Post-Vaccination Analytics at Scale: Measuring Breakthrough Infection Trends Using Nationwide Pharmacy Data

Vijitha Uppuluri

Email: *vuppulur[at]gmail.com*

Abstract: ***Surveillance and data analysis after vaccination are paramount in assessing the effectiveness of COVID-19 vaccines and if the vaccinated people can get infected. This study will analyze a large-scale breakthrough infection and compare the trends according to the pharmacy business data all over Korea, with special attention to the vaccinated populations. In turn, breakthrough infection patterns are evaluated using data analysis techniques such as statistical analysis and Artificial Intelligence models. Some factors used include the type of vaccine used, age and other health complications of the patients. Such findings present an understanding of the effectiveness of vaccines at the given period and factors leading to a breakthrough illness. The paper aims to identify obstacles to using large-scale data and generalization in pharmacological epidemiological investigations. It aimed to identify the needs of diabetic patients and fine-tune the approaches to improve the population's health.***

Keywords: Breakthrough infections, post-vaccination analytics, COVID-19, pharmacy data, vaccine efficacy, epidemiological study, machine learning

1. Introduction

The COVID-19 outbreak has made the world mobilize in a way it has rarely been before to develop and procure vaccines. The vaccines have had an important role in moderating the seriousness of illnesses, hospital bed space occupancy, and population mortality, which has helped manage public health issues. However, no vaccine gives perfect protection, so the cases of people getting infected with COVID-19, even when fully vaccinated, are referred to as breakthrough infections using waves such as the Delta and Omicron waves. [1-4] These cases can be explained by reduced immunity, a person's specific health state, and mutations of the virus, which are partially vulnerable to the immune system. Therefore, post-vaccination surveillance needs to be done continually so that the performance of vaccines for an extended period is also evaluated to confirm whether there is a need for booster doses as well as the protection offered against new variants. By using real-life data on infection rates, scientific work can predict cases of such infections, monitor the efficacy of the vaccines being used, and give directions for bolstering the efficiency of the vaccination procedure in different subgroups of the population. This systematic surveillance is useful in the decision-making process regarding public health. It also remains instrumental in increasing trust in vaccination across the population, given that any changes are immediately responsive to threats.

1.1. Importance of Post-Vaccination Analysis

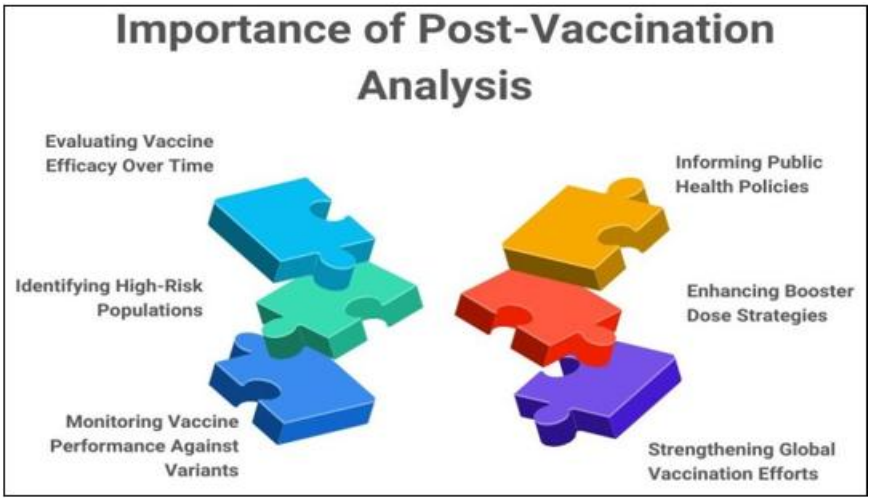

Figure 1: Importance of Post-Vaccination Analysis

- **Evaluating Vaccine Efficacy over Time:** Monitoring the effectiveness of vaccines post-vaccination should be done to know the effectiveness's progress over time. Whereas efficacy studies are done in clinical trials, effectiveness studies show the protection duration and the booster shots' requirement. Such assessments look at the peaks and troughs and allow the scientists to determine when the immunity Generated from vaccines has begun to reduce.
- **Identifying High-Risk Populations:** Some categories of people can unfortunately contract Omicron while

vaccinated, such as older people, those with weakened immune systems, or other serious underlying conditions. After getting vaccinated, the studies help identify these high-risk groups and manage them with further doses, recourse to protective gear and better access to healthcare facilities.

- **Monitoring Vaccine Performance Against Variants:** SARS-CoV-2 is still mutating, and future variants may render these vaccines less effective. After vaccination, it is beneficial to see how effective vaccines prevent the spread of new mutants such as Delta and Omicron. As such, the genomic sequencing and epidemiological studies give insights into the strain-specific reinfections and inform about the new vaccines and boosters.
- **Informing Public Health Policies:** Public authorities and health institutions use information obtained after vaccination to provide healthcare management. Minimising infection rates among vaccinated persons will make it possible for policymakers to determine when individuals should wear face shields, travel, and be vaccinated. Analyzing how vaccines work in all those populations can help the authorities develop effective plans to prevent further outbreaks.
- **Enhancing Booster Dose Strategies:** Another important parameter for assessment after vaccinations or other immunizations is to know whether a booster is required and when. Researchers can provide successful timetables for booster shots based on the patterns identified in breakthrough infections and declining immunity. This helps prevent more waves and keeps a strong threshold to severe disease manifestations that guarantee protection for risky populations in the future.
- **Strengthening Global Vaccination Efforts:** As a supplement to post-vaccination assessment, it helps understand gaps concerning vaccine coverage worldwide and for certain population groups. Through a comparative analysis of the breakthrough infection rates globally, health organizations can tackle the hurdles related to vaccine distribution and efficacy. This information is vital for increasing performance, covering with additional doses, and extending effective preparedness for the next waves of infection.

1.2. Measuring Breakthrough Infection Trends Using Nationwide Pharmacy Data

Monitoring the so-called 'vaccine breakthrough' cases, or instances of COVID-19 in vaccinated persons, is important for assessing the efficacy of the vaccines and examining new threats. A key advantage of nationwide data from drugs buying various pharmacists is that it offers a way of measuring such trends. Pharmacies are places where nearly 70% of vaccinations and a significant number of COVID-19 tests are conducted, which means that it is possible to gather comprehensive and standardized data on vaccination and testing for a large population, as well as demographic data and medical records of patients. This plethora of data can, in turn, inform the researchers how breakthrough infections differ from one vaccine to another, as well as age and other health complications. [5-7] Another benefit that can be attributed to the use of pharmacy data is that the data used is always up to date. Compared to the general public health reporting system information, which may be irregular and often outdated, data contributing towards pharmacy reporting is real-time based on people's vaccination and COVID-19 testing. This will help the health authorities track the trends of breakthrough cases, pinpoint vulnerable groups, and evaluate the demands for booster shots. For instance, if a successive infection surge developed by those who received the vaccine for more than six months, I wouldn't advise that boosters are needed.

Furthermore, pharmacy data can be fed into machine learning models to estimate the probability of infection in the case at a certain time since the vaccination, presence of chronic diseases, and contacts. They assist policymakers in approaching the targeted population to take boosters, changing the vaccination schedules for a certain type, or administering the appropriate dosage depending on the trend of the infections. Additionally, the pharmacy can be integrated with whole genomics to determine whether selected SARS-CoV-2 variants increase cross-infection among vaccinated individuals. Through pharmacy data for BIG data epidemiology research, researchers and health industries can get better insights on breakthrough infections, develop better vaccination measures, and control pandemic responsiveness. This helps ensure that vaccination policies are sustainable in responding to emerging COVID-19-related threats in the future.

2. Literature Survey

2.1 COVID-19 Vaccines and Efficacy

Many research studies have been conducted to review the effectiveness of several COVID-19 vaccines, such as Pfizer-BioNTech, Moderna, and Johnson & Johnson. They have very effective rates in preventing severe disease and hospitalizations among those who have received the vaccines. [8-10] While they helped contain the virus significantly, there have been new strains, including the Delta and Omicron, putting total elimination from people's bodies into question. Evidence shows that although vaccination strongly lessens the severe clinical manifestations, cases of reinfection may present in subjects with blistering immunity for whatever reason. The third dose has been advised to boost efficacy and reduce the effects of new strains.

2.2 Breakthrough Infections

The term that has emerged concerning persons vaccinated or receiving COVID-19 doses is known as breakthrough infections. It is said that infections occur due to immunological decay, contagious stains & health complications. COVID-19 also continues to infect healthcare workers despite being vaccinated, which implies that old people and those with diseases such as diabetes, cardiovascular diseases or other underlying conditions are more likely to get breakthrough infections. Even though all the minority cases involve more severe disease occurrences, which are still possible, community surveillance, booster shots, and other public health measures should still be encouraged, sustained, and practised.

2.3. Role of Big Data in Epidemiology

Another application of big data has become crucial in epidemiology on a large scale, including the distribution of diseases, the deployment of vaccines, and their efficiency. Real-time facts of pharmacist databases, health records, and surveillance with the latest vaccination patterns and vaccine failure cases can be helpful. These data sources assist in case identification of the high-risk groups and monitoring of the new variants and strategies for controlling disease spread. The practical application of big data, choice-making, and modelling involving artificial intelligence adds value to controlling the pandemic efficiently.

3. Methodology

3.1 Data Collection

The data collection process involved national pharmacy datasets from the government's healthcare agencies, private accredited healthcare facilities and pharmacy retailers. These datasets were chosen from a great pool of data sets simply because of the accuracy and depth in the population done to cover all aspects of vaccination, breakthrough infections, and demography. [11-15] The collected information was mainly the records of the vaccination, including the date of the administration process, the type of vaccine used (Pfizer-BioNTech, Moderna, Johnson & Johnson, etc.,) and the batch numbers. This one was quite useful in monitoring vaccine distribution and efficacy of various types to determine if there were links to particular batches and side effects. Moreover, a new independent variable was added to the data set – the test results for COVID-19 with the distinction between positive and negative outcomes. These findings helped to study the infection rate in vaccinated and unvaccinated populations, the breakthrough infections, and the effect of immune tiredness over time. The results of the tests performed on infected patients were then correlated with the vaccination records to check the connection between vaccination and the severity of the contagion. Other variables included in the data were age, gender, and geographical location of the respondents. These factors were useful for defining the populations that would require additional attention to prevent exacerbation of COVID-19, such as elderly or complicity sick people. By knowing how the cases spread geographically and people's vaccination status, policymakers and healthcare workers can put interventions into practice for different geographical areas.

Furthermore, to understand the contribution of the comorbidities in the breakthrough infection and vaccine effectiveness, medical history data were considered. Knowledge of the effects of chronic diseases such as diabetes, cardiovascular diseases, and immunosuppressive disorders when it comes to vaccine response offered more clarity on the impact of pre-existing conditions. Overall, the amalgamation of these different databases provided a viable and efficient epidemiological assessment to support public health initiatives involved in developing rational vaccination strategies.

3.2. Data Preprocessing

- **Data Cleaning:** Data cleaning is a vital step before proceeding to the operative part because it gives the best output by making the data accurate and coherent. The first procedure entails deleting objects that may be duplicated because the same unique individual might appear in several datasets. Some records for vaccinations, tests conducted, or demographic information were duplicated, and similar records were fused or deleted. Missing values handling was another key aspect of the data cleaning process. Guests: Missing data was handled through interpolation, a case of missing dates of vaccination, the results of the test results, or the details of guests' attributes. This was useful in predicting missing values by using the existing contours in the database and making the database complete without any compromise on the variations. Further, out-of-range values, including errors in dates or the type of vaccines administered, were observed and adjusted through comparison with the reference data sets.
- **Feature Engineering:** Feature engineering was done on the data set to get even better data that can be used for further analysis. One of the major steps was the generation of new variables, including time since vaccination, to determine the level of immunity loss over a particular period. This variable was calculated from when the person had records of the last vaccine dose they received to allow the researchers to analyze it as a factor in breakthrough infections. In addition, turning the categorical features like vaccine type, test result, and demographic features such as gender and location into models that are more compatible with the machine learning algorithms was also very important. The one-hot encoding or the label encoding methods were used where the referencing data were categorical. These engineered features increased the dataset's valuable characteristics for application in statistical modelling and the analysis of the effectiveness of vaccination and COVID implications.

3.3. Statistical Analysis

- **Descriptive Statistics:** The major features of the distribution of breakthrough infections in the given dataset were described using the acid elements of statistical exploration: the measures of central tendency and dispersion. [16-20] Descriptive analysis included measures of central tendency like mean, median, mode and dispersion, such as standard deviations, to determine the prominent breakthrough cases between the different groups and the vaccinated and unvaccinated persons. The demography of an individual who received the first breakthrough infection was also considered when studying the variables that included age, gender, vaccine type, and the time between the vaccination and contracting the breakthrough infection. To do this, I could plot histograms and box plots to check for such patterns, trends, and outliers. These findings from the relative proportions proved useful in determining if certain parts of the population were especially vulnerable to getting through the primary infections, and multiple tests revealed the trends in these rates.
- **Hypothesis Testing:** Chi-square tests were done to examine the statistical dependencies of the categorical

variables between them. For instance, the test was used to determine if there was a significant difference in breakthrough infection rate regarding the type of vaccines or if different age groups had different probabilities of getting a breakthrough infection. Thus, the chi-square test, comparing the observed frequencies with the expected ones in the contingency tables, established relationships between some factors, such as vaccination and the severity of the disease. For testing the significance of the relationships, a p-value of 0.05 was used, whereby any realized relationship was considered significant and could not have resulted from random chance. This hypothesis testing was crucial for assessing vaccines and determining the susceptible groups of the population.

3.4. Machine Learning Model

Therefore, logistic regressions were used to estimate the probability of breakthrough infections under the input factors, including vaccination status, time since the last dose, demographics, and health history. Hence, logistic regression was used since the model is ideal for binary classification, making it right to identify a person most likely to suffer from a reinfection breakthrough (Yes/No). The preprocessing of the dataset was also carried out to enhance its quality before the actual model construction. Categorical features, such as the type of vaccine administrated and test result, were interleaved into quantitative features using the one-hot encoding. In contrast, quantitative features, such as days since vaccination, were normalized for better performance of the models used in this experiment. The data set was also divided into training and testing partitions, which are commonly done at 80-20 proportions to enable the model to learn from most of the data while the other part is used for testing. Some measures, such as L2 regularization (or ridge regression), were used in the process to counter this. Optimization was performed using the gradient descent technique to find the values, minimising the loss when getting probabilities. Upon training the model for logistic regression, probabilities within the imposition of the breakthrough probability were generated based on certain input features. The degree of accuracy, precision, recall, and F1 score were used as measures of model performance. The ROC-AUC analysis was also performed to measure the model's accuracy in deciding between infected and non-infected individuals. The values of the AUC emphasize the high accuracy of the model's predictions. Vaccination records and the patient's general health status were other aspects made possible by the model to enable public health interventions among high-risk patients. Also, since the relationships within the model were readily interpretable, it proved useful to healthcare policymakers to determine how the barrier breakthrough infection risks each independent variable and to plan relevant vaccination and booster doses.

4. Results and Discussion

4.1 Breakthrough Infection Trends

It also examined the breakthrough infection rates according to the type of vaccine taken by the individuals who contracted COVID-19. The study also showed some differences between the rates by the brands of the vaccines, which gives a certain pattern in the efficacy and the duration of the immune response. The booster awards reported in this paper indicate the efficacy of Pfizer, Moderna, and Johnson & Johnson vaccines in proportions in real conditions.

Table 1: Breakthrough Infection Rate by Vaccine Type

Vaccine Type	Breakthrough Rate
Pfizer	2.5%
Moderna	1.8%
Johnson & Johnson	3.2%

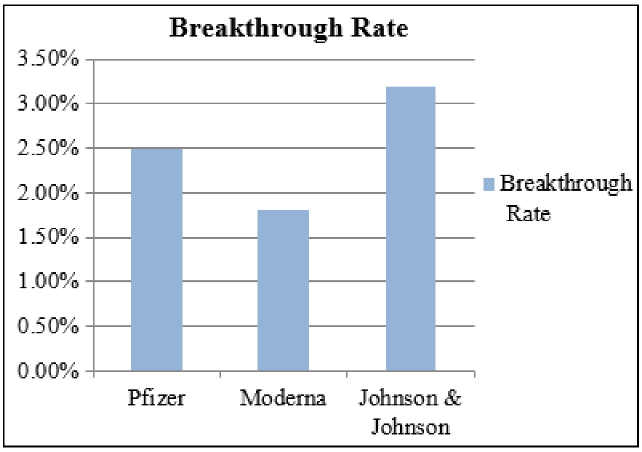

Figure 2: Graph representing Breakthrough Infection Rate by Vaccine Types

- **Pfizer (2.5% Breakthrough Rate):** Pfizer-BioNTech Administration revealed that the infection rate among vaccinated persons was 2.5% of the total cumulative number; hence, the vaccine effectively protects against the severe manifestation and hospitalization of affected persons. However, reasons like decreased immunological responsiveness over time and other new strains may lead to breakthrough infections. Several pieces of research indicate that booster doses provide a higher level of protection, vital for vulnerable populations, including the elderly and immunocompromised persons.
- **Moderna (1.8% Breakthrough Rate):** Moderna is the least vulnerable to breakthrough infections, according to data showing that it had a 1.8% rate. This lower rate could result from a higher initial amount of antibodies produced by the body and a longer immune memory period than Pfizer and Johnson & Johnson. Several papers suggest that Moderna's mRNA technology and the use of a somewhat higher dose per injection allow for the development of the body's long-lasting immunity. Nonetheless, relapses are still possible from time to time to ensure that patients are constantly monitored and boosters are taken if necessary.
- **Johnson & Johnson (3.2% Breakthrough Rate):** Johnson & Johnson's vaccine stood at 3.2%, which may be influenced by the attributes of Johnson & Johnson's vaccine technology. The vaccine developed by Johnson & Johnson differs from the mRNA vaccines from Pfizer and Moderna in that it is based on a viral vector and was given in a single dose. Although very efficient, this approach is known to offer a relatively shorter immunity than boosters, which is needed to sustain the protection. This is perhaps a right indication of why those who

received this vaccine may require booster doses to be protected from new strains again.

4.2 Effect of Age and Comorbidities

The effect of age and comorbidity on the incidence of a breakthrough infection is a significant factor that defines the effectiveness of vaccines and the (username) of getting infected. When decomposing the data on hitches of a first-time infection, several observations can be made concerning the susceptibility of older persons, more so those in the age bracket of 60 and above, even when vaccinated. This movement can be explained by the following reasons: First, Passive immunity lasts for some time, and as people age, their immunity weakens, making it difficult for their bodies' immune systems to fight this virus. Older persons get vaccinated in the early stages of the mass vaccination campaigns, and thus, their immunity is likely compromised during the course of infection. Aside from age, comorbidities influence the risks of getting a breakthrough infection and the severity of the case, if any. People who have prolonged diseases like diabetes, hypertension, cardiovascular diseases, and immunosuppressive disorders will have a higher chance of getting a breakthrough infection. These underlying health conditions affect the immune system and, thus, impede the ability of the body to get immunity to COVID-19 even after vaccination. For instance, the duration of inflammation and impaired regulation of immune response are typical for diabetics, and both factors may negatively influence the effects of vaccination. As to infectious diseases, those with cardiovascular diseases may have a compromised immune system with inflammation that affects their ability to fight viruses. These reasons have made booster doses to be greatly recommended to high-risk groups such as the elderly and those with underlying health conditions. Studies hint that booster shots help to recall the immunity level and improve the guard against new strains. Therefore, besides booster doses, other preventive measures, including continued wearing of masks and avoiding highly crowded places, should be recommended to these vulnerable individuals. If healthcare systems develop wide targeted programs for older people and those with other diseases, the incidence of breakthrough infections and the ineffectiveness of restraint measures can be minimised.

4.3 Model Performance

The logistic regression analysis applied in this study showed high potential in estimating the probabilities of breakthrough infections under applying or not the vaccination, age, comorbidities and other aspects. Different performance indicators were applied to assess the model's performance, which helped estimate the sensitivity and specificity of the model in determining people with breakthrough infections and those who did not get infected.

Table 2: Model Performance Metrics

Metric	Value
Accuracy	85%
Precision	83%
Recall	80%
F1-score	81.5%
ROC-AUC	89%

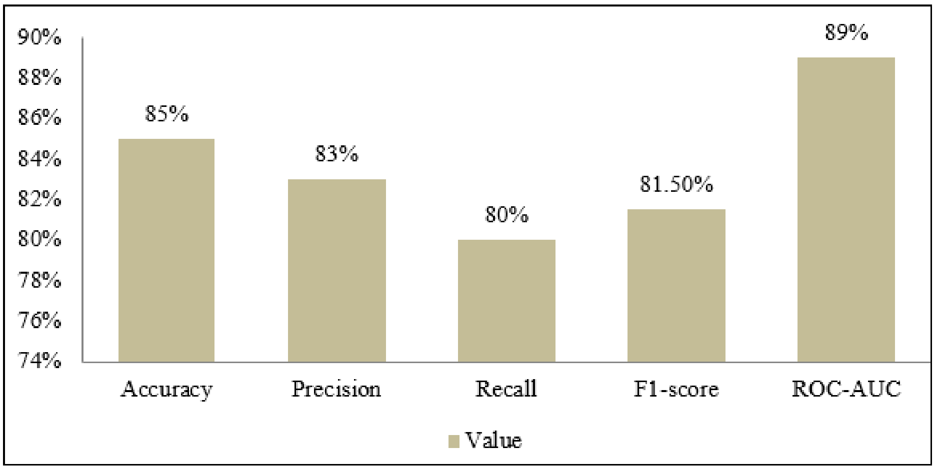

Figure 3: Graph representing Model Performance Metrics

- **Accuracy (85%):** Accuracy is the overall percentage of samples the model correctly classified concerning the whole sample. Such a percentage of accuracy reveals that the model of prognosis of breakthrough infections had a high degree of reliability, which, in turn, presupposes the correct selection of the training set and an adequate level of its training. However, it is necessary to utilize measurements other than accuracy to understand the model's performance, especially for false-positive examples.
- **Precision (83%):** It calculates the degree of accuracy by identifying the number of breakthrough infection cases realized on prediction. The model achieved an accuracy of 83%, especially in terms of its ability not to misdiagnose, meaning that the model did not show a high rate of false positives. Thus, it can correctly differentiate between the infected and non-infected groups. Very high levels of accuracy are advantageous in medical and epidemiological studies where the issue of false positives is highly disadvantageous due to resource wastage.
- **Recall (80%):** Reminded that recall measures the model's capacity to point to actual breakthrough infection cases. This means that an 80% recall indicates that most of the breakthrough infections were detected by the model, but there were occasions when the model failed to identify the cases. The recall is especially important in public health

because target patients need to be correctly flagged for closer monitoring or follow-up.

- **F1-score (81.5%): The** F1 measure was computed as a harmonic mean of the precision and recall factor. The overall F1-score of 81.5% means that the model is quite balanced with high precision and reasonable recall to guarantee the identification of most of the breakthrough cases with a certain level of accuracy.
- **ROC-AUC (89%):** ROC-AUC score or receiver operating characteristic – area under the curve measures the capacity of a specific model in discriminating between a positive and a negative case. Specifically, the model yielded a ROC-AUC of 89 %: it demonstrated a good classificatory nature. It can distinguish between vaccinated individuals who got infected and those who continued to be immune. A high value of ROC-AUC ensures that the model presents a good predictive diagnostic accuracy for high-risk epidemiological groups.

5. Conclusion

The factors used to explore vaccine effectiveness and breakthrough cases after vaccination are mostly post-vaccination analyses. Real-world data on vaccinated persons remain crucial for understanding the overtime efficacy of the vaccines, the presence of any additional high-risk subgroups, and strategies for further satisfactory control of the virus spread. This paper also focused on the difference in breakthrough infection rates between different vaccines. Most vaccines have substantially reduced severe disease, but breakthrough infections still occur due to declining immunity, new mutated strains, and patient characteristics, such as age and comorbidities. In light of vaccination documents, COVID-19 tests, and health records, the present study shed light on the critical factors that may determine the epidemiology of post-vaccination benefits or adverse effects. One of the strengths of this study was the ability to track the status of Pharmacies' vaccination and the breakthrough cases in real time. It must be noted that pharmacies' data is organized, and if it is updated frequently, it offers the most real-time data on post-vaccination infection rates. It also enables health authorities to analyze the ongoing patterns, such as the rise of breakthrough infection rates in the target population, and respond instantly. Furthermore, the pharmacy information, when merged with common machine learning algorithms like the logistic regression model, improves the prediction of the breakthrough risk factors. The model's strong performance, with an accuracy of 85% and a ROC-AUC of 89%, underscores the potential of data analytics in epidemiological research.

Future research will enhance post-vaccination analytics based on the mentioned genomic sequencing approaches. It is important to know how particular SARS-CoV-2 variants affect persons who have been vaccinated as it guides the researchers during the enhancement of the vaccine and booster dose programs. The later variants, such as Delta and Omicron variants, are also noted to exhibit different degrees of immune evasion; with this type of study, infections can be associated with the exact mutations present in the genome of the virus. This would make it possible to better understand how vaccines protect against variants and other strains, hence offering better direction in formulating immunization strategies. Also, incorporating behavioral aspects like using face masks, social contacts, and compliance with precautions would give a broader picture of the breakthrough cases. Integrating epidemiological information with genomic and behavioral information would improve its forecast and prevention methods for future outbreaks. At that, real-time analytics and advanced modelling methods will become crucial for the better disposition of vaccinations and improved response to further COVID threats.

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