability of having received the full cycle of vaccination shots. A vaccinated passenger is assumed to have been inoculated with one out of four possible vaccines, with probabilities according to the vaccination coverage distribution observed in Brazil (Ministério da Saúde 2022; Governo do Estado de São Paulo 2022). Each vaccine has its own effectiveness rate against severe disease and infection, which is age and time dependent; however, here we assume a mean value based on the report by Fundação Oswaldo Cruz (2021). The vaccination coverage and vaccine effectiveness can be seen in Table 1. The given effectiveness relates to full vaccination cycle.

Table 1: Vaccination factors.

Type	Vaccine Coverage	Vaccine Effectiveness
CoronaVac	34.46%	68%
Oxford/Astra-Zeneca	32.18%	87%
BioNTech/Pfizer	29.49%	95%
Janssen	3.87%	70%

2.2 Transmission Model

In this study, only airborne transmission is considered, and it happens when an individual inhales air that contains germs; that is the most common form of transmission for respiratory diseases, such as influenza and COVID-19. The adopted airborne transmission model follows Smieszek (2009), Schultz and Fuchte (2020). The probability of a passenger being exposed to an infectious pathogen (P_{air}) during the boarding process depends on some factors: (i) the infectivity of the virus (θ), (ii) the shedding rate of the virus (*SR*), (iii) the distance to the infected person ($dist$), (iv) the amount of time exposed to the virus ($step$) and (v) the vaccination dumping factor (*vaccine*). Equation 1 gives the airborne exposure risk for each time step. All calibration parameters follow Schultz and Fuchte (2020).

$$P_{air_{step}} = 1 - exp(-\theta * SR * dist * step * vaccine) \quad (1)$$

The parameter θ is set as $1/20$. The shedding rate (*SR*), which is the rate that the virus is shed into the environment, is modeled as a bell-shaped function, given in equation (2), whose parameters are set to: $a_x = 0.6$, $b_x = 2.5$, $c_x = 0.25$, $a_y = 0.65$, $b_y = 2.7$, and $c_y = 0$, in which the indexes x and y correspond to the distances in each axis of a given passenger to the infected passenger. Yet, if the passenger is in a seat shuffle state or storing luggage, the shedding rate is multiplied by 2. *dist* refers to the euclidean distance between a given passenger and the index passenger at a given time step. $step$ is the simulation's time step (1/20 s).

$$SR = \prod_{(z \in x,y)} \left[1 + \left(\frac{|z - c_z|}{a_z} \right)^{2*b_z} \right]^{-1} \quad (2)$$

Lastly, *vaccine* is the dumping factor related to the vaccination. As already stated, each passenger has the chance of receiving the immunization from one vaccine type. This factor is calculated as $vaccine = 1 - effect$, where $effect$ is the corresponding vaccine effectiveness, which value is taken from Table 1. The assumption that the vaccine effectiveness against disease development is a dumping factor to the transmission is made because there are still not enough studies that evaluate this effectiveness against transmission (Stokel-Walker 2022). However, as less individuals develop symptoms and more severe complications, it is also expected that the spreading and transmission is decreased (Mostaghimi et al. 2022). Therefore, it is reasonable to assume that vaccine effectiveness decreases the risk to exposure (Stokel-Walker 2022).

Thus, the probability of exposure for for each passenger, along the whole boarding process is given in equation (3), below.

$$P_{air} = 1 - \prod_{step} (1 - P_{air_{step}}) \quad (3)$$

2.3 Other Simulation Parameters

Other simulation parameters are: (i) the passenger flow rate, (ii) the overhead bin capacity, (iii) the number of passengers on board, and (iv) the boarding strategy.

The passenger flow rate is the rate at which passengers enter the airplane. In reality, this rate depends on gate control, where airline's employees check the passenger's identification and ticket. This rate rate may vary within a flight and between flights, as it depends on when the boarding process starts and when passengers decide to board (at the beginning or at the end of the process). In the present simulation model, this parameter is modeled as a normal random variable with mean of 14.1 pax/min and standard deviation of 2 pax/min (Schultz 2018). Only one flow rate is sampled from distribution for each simulation run; within a run, successive individuals enter the airplane with a uniform rate.

The overhead bin is modeled as having a maximum capacity of 2 pieces of luggage per row. When a passenger finds a full bin, an extra time is added (*extratime*), following an exponential function, according to equation (4). This extra time is a function of the number of failed attempts to storage a bag due to reaching full capacity of the bin ahead, i.e., it is a function of the number of extra pieces above capacity ($counter$).

$$extratime[s] = 5 * exp(0.05 * counter) \quad (4)$$

Lastly, the number of passengers allowed on board is 186, and they came on board randomly, not following any special order, and are allowed inside in a First-Come-First-Serve (FCFS) fashion.

2.4 Scenarios Setup

As the main objective of the present study is to evaluate the effect of vaccination on the risk of exposure to airborne infectious disease, only one factor is assessed: the percentage of passengers fully vaccinated that come on board. This factor takes 5 levels: (i) 0%, (ii) 25%, (iii) 50%, (iv) 75%, and (v) 100% of passengers being fully vaccinated.

2.5 Simulation Process

A diagram of the simulation process is shown in Figure 2, for better visualization. At the beginning of the simulation, all agents are placed at the front left door of the airplane, and they stay there until they are allowed to enter the cabin, according to the sampled flow rate and following the random boarding strategy. Considering that there is a crew member aiding the passengers, individuals walk to their seat without making any mistakes (passengers do not get lost inside the cabin). Before reaching their row, passengers check for seat interference; in positive case, he or she enters seat shuffle state, while standing in the aisle during the set time delay. Then, if the passenger is in possession of a carry-on luggage, he/she checks the overhead bin; if there is space available, the passenger will block the aisle until the time delay ends; if the bin is full, then extra time is added and the passenger stays in the aisle. During these moments, if other passengers approach, they must keep standing behind, until the interference is resolved, and they can finally resume movement. Then, the passenger moves towards the assigned seat and stays there until the end of the simulation. The simulation starts when the first passenger gets into the airplane and ends when the last passenger seats. The simulation output generated corresponds to the probability of exposure to airborne infectious disease for each passenger.

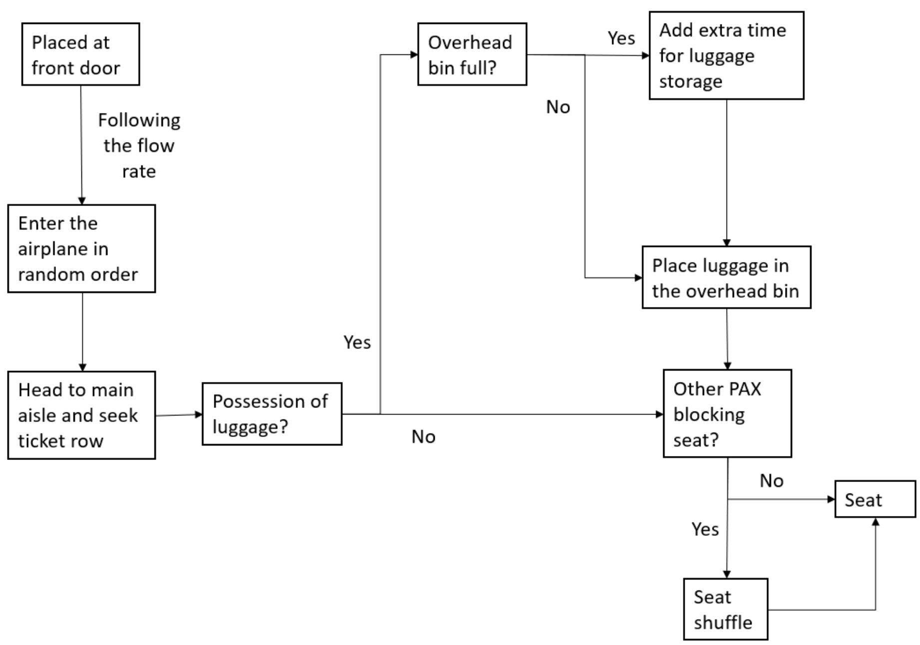

Figure 2: Diagram of the simulation process.

3 RESULTS AND DISCUSSION

A total of five simulation scenarios were considered, each corresponding to one level of percentage of vaccinated passengers; for each scenario, 200 replications were run for statistical relevance. It is important to stress that the obtained results should be analysed as indications and suggestions of tendencies and should be used for comparative purposes only. The model was not validated with real data, but it was thoroughly verified in order to guarantee that it works as designed.

First, the distributions of estimated exposure probabilities were obtained for each simulated scenario. Figure 3 shows the corresponding distribution of aggregated results of all passengers on board for all runs of one given scenario. The distribution is highly asymmetrical, with most results near zero and only a few occurrences with higher probabilities. Due to the high distribution skewness, the mean does not seem to be a good summary statistics; thus, only data for median and standard deviation will be analysed next. All other scenarios presented similar behavior and the resulting density plots are omitted from this report.

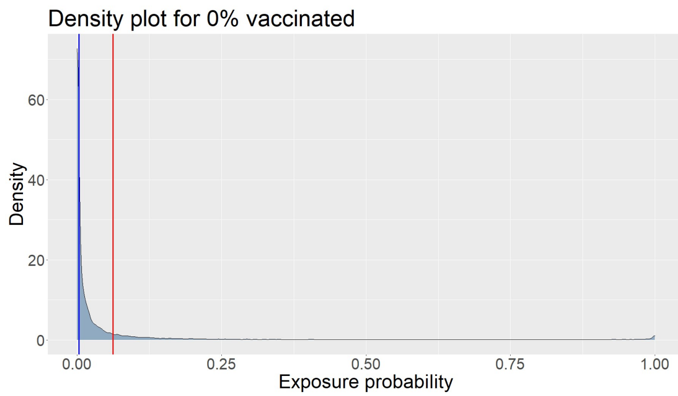

Figure 3: Density plot of airborne exposure probabilities of passengers for the scenario which 0% of passengers are vaccined. The blue line represents the median and the red line represents the mean.

The order in which passengers enter the airplane can greatly vary. In a given run, a specific passenger may come on board at the beginning of the process while, in another run, he or she may be the last one to get on board. This situation considerably affects the variation of the exposure risk for individuals. Thus, it is useful to evaluate the spatial distribution of exposure probability, when the index patient if fixed at seat 14E. The heat maps for medians and standard deviations for each scenario are given in Figure 4.

In Figure 4 (a), heat maps give the spatial distributions for medians (on the left) and standard deviations (on the right) for a scenario that corresponds to the situation in which there are no vaccinated passengers on board. As expected, the overall risk of exposure is the highest among the investigated scenarios. Not only the medians are high (about 90%), but also the standard deviations along the airplane vary significantly. It means that, overall the risk is low; however, there are cases where higher probabilities can be observed, especially in the seats located nearby the index patient. The adjacent seats also present high standard deviations; this happens due to the randomness of the boarding order. In a given simulation run, the adjacent passenger to the index patient can board right after him or her; in another run, that passenger can board in a different moment, staying less time in proximity to the infectious passenger and, therefore, being less exposed. This variability is clearly observed in the standard deviations heat map, on the right. Similarly, rows (b), (c), (d) and (e) correspond to the scenarios in which the proportion of fully vaccinated passengers gradually increase, until reaching the rate of 100%.

When comparing the heat maps from (a) through (e), the medians, especially for the passengers next to the index patient, significantly decrease, descending to values close to 0% median risk. For the standard deviation maps, throughout the airplane, the variability also decreases. In (a), values of 25% can be observed, whereas in (e), the highest value is about 10%. As the vaccine effectiveness is assumed to be a dumping factor in the exposure risk, as a higher number of passengers gets fully immunized, it is to be expected that the overall risk of exposure decrease.

Interesting remarks can be made by analyzing the standard deviations for the passengers in the vicinity of the index patient: although there is a considerable decrease in these values as the percentage of vaccinated

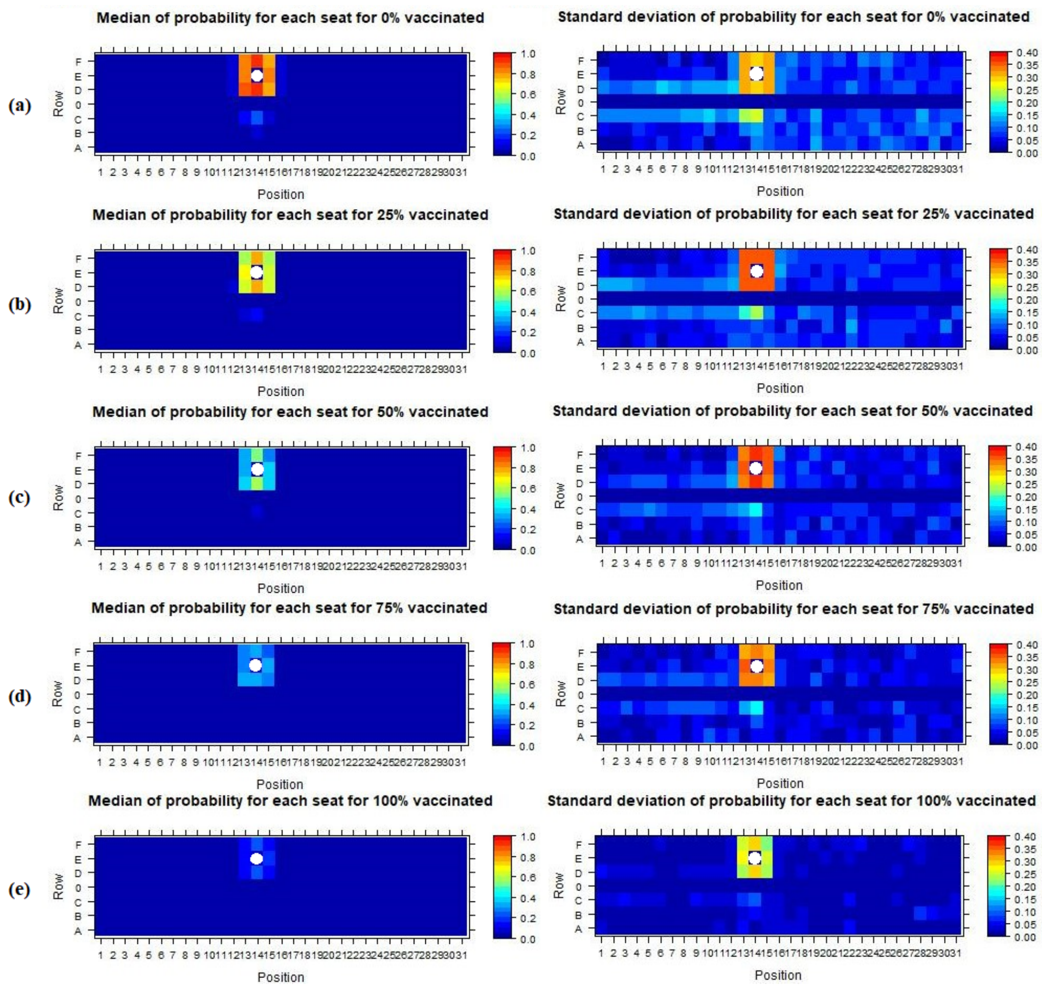

Figure 4: Heat maps of the medians and standard deviations for each of investigated scenarios, regarding the proportion of fully vaccinated passengers on board: (a) 0%, (b) 25%, (c) 50%, (d) 75%, and (e) 100%. Index patient is represented by a white dot.

passengers increase, the standard deviations are still high, reaching values of in the order of 30%, even in the scenario in which 100% of passengers are fully vaccinated. Therefore, further analysis is done considering only the passengers in seats adjacent to the infectious passenger, i.e., we consider the results concerning only passengers allotted to seats 13D, 13E, 13F, 14D, 14F, 15D, 15E and 15F.

Boxplots indicating the distributions of probability of exposure for the selected seats are given in Figure 5. The first important result is that the medians significantly decrease with the increase of vaccination percentage: from around 85% in the first scenario, to about 16% in the last case. This indicates that, as expected, the vaccination decreases exposure even when someone is seating next to an infected person.

The boxplots also shows a high variability for the data, with every scenario indicating risks close to 0% as well as close to 100% probability. This happens due to the absence of boarding order. As 200 runs are performed per scenario, it would be expected that both extremes be seen: a passenger boarding close to the index patient at the beginning of the process (keeps proximity to the infectious passenger for the longest period), and a passenger boarding very farther away (shortest time in proximity to the infectious passenger). The boxplots also show a shift in the quantiles of the distributions. While in the first scenario most occurrences happen between the minimum value and the median, in the last scenario, most occurrences happen between the median and the maximum values. In order to better visualize this

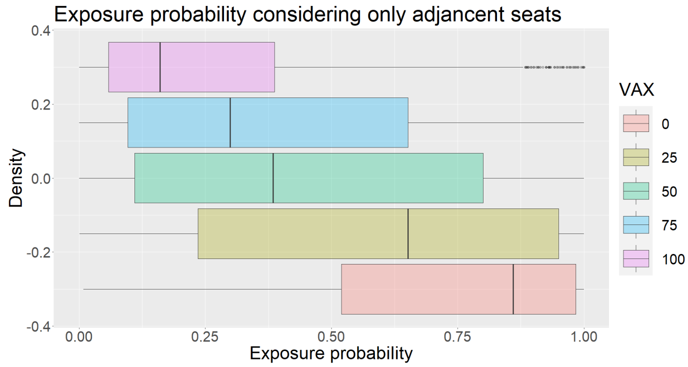

Figure 5: Boxplots of the distribution of exposure probabilities for each scenario of percentage of vaccinated passengers on board, considering only the adjacent passengers to the index patient.

change, the density plots of the exposure probabilities for all scenarios regarding the adjacent passengers are given in Figure 6.

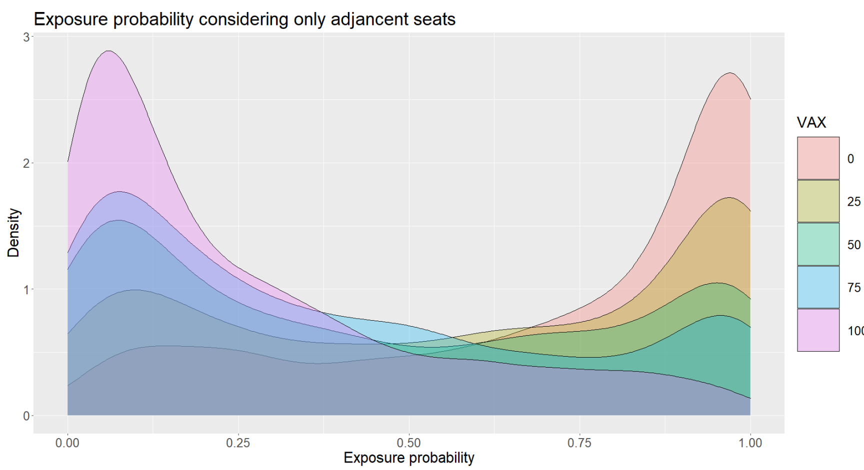

Figure 6: Density plots of exposure probabilities for the evaluated scenarios, considering only the passengers in seats adjacent to the index patient.

From Figure 6, it is possible to see a clear change in the distribution with the variation of the number of vaccinated individuals on board. When there are no vaccinated passengers (red plot), the most occurrences happen near 100% and fewer near zero. As the number of vaccinated individuals increase, there is an inversion in distribution. In the scenario with 100% vaccination (pink plot), most probabilities are near zero. This supports the conclusion that the vaccination decreases the risk of exposure to infectious diseases. Most passengers are exposed to a smaller risk. Even though there are still occurrences of higher probabilities, they are a minority of cases, reinforcing the need of mass vaccination.

Due to the fact that the maximums and minimums of all scenarios are very similar, we perform the Kruskal-Wallis test, using the R statistical package. This is a non-parametric test that indicates if at least one sample stochastically dominates another, i.e., whether the distributions are different. The results, given in Table 2, indicate significance with a p-value of 2.2e-16, which means that at least a pair of distributions are statistically different. Since the Kruskal-Wallis test is significant, a post-hoc analysis is performed in order to identify which distributions are different in a pair-wise comparison. In order to do that, a Dunn's test is performed. With p-values of 0, it is possible to conclude that all distributions are statistically different from each other.

Table 2: Kruskal-Wallis and Dunn's statistical tests.

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Kruskal-Wallis rank sum test

data: AIR and VAX
Kruskal-Wallis chi-squared = 5672.4906, df = 4, p-value = 0
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Table 3, below, gives a summary of the simulation results for the risk of exposure both for the cabin as a whole, and for only the passengers in seats adjacent to the index patient.

Table 3: Summary of simulation results.

Vaccination rate	0%	25%	50%	75%	100%
Median (overall)	0.36%	0.16%	0.07%	0.05%	0.03%
Standard Deviation (overall)	17.67 %	15.53%	12.87%	11.42%	7.80%
Median (adjacent)	85.95%	65.11%	38.40%	29.90%	16.04%
Standard Deviation (adjacent)	30.70%	35.36%	35.32%	32.86%	25.84%

Note that, as the proportion of fully vaccinated passengers increases, the overall risk of exposure to infectious airborne disease decreases throughout the aircraft cabin. It is observed a statistically significant decrease in median exposure risk of approximately 92%, from 0.36% (scenario with no vaccinated passengers) to 0.03% (scenario with passengers fully vaccinated). Even if the proportion of fully vaccinated passengers on board increases from 0% to only 50%, the median exposure risk drops more than 80%, from 0.36% to 0.07%. For passengers seating next to the index patient, the median risk decreases approximately 55%, from 86% (0% vaccinated passengers) to 38% (50% vaccination rate); if the vaccination rate increases from 0% to 100%, a drop of approximately 81% is observed, from 85% (scenario with no vaccinated passengers) to 16% (scenario with passengers fully vaccinated). In summary, if at least 50% of the passengers on board are fully vaccinated, there is a significant decrease of median risk of exposure, for all passengers, independently of seat location (80%). That drop in risk of exposure, however, is not uniform; when only the passengers in seats adjacent to the index patient are considered, the same drop in risk is observed only when all passengers on board are fully vaccinated. All these results provide quantitative evidence of not only of the importance of mass immunization, but it also indicates that, when full immunization is not guaranteed for 100% of passengers, it may be recommended to avoid full occupancy of the aircraft, as suggested by previous research (Dietrich et al. 2021).

4 CONCLUDING REMARKS

Vaccination against COVID-19 is still disproportionate across different regions of the world, with some countries having a significant part of the population fully vaccinated while, in others, only a minority of the population have received full immunization. As the severity of the pandemic seems to gradually subside and people feel more willing to take risks in order to resume normal daily activities, an increase in air travel volume is observed. Therefore, the objective of this study was to generate empirical (although simulated) evidence on the importance of vaccination in decreasing the risk of exposure to airborne infectious diseases during air travel.

In order to do that, we evaluated the effect of vaccines in the exposure risk to infectious diseases during the boarding process in a commercial airplane. Using an agent-based simulation model, different levels for the proportion of fully vaccinated passenger on board were evaluated, varying from 0% to 100%.

As the proportion of fully vaccinated passengers increase, the overall risk of exposure to infectious airborne disease decreases, throughout the aircraft cabin. It is observed a statistically significant decrease in median exposure risk of more than 80% when only 50% of passengers on board are fully vaccinated, compared with a scenario in which no passengers are vaccinated; there is a 92% total decrease in risk of exposure if the vaccination rate is 100%. Such drop in risk of exposure is not uniform throughout the cabin, and passengers in seats adjacent to an infectious passenger are at a much larger risk; the median risk decreases approximately 55%, if 50% of passengers on board are fully vaccinated, and 81%, if all passengers are fully vaccinated, when compared with the scenario when there are no vaccinated passengers on board. Such results provide quantitative evidence of not only of the importance of mass immunization, but it also indicates that, when full immunization is not guaranteed for 100% of passengers, it may be recommended to avoid full occupancy of the aircraft, by implementing physical distancing when assigning seats in aircraft cabins.

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