A Risk Prediction Model and Risk Score of SARS-CoV-2 Infection Following Healthcare-Related Exposure

Kantarida Sripanidkulchai 1, Pinyo Rattanaumpawan 2, Winai Ratanasuwan 1, Nasikarn Angkasekwinai 2, Susan Assanasen 2, Peerawong Werarak 1, Oranich Navanukroh 1, Phatharajit Phatharodom 1, and Teerapong Tocharoenchok 3,*

1 Department of Preventive and Social Medicine, Faculty of Medicine Siriraj Hospital, Mahidol University, Bangkok 10700, Thailand
2 Division of Infectious Diseases and Tropical Medicine, Department of Medicine, Faculty of Medicine Siriraj Hospital, Mahidol University, Bangkok 10700, Thailand
3 Division of Cardiothoracic Surgery, Department of Surgery, Faculty of Medicine Siriraj Hospital, Mahidol University, Bangkok 10700, Thailand
* Correspondence: teerapong.toc@mahidol.ac.th; Tel.: +66-8-9688-0179

Abstract: Hospital workers are at high risk of contact with COVID-19 patients. Currently, there is no evidence-based, comprehensive risk assessment tool for healthcare-related exposure; so, we aimed to identify independent factors related to COVID-19 infection in hospital workers following workplace exposure(s) and construct a risk prediction model. We analyzed the COVID-19 contact tracing dataset from 15 July to 31 December 2021 using multiple logistic regression analysis, considering exposure details, demographics, and vaccination history. Of 7146 included exposures to confirmed COVID-19 patients, 229 (4.2%) had subsequently tested positive via RT-PCR. Independent risk factors for a positive test were having symptoms (adjusted odds ratio 4.94, 95%CI 3.83–6.39), participating in an unprotected aerosol-generating procedure (aOR 2.87, 1.66–4.96), duration of exposure >15 min (aOR 2.52, 1.82–3.49), personnel who did not wear a mask (aOR 2.49, 1.75–3.54), exposure to aerodigestive secretion (aOR 1.5, 1.03–2.17), index patient not wearing a mask (aOR 1.44, 1.01–2.07), and exposure distance <1 m without eye protection (aOR 1.39, 1.02–1.89). High-potency vaccines and high levels of education protected against infection. A risk model and scoring system with good discrimination power were built. Having symptoms, unprotected exposure, lower education level, and receiving low potency vaccines increased the risk of laboratory-confirmed COVID-19 following healthcare-related exposure events.

Keywords: COVID-19; SARS-CoV-2; occupational exposure; risk factors; personal protective equipment

1. Introduction

Healthcare workers are at high risk for exposure to COVID-19, both in the community and in the workplace when caring for patients [1]. Infection prevention and control practices are recommended for all hospital workers and include the use of personal protective equipment, physical distancing, source control measures, immunization, and post-exposure management [2]. The early assessment of risk and prompt management are important to protect the health and safety of personnel to prevent in-hospital transmission [3]. On the other hand, the isolation and quarantine associated with COVID-19 that are required of health workers place additional strain on healthcare services during periods of high demand. The individualized estimation of the infection risk of certain exposure of health workers is needed to guide optimal prevention and response strategies.

The exposure risk assessment and management system is currently mainly based on expert opinion, because only a few studies have addressed this problem, and there is the significant heterogeneity of operational definitions for variables that influence exposure risk, such as the measurement of contact duration, distance, the use of a face mask versus a
respirator with eye protection, and differing vaccine regimens and efficacies [4–9]. Further, most COVID-19 healthcare exposure studies categorized exposure risk using multiple measures in combination (without complete details of individual exposure) and were conducted during periods when less contagious variants were circulating and different vaccine products and regimens were employed [9–11].

In the third quarter of 2021, Siriraj Hospital, a 2300-bed referral center in Bangkok with more than 16,000 employees, conducted more than 200 SARS-CoV-2 genetic tests per day for its personnel. Adapted from USCDC, WHO, European and Thailand public health interim guidelines, the hospital risk assessment and management system classified the risk of exposure and recommended appropriate testing times, work restrictions, and quarantine for those who were exposed to confirmed patients with COVID-19 [12–16]. Independent factors associated with COVID-19 infection could be identified using the large and detailed exposure dataset, demographic data, vaccination history, and complete entry and exit test status.

The objectives of this study are to identify independent factors associated with SARS-CoV-2 infection detected via RT-PCR in hospital workers following exposure(s) to confirmed positive patients and to build an evidence-based quantitative risk model and risk score for healthcare-related exposure.

2. Materials and Methods
2.1. Study Design, Setting, and Protocol

This study is a retrospective cohort analysis. From July 2021 to January 2022, during the increase in the number of cases of COVID-19 caused by the Delta variant, the hospital implemented a contact tracing and risk evaluation system based on exposure characteristics and immunization status to guide risk-specific SARS-CoV-2 tests, work restriction, and quarantine recommendations (Supplementary Tables S1–S3). Hospital workers who had been exposed to a confirmed case within the contagious period or had any symptoms related to SARS-CoV-2 (Appendix A) were evaluated as per hospital guidelines.

2.2. Data Collection and Preparation

Data collection was completed by exposed hospital workers or their representatives directly into a computer spreadsheet (infected person, worker identification, event details, symptoms, and immunization record). Completeness and accuracy were validated using mandatory field entry, data validation, and logic checks with feedback confirmation by responsible infection control officers. If personnel had multiple exposures to the same index person, the risk would be assigned to the highest risk event, and recommendations would be arranged according to the latest significant exposure. The classification of exposure risk (high, moderate, low or insignificant—based on the characteristics of exposure and the use of personal protective equipment (PPE) according to the consensus of the experts of the hospital detailed in Supplementary Table S1) and the recommendation were assigned by infectious disease specialists with the aid of software developed by the hospital. This exposure risk category was not introduced directly to the logistic regression model as all individual exposure criteria had already been included.

The variables of interest that were not included in the initial dataset (age, gender, education, and SARS-CoV-2 test results) and those subject to recall errors (immunization record) were provided by the hospital informatics and data innovation center. Missing and conflicting data were manually imputed based on available electronic hospital records.

2.3. Study Definition
2.3.1. Vaccine Formula and Potency Grouping

COVID-19 vaccination at least 14 days before exposure was considered to exert a full protective effect and was defined as the completion of the last dose. Due to the wide variety of vaccine combinations among Thai health workers [17], we classified all combination states into three distinct potency groups according to criteria adapted from Thai COVID-19
vaccination guidelines for a booster shot from the Ministry of Public Health in December 2021 (Supplementary Table S4) [18,19]. Low-potency combinations included any number of doses of an inactivated vaccine product, or a single dose of any other product (viral vector or mRNA). Moderate-potency combinations included two or more doses of an inactivated vaccine and at least one dose of either a viral vector product or an mRNA product. High-potency combinations included any dose of an inactivated product with at least one dose of viral vector product plus one dose of mRNA platform, or at least two doses of mRNA platform.

2.3.2. Laboratory Analysis and Case Definition

COVID-19 was diagnosed via SARS-CoV-2 genetic detection from respiratory samples using a real-time RT-PCR test, Allplex™ 2019-nCoV Assay (Seegene®, Seoul, Korea). The cycle threshold of <40 for the E and N gene and <42 for the RdRp gene was considered positive. To resolve the discrepancies between different genes tested, infectious disease specialists would define the status of the case based on their history and subsequent test(s).

2.4. Statistical Analysis

Continuous variables were reported as means with standard deviation and medians with interquartile range, while categorical data were reported using frequencies and percentages. The variables between groups were compared using the independent sample T test or Pearson’s chi-square test (or nonparametric equivalents where appropriate), with statistical significance defined as a p value less than 0.05. Using multiple logistic regression, all variables with a p value less than 0.25 from univariate pre-screening entered the model provided they were present in at least 1% of the sample. Using the stepwise multivariate analysis, the variables that did not contribute to the model were eliminated either by exclusion or collapse to another category, whichever yielded maximal discrimination power from the ROC curve analysis. An additive risk score of predicted probability of COVID-19 infection was developed with coefficients from the final model (Appendix B). Model fit was accessed using the Hosmer and Lemeshow test. The logistic exposure risk calculator was built and is available at https://bit.ly/3uEi4W2 (accessed on 15 May 2022). All analyses were performed using SPSS™ software version 26.0 (IBM Corporation, Armonk, NY, USA) and Microsoft Excel™ software version 2203 (Microsoft Corporation, Redmond, WA, USA).

3. Results

The study flow diagram is illustrated in Figure 1. From 15 July to 31 December 2021, more than 19,000 hospital workers exposed to confirmed SARS-CoV-2 patients or who had symptoms related to COVID-19 were reported to infectious disease specialists. A total of 8557 entries were arranged for the RT-PCR test(s). After the exclusion of entries outside the scope of the study (uncertain contact history with various reasons for the RT-PCR test), duplicate entries and those without sufficient data for analysis, 7146 exposures were retained in the final dataset.

3.1. Baseline Characteristics

Of the 7146 exposures of 5449 hospital workers, 299 (4.2%) cases of COVID-19 infection were confirmed. The incidence of included events and COVID-19 detection gradually decreased during the study period (Supplementary Figure S1). The baseline characteristics of the included entries are listed in Table 1. The median age (range) of exposed hospital workers was 32 years (18–88), with women (73.8%) and healthcare personnel (Appendix A, 85.6%) being predominant. Among the hospital workers, the most common occupations were nurses and nurse/physician assistants (41.1%) followed by physicians/dentists and dentist assistants (12.6%), janitorial staff (12.3%), and administrative staff (12.3%). Less than 1% of the entries came from hospital workers with previous COVID-19 disease, and no hospital worker experienced repeated infection during the study period. In general, SARS-CoV-2 detections were more prevalent in exposures of workers with lower education.
(primary or secondary school; 7.7%), exposures without proper personal protective equipment or hygiene (i.e., high-risk exposure; 8.1%), exposures accompanied by fever or other symptoms related to COVID-19 (Appendix A, 14.3%), and exposures of hospital workers who had received vaccine combinations of lower potency (low potency; 14%).

Figure 1. Consort type study flow diagram.

Table 1. Characteristics of occupational exposures to COVID-19 of hospital workers.

| Characteristics                          | Subsequent COVID-19 Infection within 14 Days after Last Exposure | Total | p Value |
|-----------------------------------------|------------------------------------------------------------------|-------|---------|
|                                         | No                  | Yes   | Event Rate | n = 7146 | % of Total |
| Demographic                             | n = 6847            | n = 299 | 34.98, 10.50 | 0.216 |
| Age at exposure, year                   | 34.95, 10.49        | 35.72, 10.64 | 34.98, 10.50 | 0.216 |
| Mean, standard deviation                | 32 (27–42)          | 35 (26–44) | 32 (27–42) | 0.186 |
| Median (interquartile range)            | 0.067               |          |          |         |
| Gender                                  | Male                | Female  | 1781          | 5066    | 92       | 207     | 4.9%     | 3.9%   | 1873 | 5273 | 73.8% |
| Gender                                  | 1599                | 5066    | 1.7%          | 7.7%   | 1732 | 133 | 21.4% | 1.7% | 1320 | 73.8% |
| The highest education attainment        | Primary or secondary school | Associate’s degree | Bachelor’s degree | Master’s degree | Doctoral degree | 1599 | 133 | 7.7% | 1732 | 21.4% | 1320 | 73.8% | 344 | 5 | 1.4% | 349 | 4.9% |
| Characteristics                                      | Subsequent COVID-19 Infection within 14 Days after Last Exposure | Total | p Value |
|------------------------------------------------------|---------------------------------------------------------------|-------|---------|
|                                                      | No    | Yes    | Event Rate | n = 299 | n = 7146 | % of Total |         |
| Role of hospital worker                              |       |        |            |         |         |          |         |
| Healthcare personnel                                | 5864  | 253    | 4.1%       | 6117    | 86.6%    |          | 0.620   |
| Non-healthcare personnel                            | 983   | 46     | 4.5%       | 1029    | 14.4%    |          |         |
| COVID-19 vaccination status                         |       |        |            |         |         |          |         |
| Vaccines                                            |       |        |            |         |         |          |         |
| CoronaVac–CoronaVac                                  | 3684  | 190    | 4.9%       | 3874    | 54.2%    |          | <0.001  |
| CoronaVac–CoronaVac–ChAdOx-1                        | 1203  | 47     | 3.8%       | 1250    | 17.5%    |          |         |
| CoronaVac–CoronaVac–BNT162b2                         | 1070  | 18     | 1.7%       | 1088    | 15.2%    |          |         |
| ChAdOx-1                                            | 284   | 10     | 3.4%       | 294     | 4.1%     |          |         |
| ChAdOx-1–ChAdOx-1                                   | 219   | 9      | 3.9%       | 228     | 3.2%     |          |         |
| None                                                | 117   | 19     | 14.0%      | 136     | 1.9%     |          |         |
| ChAdOx-1–BNT162b2                                    | 116   | 1      | 0.9%       | 117     | 1.6%     |          |         |
| Others                                               | 154   | 5      | 3.1%       | 159     | 2.2%     |          |         |
| Potency of COVID-19 Vaccines *                       |       |        |            |         |         |          | <0.001  |
| None                                                | 117   | 19     | 14.0%      | 136     | 1.9%     |          | §       |
| Low-potency vaccines                                 | 4025  | 202    | 4.8%       | 4227    | 59.2%    |          |         |
| Moderate-potency vaccines                            | 2537  | 77     | 2.9%       | 2614    | 37.6%    |          |         |
| High-potency vaccines                                | 168   | 1      | 0.6%       | 169     | 2.4%     |          |         |
| The interval between the last dose of COVID-19 vaccines and exposure, day |       |        |            |         |         |          |         |
| Mean, standard deviation                             | 72.07 | 33.36  | 73.78, 29.68 | 72.14 | 33.22 | 0.351 |         |
| Median (interquartile range)                         | 72 (47–93) | 75 (57–95) | 72 (48–93) | 0.302 |         |         |
| Missing data                                         | 207   | 21     | 3.2%       | 228     |          |          |         |
| Previous COVID-19 infection                         |       |        |            |         |         |          | 0.755   |
| Absence                                             | 6564  | 290    | 4.2%       | 6854    | 99.1%    |          | #       |
| Presence                                            | 62    | 3      | 4.6%       | 65      | 0.9%     |          |         |
| Exposure characteristics                              |       |        |            |         |         |          | <0.001  |
| Infected person was wearing a mask/N95 respirator during exposure |       |        |            |         |         |          |         |
| Yes                                                  | 2897  | 61     | 2.1%       | 2958    | 41.4%    |          |         |
| No                                                   | 3950  | 238    | 5.7%       | 4188    | 58.6%    |          |         |
| Distance of contact                                  |       |        |            |         |         |          | <0.001  |
| More than 1 m                                       | 1510  | 40     | 2.6%       | 1550    | 21.7%    |          |         |
| Less than 1 m                                       | 5337  | 259    | 4.6%       | 5596    | 78.3%    |          |         |
| Duration of exposure                                 |       |        |            |         |         |          | <0.001  |
| Less than 15 min                                     | 3380  | 53     | 1.5%       | 3433    | 48.0%    |          |         |
| More than 15 min                                     | 3467  | 246    | 6.6%       | 3713    | 52.0%    |          |         |
| Exposed hospital worker was wearing a mask/N95 respirator during exposure |       |        |            |         |         |          | <0.001  |
| Yes                                                  | 4535  | 91     | 2.0%       | 4626    | 64.7%    |          |         |
| No                                                   | 2312  | 208    | 8.3%       | 2520    | 35.3%    |          |         |
| Exposed hospital worker was wearing a face shield during exposure |       |        |            |         |         |          | <0.001  |
| Yes                                                  | 1941  | 38     | 1.9%       | 1979    | 27.7%    |          |         |
| No                                                   | 4906  | 261    | 5.1%       | 5167    | 72.3%    |          |         |
| Infected person was undergoing aerosol-generating procedures |       |        |            |         |         |          | 0.186   |
| No                                                   | 6465  | 277    | 4.1%       | 6742    | 94.3%    |          |         |
| Yes; exposed hospital worker was wearing N95 respirator/PAPR and face shield |       |        |            |         |         |          |         |
| Yes                                                  | 77    | 2      | 2.5%       | 79      | 1.1%     |          |         |
| No                                                   | 298   | 50     | 14%        | 348     | 4.9%     |          |         |
| Exposed hospital worker had direct contact with the aerodigestive secretion of the infected person |       |        |            |         |         |          | <0.001  |
| No                                                   | 6549  | 249    | 3.7%       | 6798    | 95.1%    |          |         |
| Yes                                                  | 298   | 50     | 14%        | 348     | 4.9%     |          |         |
### Table 1. Cont.

| Characteristics                                                                 | Subsequent COVID-19 Infection within 14 Days after Last Exposure | Total | p Value |
|---------------------------------------------------------------------------------|---------------------------------------------------------------|-------|---------|
|                                                                                 | No                | Yes               | Event Rate | % of Total |
|                                                                                 | n = 6847          | n = 299           | n = 7146    | % of Total |
| Exposure risk category by infectious disease physicians                          |                   |                   |             | <0.001     |
| Low risk                                                                         | 2263              | 17                | 0.7%        | 2280        | 31.9%     |
| Moderate risk                                                                    | 1684              | 39                | 2.3%        | 1723        | 24.1%     |
| High risk                                                                        | 2558              | 224               | 8.1%        | 2782        | 38.9%     |
| Insignificant exposure with symptom(s) or reason(s) for RT-PCR                   | 342               | 19                | 5.3%        | 361         | 5.1%      |
| Symptom of exposed hospital worker                                              |                   |                   |             | <0.001     |
| Fever or other COVID-19-related symptoms                                         | 5073              | 103               | 2.0%        | 5176        | 79.1%     |
| Presence                                                                         | 1174              | 196               | 14.3%       | 1370        | 20.9%     |

RT-PCR: reverse transcriptase–polymerase chain reaction, § linear-by-linear association, # Fisher’s Exact test, other p value from independent samples T-test, Pearson Chi-Square test, or independent-samples Mann-Whitney U test, * adapted from Thai COVID-19 Vaccination Guidelines for a Booster Shot, Ministry of Public Health, December 2021.

All events were classified into four exposure risk categories: low (31.9%), moderate (24.1%), high (38.9%), and insignificant risk (but being tested due to COVID-19-related symptoms) (5.1%). This risk classification was highly correlated with the SARS-CoV-2 detection rate (0.7%, 2.3%, 8.1%, and 5.3%; p < 0.001). Most exposures (98.1%) came from personnel who had received at least one dose of the vaccine. The median interval from the last vaccination to the day of exposure was 72 days (range 14 to 236). More than half of the hospital workers (54.2%) received two doses of CoronaVac (SINOVAC Biotech, Beijing, China), 17.5% received an additional ChAdOx-1 (AstraZeneca, Oxford, UK; Cambridge, UK), 15.2% received an additional BNT162b2 (Pfizer-BioNTech, New York, USA; Mainz, Germany) vaccination as a booster, and 11.2% had other vaccine combinations. The remaining 136 exposures came from hospital workers who were not vaccinated at the time of exposure (1.9%).

Among the events with subsequent COVID-19 infection, the median time to detection after the last exposure was four days (interquartile range 1 to 7), with 90% of all detections occurring within 11 days from the last exposure (Supplementary Figure S2). No mortality was observed during the study period.

### 3.2. Factors Associated with SARS-CoV-2 Infection

After prescreening with univariate logistic regression, twelve factors entered the preliminary main effect model (Table 2), and nine remained in the final logistic model. There were two baseline characteristics and seven exposure-related factors that contributed to the risk of SARS-CoV-2 infection. All independent factors and weights associated with them are shown in Table 3. To calculate the predicted probability for SARS-CoV-2 genetic detection using an additive risk score, the points for factors present in a particular exposure are added to give an approximate percentage, as outlined in Table 4.
Table 2. Logistic regression analysis of variables associated with occupational SARS-CoV-2 infection among hospital workers.

| Variable                                      | Univariable Analysis | Multivariable Analysis |
|-----------------------------------------------|----------------------|------------------------|
|                                               | Crude OR (95% CI)    | p Value                | Adjusted OR (95% CI) | p Value      |
| **Demographic**                               |                      |                        |                      |              |
| Age (year)                                    | 1.01 (1–1.02)        | 0.216                  | 1.01 (1–1.02)        | 0.053        |
| Male gender                                   | 1.26 (0.98–1.63)     | 0.068                  | 1.11 (0.83–1.48)     | 0.480        |
| The highest education attainment              |                      |                        |                      |              |
| Primary or secondary school (reference)       |                      |                        |                      |              |
| Associate’s                                   | 0.64 (0.47–0.86)     | 0.004                  | 0.76 (0.54–1.06)     | 0.106        |
| Bachelor’s                                    | 0.34 (0.25–0.45)     | <0.001                 | 0.44 (0.32–0.61)     | <0.001       |
| Master’s                                      | 0.19 (0.1–0.34)      | <0.001                 | 0.31 (0.17–0.58)     | <0.001       |
| Doctoral                                      | 0.18 (0.07–0.43)     | <0.001                 | 0.36 (0.14–0.92)     | 0.033        |
| Role of worker: Healthcare personnel          | 0.92 (0.67–1.27)     | 0.620                  |                      |              |
| **Exposure characteristics**                  |                      |                        |                      |              |
| Infected person was not wearing a mask/N95 respirator during exposure | 2.86 (2.15–3.81) | <0.001 | 1.45 (1–2.1) | 0.048 |
| Distance of exposure less than 1 m            | 1.83 (1.31–2.57)     | <0.001                 | 1.4 (0.97–2)         | 0.069        |
| Duration of exposure more than 15 min         | 4.53 (3.35–6.11)     | <0.001                 | 2.51 (1.81–3.48)     | <0.001       |
| Exposed hospital worker not wearing a mask/N95 respirator during exposure | 4.48 (3.49–5.77) | <0.001 | 2.54 (1.72–3.76) | <0.001 |
| Exposed hospital worker not wearing face shield or goggles during exposure | 2.72 (1.93–3.83) | <0.001 | 1.25 (0.78–1.98) | 0.353 |
| Infected person was undergoing aerosol-generating procedures | 0.156                | 0.001                  |                      |              |
| No (reference)                                |                      |                        |                      |              |
| Yes; exposed HCP was wearing N95 respirator/PAPR and face shield | 0.61 (0.15–2.48) | 0.486 | 1.28 (0.29–5.66) | 0.748 |
| Yes; exposed HCP was not wearing N95 respirator/PAPR and face shield | 1.53 (0.96–2.44) | 0.075 | 2.86 (1.64–5) | <0.001 |
| Exposed hospital worker had direct contact with aerodigestive secretion of the infected person | 4.41 (3.19–6.11) | <0.001 | 1.48 (1.02–2.15) | 0.038 |
| **Symptoms of exposed hospital worker**       |                      |                        |                      |              |
| Fever or other COVID-19-related symptoms       | 5.44 (4.26–6.95)     | <0.001                 | 4.9 (3.78–6.34)      | <0.001       |
| **COVID-19 vaccination status**               |                      |                        |                      |              |
| Potency of COVID-19 vaccines *                |                      |                        |                      |              |
| None (reference)                              | <0.001               | 0.001                  |                      |              |
| Low-potency vaccines                          | 0.31 (0.19–0.51)     | <0.001                 | 0.31 (0.18–0.54)     | <0.001       |
| Moderate-potency vaccines                     | 0.19 (0.11–0.32)     | <0.001                 | 0.16 (0.09–0.3)      | <0.001       |
| High-potency vaccines                         | 0.04 (0.01–0.28)     | 0.001                  | 0.05 (0.01–0.41)     | 0.005        |
| The interval between the last dose of COVID-19 vaccines and exposure (day) | (1–1.01) | 0.402 | | |
| Previous COVID-19 infection: Yes              | 1.1 (0.34–3.51)      | 0.878                  |                      |              |

* Adapted from Thai COVID-19 Vaccination Guidelines for a Booster Shot, Ministry of Public Health, December 2021.
Table 3. Independent risk factors associated with subsequent SARS-CoV-2 infection after occupational exposure among hospital workers, coefficients from the final logistic model, and weight (point) for the risk score.

| Risk Factor                                                                 | \( \beta \) | Odds Ratio (95% CI) | \( p \) Value | Point |
|-----------------------------------------------------------------------------|--------------|----------------------|---------------|------|
| The highest education attainment                                            |              |                      |               |      |
| Primary or secondary school (reference)                                     |              |                      |               |      |
| Undergraduate (associate’s or bachelor’s)                                   | −0.64        | 0.53 (0.4–0.68)      | <0.001        | 3    |
| Postgraduate (master’s or doctoral)                                        | −1.13        | 0.32 (0.19–0.55)      | <0.001        | 1    |
| Infected person was not wearing a mask/N95 respirator during exposure       | 0.37          | 1.44 (1.01–2.07)      | 0.046         | 1    |
| Distance of exposure less than 1 m without a face shield                    | 0.33          | 1.39 (1.02–1.89)      | 0.038         | 1    |
| Duration of exposure more than 15 min                                       | 0.93          | 2.52 (1.82–3.49)      | <0.001        | 3    |
| Exposed hospital worker was not wearing a mask/N95 respirator during exposure | 0.91          | 2.49 (1.75–3.54)      | <0.001        | 3    |
| Exposed hospital worker was not wearing an N95 respirator and face shield/goggles while the infected person was undergoing aerosol-generating procedure | 1.05          | 2.87 (1.66–4.96)      | <0.001        | 3    |
| Exposed hospital worker had direct contact with the aerodigestive secretion of the infected person | 0.40          | 1.5 (1.03–2.17)      | 0.033         | 1    |
| Fever or other COVID-19-related symptoms                                    | 1.60          | 4.94 (3.83–6.39)      | <0.001        | 5    |
| Potency of COVID-19 vaccines *                                              |              |                      |               |      |
| None (reference)                                                            |              |                      |               | 9    |
| Low-potency vaccines                                                        | −1.19        | 0.3 (0.17–0.53)       | <0.001        | 5    |
| Moderate-potency vaccines                                                   | −1.79        | 0.17 (0.09–0.3)       | <0.001        | 4    |
| High-potency vaccines                                                       | −2.98        | 0.05 (0.01–0.4)       | 0.004         | 0    |
| Constant                                                                    | −3.69        |                      | <0.001        |      |

* Adapted from Thai COVID-19 Vaccination Guidelines for a Booster Shot, Ministry of Public Health, December 2021.

Table 4. The predictive score for SARS-CoV-2 infection after occupational exposure among hospital workers.

| Total Point | Predicted Probability of COVID-19 Infection (%) |
|-------------|-----------------------------------------------|
| 0–9         | 0.05–0.93                                     |
| 10–14       | 1.28–4.60                                     |
| 15–16       | 6.28–8.51                                     |
| 17–19       | 11.44–19.94                                   |
| 20–23       | 25.70–48.09                                   |
| 24–29       | 56.27–86.92                                   |

Having a fever or other COVID-19-related symptoms was the strongest risk factor for SARS-CoV-2 genetic detection (adjusted OR 4.94, 95% CI 3.83–6.39). Other strong risk factors included performing an aerosol-generating procedure without full protection (aOR 2.87, 1.66–4.96), prolonged duration of contact (aOR 2.52, 1.82–3.49), and personnel not wearing a mask (aOR 2.49, 1.75–3.54). Direct contact with aerodigestive secretion, the infected person not wearing a mask, and close contact without proper eye protection carried smaller risks. Vaccination was protective against infection: aOR 0.05 (high-potency combinations), aOR 0.17 (moderate-potency combinations), and 0.3 (low-potency combination). Hospital workers with higher levels of education level were less likely to be infected.

The model fit was confirmed using the Hosmer and Lemeshow test (Chi-square 8.960, \( p \) 0.346). The discrimination power of the final logistic model and the risk scoring system accessed via ROC curves are depicted in Figure 2, which confirms the model’s performance. The exposure risk categories also demonstrated good predictive power in the parallel analysis (adjusted OR 2.58 for moderate-risk and 8.53 for high-risk contact; Supplementary Table S5), but with a smaller area under the ROC curve at 0.827 (95% CI 0.804–0.849).
WHO [23] also increased the risk of infection. One interesting finding to be noted is that an exposure distance of <1 m and not using an eye protection device failed to reach statistical significance in the preliminary effect model but showed significance when considering both factors together (i.e., a face shield is only beneficial when in close contact). This supports the adequacy of the universal droplet precautions despite recent evidence in favor of airborne precautions [24,25] given that no aerosol-generating procedure is being performed.

The most common vaccine regimen in this study, two doses of inactivated vaccines (low potency), provided the least protection against infection, while the second most common regimen, heterologous boosted inactivated vaccines (moderate potency), provided slightly better protection but much less when compared with the viral vector-mRNA combination (high potency). This is consistent with the previous report from Sritipsukho et al. [17] which underlined the importance of vaccine type over the number of doses. Our findings also validated our COVID-19 exposure risk category approach which was used to determine the need for RT-PCR testing and isolation during a period of manpower and resource limitation.

Although symptoms related to COVID-19 should be considered as a consequence of infection rather than a risk factor for infection, our data support that all symptomatic health workers with an exposure history during the epidemic should be tested, regardless of contact risk and immunologic status, provided that this policy does not overwhelm laboratory testing capacity. A significant portion of infected hospital workers tested positive before the initial recommended test date(s), which implied the benefit of the early test (and

Figure 2. Areas under the ROC curve for the final logistic model (A) and the risk scoring system (B).

4. Discussion

Using information acquired from contact tracing during the Delta peak at 86–99% in the community [20–22], we developed a risk prediction model to estimate the risk of infection for hospital workers with different vaccination regimens following exposure to confirmed COVID-19 cases. Exposure type, the presence of symptoms, the appropriate use of PPE, education level, vaccination regimen, and time since the last dose each contributed important information regarding the risk of infection.

Having a fever or other COVID-19-related symptoms within two weeks was strongly predictive of a positive test. Similar to the previous report by Pienthong et al. [8], failure to comply with protective measures increased the risk of infection. For example, commencing an aerosol-generating procedure (Appendix A) without proper protective equipment (including an N95 respirator and eye protection) was the highest procedural risk in this study, followed closely by a prolonged duration of exposure and the worker not wearing a mask. Other violations of standard precautions and the improper use of PPE recommended by the WHO [23] also increased the risk of infection. One interesting finding to be noted is that an exposure distance of <1 m and not using an eye protection device failed to reach statistical significance in the preliminary effect model but showed significance when considering both factors together (i.e., a face shield is only beneficial when in close contact). This supports the adequacy of the universal droplet precautions despite recent evidence in favor of airborne precautions [24,25] given that no aerosol-generating procedure is being performed.

The most common vaccine regimen in this study, two doses of inactivated vaccines (low potency), provided the least protection against infection, while the second most common regimen, heterologous boosted inactivated vaccines (moderate potency), provided slightly better protection but much less when compared with the viral vector-mRNA combination (high potency). This is consistent with the previous report from Sritipsukho et al. [17] which underlined the importance of vaccine type over the number of doses. Our findings also validated our COVID-19 exposure risk category approach which was used to determine the need for RT-PCR testing and isolation during a period of manpower and resource limitation.
early detection) triggered by symptoms. This contrasts with other studies on symptomatic patients presenting at health services which demonstrated poor diagnostic accuracy of signs and symptoms [26,27]. An explanation might be that, in addition to being symptomatic, all of our included subjects must have certain exposure to an infected person.

Consistent with a 2020 study by Chadeau-Hyam et al., the level of education of the hospital workers was inversely correlated with the risk of testing positive [28]. This could be explained by better health literacy, self-awareness, and hygiene discipline. Educational achievement is also correlated with occupations that pose different risks of COVID-19 infection [29]. Improved educational interventions are additionally needed to increase awareness among workers with lower levels of education.

Most of the COVID-19 risk calculators available provide a very crude risk estimate based primarily on location, the nature of the activity, and the safety measures being taken [30]. Our risk calculator and score, on the contrary, provide an individualized risk assessment based on detailed exposure characteristics adjusted for vaccination status and socioeconomic background through educational attainment. To a certain extent, this tool has the utility to triage exposed individuals to prevent further infections in healthcare settings.

This study has several limitations. We did not include the severity of cases that got infected (i.e., CT value or hospitalization). Due to the retrospective nature of the observational study, some demographic information may have been missed. Furthermore, most of the data were entered by various staff with different levels of health knowledge. Therefore, misclassification may be an issue. The external validation of the risk model was also difficult to perform due to the rapid shift in the variants of concern and vaccine-induced immunity over time.

5. Conclusions

Having symptoms of COVID-19, inadequate personal protection, low education level, and not receiving a vaccine or receiving a low-potency vaccine regimen were found to be the main risks for COVID-19 infection among all healthcare-related exposures. Our quantitative exposure risk model and risk score have good predictive value and could help combat further spread among hospital workers according to their actual probability of infection.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/tropicalmed7090248/s1, Figure S1: Daily number and cumulative percentage of occupational exposures among healthcare personnel in the study, 15 September to 31 December 2021; Figure S2: Distribution of SARS-CoV-2 PCR assay detection day after last known exposure; Table S1: Exposure-characteristics-based risk classification; Table S2: Management of contact hospital workers in terms of guided testing and quarantine duration based on contact risk and vaccination history; Table S3: Definition of immunization during the study period; Table S4: Vaccine regimen potency grouping, adapted from Thai COVID-19 vaccination guidelines for a booster shot from the Ministry of Public Health as of December 2021; Table S5: Parallel analysis of variables associated with SARS-CoV-2 infection using exposure risk category, the final logistic model.

Author Contributions: Conceptualization, P.R. and T.T.; methodology, P.R. and T.T.; software, T.T.; formal analysis, P.R. and T.T.; investigation, K.S. and T.T.; data curation, K.S., P.R., W.R., N.A., P.W., S.A., P.P. and O.N.; writing—original draft preparation, K.S.; writing—review and editing, T.T., P.R., N.A. and S.A.; visualization, T.T.; supervision, P.R. project administration, K.S. and T.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: This study was approved by the Siriraj Institutional Review Board on 5 November 2021, which was in full compliance with international guidelines for human research protection such as the Declaration of Helsinki (Study Code 838/2564(IRB4)).

Informed Consent Statement: The patient consent was waived as it contained minimal risk to the subject.
Data Availability Statement: The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Acknowledgments: We thank the members of Infection Control Nurses, infectious disease specialists, Siriraj Informatics and Data Innovation Center, staff from the Department of Microbiology, Department of Immunology, and chiefs or representatives of each Division from the Faculty of Medicine Siriraj Hospital, Mahidol university who made the data reliable and available. We express our gratitude to Mark Simmerman for his insightful comments on manuscript and language editing. We also acknowledge the contributions of Chulaluk Komoltri from the clinical epidemiology unit for advice in the statistical analysis of this study.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Definition

- Healthcare workers or healthcare personnel include but are not limited to emergency medical service personnel, nurses, nursing assistants, physicians, technicians, therapists, phlebotomists, pharmacists, students and trainees, contractual staff not employed by the healthcare facility, and persons not directly involved in patient care, but who could be exposed to infectious agents that can be transmitted in the healthcare setting (e.g., clerical, dietary, environmental services, laundry, security, engineering and facilities management, administrative, billing, and volunteer personnel).

- Aerosol-generating procedure: a procedure that could generate more infectious aerosols than coughing, sneezing, talking, or breathing:
  - Open suctioning of airways;
  - Sputum induction;
  - Cardiopulmonary resuscitation;
  - Endotracheal intubation and extubation;
  - Non-invasive ventilation (e.g., BiPAP or CPAP);
  - Bronchoscopy;
  - Manual ventilation;
  - Nebulizer administration and high-flow oxygen delivery.

- Symptoms related to SARS-CoV-2 infection:
  - Fever or chill;
  - Fatigue;
  - Muscle ache;
  - Headache;
  - Cough;
  - Runny nose;
  - Sore throat;
  - Loss in the sense of smell or taste;
  - Shortness of breath;
  - Nausea;
  - Vomiting;
  - Diarrhea.

Appendix B. Mathematical Component of Risk Score

- For each independent risk factor:
  \[
  \text{Weight (point)} = \left\lfloor \frac{\beta_i}{\beta_{\min}} + \frac{1}{2} \right\rfloor, \quad \text{where } \beta_{\min} = 0.328344912
  \]
  \[\text{(A1)}\]

- For protective factor: education:
  \[
  \text{Weight (point)} = \left\lfloor \frac{\beta_i}{\beta_{\min}} + \frac{1}{2} \right\rfloor + 3, \quad \text{where } \beta_{\min} = 0.328344912
  \]
  \[\text{(A2)}\]
For protective factor: vaccination:
\[
\text{Weight (point)} = \left[ \frac{\beta_i}{\beta_{\text{min}}} + \frac{1}{2} \right] + 9, \quad \text{where } \beta_{\text{min}} = 0.328344912
\]  

References

1. Wang, D.; Hu, B.; Hu, C.; Zhu, F.; Liu, X.; Zhang, J.; Wang, B.; Xiang, H.; Cheng, Z.; Xiong, Y.; et al. Clinical Characteristics of 138 Hospitalized Patients With 2019 Novel Coronavirus-Infected Pneumonia in Wuhan, China. JAMA 2020, 323, 1061–1069. [CrossRef]

2. Branch-Elliman, W.; Savor Price, C.; McGeer, A.; Perl, T.M. Protecting the frontline: Designing an infection prevention platform for preventing emerging respiratory viral illnesses in healthcare personnel. Infect. Control Hosp. Epidemiol. 2015, 36, 336–345. [CrossRef]

3. COVID-19: Occupational Health and Safety for Health Workers: Interim Guidance. Available online: https://www.who.int/publications/i/item/WHO-2019-nCoV-HCW_advice-2021-1 (accessed on 29 May 2022).

4. Ashinowo, M.E.; Dubik, S.D.; Duti, V.; Amegah, K.E.; Ashinowo, A.; Larsen-Reindorf, R.; Kaba Akoriryea, S.; Kuma-Abogaaye, P. Healthcare Workers Exposure Risk Assessment: A Survey among Frontline Workers in Designated COVID-19 Treatment Centers in Ghana. J. Prim. Care Community Health 2020, 11, 2150327209694883. [CrossRef] [PubMed]

5. Maltezou, H.C.; Dedoukou, X.; Tseroni, M.; Tsonou, P.; Raftopoulos, V.; Papadima, K.; Mouratidou, E.; Poufta, S.; Panagiotakopoulos, G.; Hatzigeorgiou, D.; et al. SARS-CoV-2 Infection in Healthcare Personnel with High-risk Occupational Exposure: Evaluation of 7-Day Exclusion From Work Policy. Clin. Infect. Dis. 2020, 71, 3182–3187. [CrossRef] [PubMed]

6. Wang, Y.; Wang, L.; Zhao, X.; Zhang, J.; Ma, W.; Zhao, H.; Han, X. A Semi-Quantitative Risk Assessment and Management Strategies on COVID-19 Infection to Outpatient Health Care Workers in the Post-Pandemic Period. Risk Manag. Healthc. Policy 2021, 14, 815–825. [CrossRef] [PubMed]

7. Cook, T.M. Personal protective equipment during the coronavirus disease (COVID) 2019 pandemic—A narrative review. Anesthesiology 2020, 75, 920–927. [CrossRef] [PubMed]

8. Pienthong, T.; Khawcharoenporn, T.; Apisarnthanarak, P.; Weber, D.J.; Apisarnthanarak, A. Factors Associated with COVID-19 Infection Among Thai Health Care Personnel with High Risk Exposures: The Important Roles of Double Masking and Physical Distancing while Eating. Infect. Control Hosp. Epidemiol. 2022, 1–9. [CrossRef]

9. Gragnani, C.M.; Fernandes, P.; Waxman, D.A. Validation of Centers for Disease Control and Prevention level 3 risk classification for healthcare workers exposed to severe acute respiratory coronavirus virus 2 (SARS-CoV-2). Infect. Control Hosp. Epidemiol. 2021, 42, 483–485. [CrossRef] [PubMed]

10. Vargese, S.S.; Dev, S.S.; Soman, A.S.; Kurian, N.; Varghese, V.A.; Mathew, E. Exposure risk and COVID-19 infection among frontline health-care workers: A single tertiary care centre experience. Clin. Epidemiol. Glob. Health 2022, 13, 100933. [CrossRef] [PubMed]

11. Wan, K.S.; Tok, P.S.K.; Yoga Ratnam, K.K.; Aziz, N.; Isahak, M.; Ahmad Zaki, R.; Nik Farid, N.D.; Hairi, N.N.; Rampal, S.; Ng, C.W.; et al. Implementation of a COVID-19 surveillance programme for healthcare workers in an upper-middle-income country. PLoS ONE 2021, 16, e0249394. [CrossRef] [PubMed]

12. Interim Guidance for Managing Healthcare Personnel with SARS-CoV-2 Infection or Exposure to SARS-CoV-2. Available online: https://www.cdc.gov/coronavirus/2019-ncov/hcp/guidance-risk-assesment-hcp.html (accessed on 13 May 2022).

13. Interim Infection Prevention and Control Recommendations for Healthcare Personnel during the Coronavirus Disease 2019 (COVID-19) Pandemic. Available online: https://www.cdc.gov/coronavirus/2019-ncov/hcp/calculated-risk-assessment-for-healthcare-personnel.html (accessed on 13 May 2022).

14. Contact Tracing in the European Union: Public Health Management of Persons, Including Healthcare Workers, Who Have Had Contact with COVID-19 Cases—Fourth Update. Available online: https://www.ecdc.europa.eu/en/covid-19-contact-tracing-public-health-management (accessed on 13 May 2022).

15. Risk Assessment and Management of Exposure of Health Care Workers in the Context of COVID-19: Interim Guidance. Available online: https://www.who.int/publications/i/item/risk-assessment-and-management-of-exposure-of-health-care-workers-in-the-context-of-covid-19-interim-guidance (accessed on 15 May 2022).

16. Guidelines for Surveillance and Investigation of Coronavirus Disease 2019 (COVID-19). Available online: https://www.cdc.gov/coronavirus/2019-ncov/hcp/infection-control-recommendations.html (accessed on 13 May 2022).

17. Sritipsukho, P.; Khawcharoenporn, T.; Sirirumnurgwhong, B.; Damronglerd, P.; Suwanantar, N.; Satdhabudha, A.; Chaiyakulsi, C.; Sinlapamongkolkul, P.; Tangsathapornpong, A.; Bunjongmanee, P.; et al. Comparing real-life effectiveness of various COVID-19 vaccine regimens during the delta variant-dominant pandemic: A test-negative case-control study. Emerg. Microbes Infect. 2022, 11, 585–592. [CrossRef] [PubMed]

18. Ministry of Public Health’s Guidelines for Vaccination against COVID-19. Available online: https://ddc.moph.go.th/vaccine-covid19/getFiles/14/1639630797714.pdf (accessed on 21 May 2022).

19. Ministry of Public Health’s Guidelines for COVID-19 Vaccination as a Booster Shot. Available online: https://ddc.moph.go.th/vaccine-covid19/getFiles/14/1640232499139.pdf (accessed on 21 May 2022).
20. Report on the Results of Surveillance for COVID-19 Strains during 24–30 July 2021. Available online: https://www3.dmsc.moph.go.th/post-view/1234 (accessed on 20 May 2022).
21. Report on the Results of Surveillance for COVID-19 Strains during 2–8 October 2021. Available online: https://www3.dmsc.moph.go.th/post-view/1328 (accessed on 20 May 2022).
22. Report on the Results of Surveillance for COVID-19 Strains during 1 November–11 February 2022. Available online: https://www3.dmsc.moph.go.th/post-view/1481 (accessed on 20 May 2022).
23. Infection Prevention and Control during Health Care When Coronavirus Disease (COVID-19) Is Suspected or Confirmed: Interim Guidance. Available online: https://apps.who.int/iris/handle/10665/332879 (accessed on 20 May 2022).
24. Bahl, P.; Doolan, C.; de Silva, C.; Chughtai, A.A.; Bourouiba, L.; MacIntyre, C.R. Airborne or Droplet Precautions for Health Workers Treating Coronavirus Disease 2019? J. Infect. Dis. 2022, 225, 1561–1568. [CrossRef] [PubMed]
25. Lewis, D. Why the WHO took two years to say COVID is airborne. Nature 2022, 604, 26–31. [CrossRef] [PubMed]
26. French, N.; Jones, G.; Heuer, C.; Hope, V.; Jefferies, S.; Muellner, P.; McNeill, A.; Haslett, S.; Priest, P. Creating symptom-based criteria for diagnostic testing: A case study based on a multivariate analysis of data collected during the first wave of the COVID-19 pandemic in New Zealand. BMC Infect. Dis. 2021, 21, 1119. [CrossRef] [PubMed]
27. Struyf, T.; Deeks, J.J.; Dinnes, J.; Takwoingi, Y.; Davenport, C.; Leeflang, M.M.; Spijker, R.; Hooft, L.; Emperador, D.; Domen, J.; et al. Signs and symptoms to determine if a patient presenting in primary care or hospital outpatient settings has COVID-19. Cochrane Database Syst. Rev. 2021, 2, CD013665. [CrossRef] [PubMed]
28. Chadeau-Hyam, M.; Bodinier, B.; Elliott, J.; Whitaker, M.D.; Tzoulaki, I.; Vermeulen, R.; Kelly-Irving, M.; Delpierre, C.; Elliott, P. Risk factors for positive and negative COVID-19 tests: A cautious and in-depth analysis of UK biobank data. Int. J. Epidemiol. 2020, 49, 1454–1467. [CrossRef] [PubMed]
29. Lu, M. The Front Line: Visualizing the Occupations with the Highest COVID-19 Risk. Available online: https://www.visualcapitalist.com/the-front-line-visualizing-the-occupations-with-the-highest-covid-19-risk/ (accessed on 20 May 2022).
30. Eisenstein, M. What’s your risk of catching COVID? Nature 2020, 589, 158–159. [CrossRef]