**Protective effectiveness of SARS-CoV-2 infection risk between hybrid and vaccine-induced immunity against the omicron variant**

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**Abstract (304 words)**

**Background.** Immunogenicity research indicates that the effectiveness of vaccines might decline over time, although it is not clear how this reduction translates to protective effectiveness against breakthrough infections. We examined the antibody decay trend and associated infection risks across age groups between hybrid and vaccine-induced immune populations based on community-based nationwide surveillance after the Omicron wave in South Korea.

**Methods:** We constructed a cohort of the hybrid and vaccine groups based on serology (S and N status) information. We then performed Kaplan-Meier survival analyses and Cox proportional hazards regression to compare the protective efficacy of the two groups, focusing on the probability of remaining free from infection after the initial surveillance period. We used mixed-effects logistic regression models to quantify the protective efficacy, defined as the probability of remaining infection-free, associated with antibody levels across age subgroups by the immunity groups.

**Results:** The hybrid group maintained about 2 times higher antibody levels (~10,000) at 12 months from the last immunological events compared to the vaccine group. Although the antibody decay trend was similar across age groups, the protection effectiveness against infection was more quickly decreased for the>60 age group but in a greater magnitude for the <20 age group over time in the vaccine group. Considering the time to infection, >20 age group shows 42-69% lower hazard ratio of infection than <20 age group with increasing risk trends with older age groups. To expect >80% probability of remaining infection-free, different S antibody levels thresholds are estimated as >250,000, 20,000, and 15,000 for <20, >60, and 40-60 age groups among the vaccine group.

**Conclusion**: Our findings highlight that children without previous infection is the high risk and priority group for booster vaccine [1]. Moreover, adults aged ≥65 years are more likely to rely upon vaccination to increase immunity that might have waned and might need more frequent vaccine doses to maintain protection.

**Introduction**

Both natural SARS-CoV-2 infection and COVID-19 vaccination play crucial roles in developing population-level immunity. [REF] While immune responses are complex and multifaceted, epidemiological studies often rely on measurable indicators like antibodies to assess population immunity and the durability of antibody responses following infection and/or vaccination [2]. Immunogenicity research indicates that the effectiveness of vaccines might decline over time, as measured by primarily decreasing antibody titers and vaccine effectiveness (breakthrough infections) [3], [4]. However, it is not clear how this reduction translates to protective effectiveness against infection [5]. Moreover, estimating the magnitude and durability of this protection in the population has become a challenge because of the surge in the omicron (B.1.1.529) variant, which has resulted in many individuals with hybrid immunity (immunity developed through a combination of SARS-CoV-2 infection and vaccination), varying rates and timings of past infection and vaccination, multiple types of vaccination and numbers of doses, and variants of concern that can escape pre-existing immunity [6]. Moreover, most existing seroepidemiological studies have focused on specific groups (e.g., healthcare workers or specific high-risk immune-suppressed patients [7]), and the durability of antibody responses after infection and/or vaccination is less well explored within the general population [8], [9].

Systematic reviews of SARS-CoV-2 vaccine effectiveness studies estimated the durability of protection conferred by previous infection combined with previous vaccination (i.e., hybrid immunity) and previous infection alone against multiple clinical outcomes of SARS-CoV-2 infection caused by the omicron variant [4] [10]. They found that both previous infection alone and hybrid immunity conferred rapidly waning protection against SARS-CoV-2 infection with the omicron variant but high and sustained protection against hospital admission or severe disease due to the omicron variant than vaccination alone. Several epidemiological studies also show hybrid immunity had the highest magnitude and durability of protection against all outcomes, emphasizing the importance of providing vaccination to previously infected individuals as infection-induced protection against reinfection wanes rapidly, but vaccination further increases durability [11][12][13]. However, the waning of hybrid immunity, particularly due to Omicron infections, is not yet characterized in magnitude or duration. More data are needed for a precise quantification of the immune protection from hybrid immunity compared with vaccine-induced immunity normalized for the same antigen exposure.

In South Korea, a large majority of the population has either hybrid or vaccine-induced immunity, with only 8% having previous infection alone and 10% with no immunity. In this study, we directly compared anti-S levels and the relative incidence of breakthrough infections between groups with hybrid immunity and those with vaccine-induced immunity, given that neutralizing antibodies are a subset of spike (S) antibodies. We utilized data from a nationwide community-based cohort, allowing for large-scale analysis across various age subgroups. This cohort enabled us to conduct follow-up assessments with repeated antibody testing in August and December 2022, alongside detailed demographic and clinical characterization. The objectives of this research are threefold: First, we assessed the variation in anti-S antibody waning following the last immunological event across different age subgroups, comparing hybrid immunity with vaccine-induced immunity. Second, we evaluated the protective efficacy of these two groups over time, specifically focusing on the probability of remaining free from COVID-19 infection. Third, we examined the overall impact of anti-S antibody levels on the probability of remaining infection-free, comparing the effects across age groups between hybrid and vaccine-induced immunity cohorts.

Here we assess serological immune response after SARS-CoV-2 breakthrough infection in persons with primary and booster vaccination with and without previous infection. First, we determine the sensitivity of N-antibodies as a tool to identify breakthrough infection. Subsequently, we investigate the boosting of Spike S1-specific responses after breakthrough infection and the influence of time since vaccination and N-seroconversion on the S1-specific antibody levels. The study was performed during the transition period of the Delta variant to Omicron[9](https://www.nature.com/articles/s41598-023-45718-8#ref-CR9), which provided a unique basis to relate immune activation to the virus strain involved. Therefore, lastly, we investigate the change in the response towards the variant of infection as an indication for the development of broader hybrid immunity [14].

# **Methods**

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## **Sample Collection and Definitions.** A nationwide community-based surveillance study was conducted from August to December 2022, during the 6th and 7th epidemic peaks of COVID-19 in South Korea. This study involved 258 public health centers and 113 private medical facilities across 259 cities and counties. A representative sample of 9,945 individuals aged 5 and older was randomly selected from 5,000 households. Data collection was conducted through one-on-one interviews by trained surveyors using tablets to ensure accuracy. More detailed descriptions of the cohort study design and data collection methods are published elsewhere [15].

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Figure 1: Flow Chart Illustrating the Cohort Study Design

**Inclusion/Exclusion criteria.** In this analysis, we defined the cohort by the following four distinct immunity types: hybrid-induced immunity (*S*+*N* +), vaccine-induced immunity (*S*+*N−*), infection-induced immunity (*S−N* +), and naive (*S−N−*) [16], [17]. Notably, the hybrid-induced and vaccine-induced immunity groups comprised over 98% of the cohort population (Figure 1). Consequently, subsequent research focused primarily on these two groups. The demographic and clinical characteristics of the two groups are described in Table 1.

We analyzed two primary outcomes: S antibody levels at the first and second surveillance points (Figure 2) and the occurrence of confirmed infection events between these points (Figure 3). To ensure the validity of our assessment of S antibody levels on the protective effectiveness against COVID-19 infection (Figure 3), we implemented the following exclusion criteria. Individuals not participating in the second survey were excluded as we cannot determine the infection outcome. Individuals who were vaccinated between the first and second surveillance periods were also excluded to maintain the relevance of initial S antibody levels at the first surveillance to the infection outcome. We also excluded abnormal cases where the S antibody level increased at the second surveillance than the first surveillance without any confirmed/reported infection or vaccination during that period. While these cases can be either undetected infections (or vaccination) before the second surveillance, we took a conservative approach as it is uncertain to claim the specific reasons.

**Statistical analyses**. We began by conducting descriptive analyses to generate trajectory plots that tracked the average changes in S antibody levels across different immunity groups and age subgroups following immunological events. Next, we used Kaplan-Meier survival analysis to compare the protective efficacy between the two primary immunity groups, focusing on the probability of remaining COVID-19-free after the initial surveillance period. In the Cox-hazard model, we focused on immunity type and age as the primary variables of interest to evaluate their direct effects on the risk of infection. While other factors such as sex, education, and health status were considered, they were excluded to avoid potential overfitting and multicollinearity. These factors contributed to unexplained variability in the model, which was captured in the residuals.

Motivated by the differing infection statuses across immunity groups, we further examined the relationship between S antibody levels and infection status. For this, we constructed cohort groups for both hybrid and vaccine-only immunity groups, using logistic regressions to evaluate infection risk and identify significant risk factors. The outcome in each group was defined as infection status during the first and second surveillance periods. To address potential imbalances in the case-control data, we applied the nested case-control (NCC) method using the R package ‘Epi’ [18], matching cases and controls by age and S antibody levels. Other characteristics, such as sex, education, and income, were treated as potential confounders but not included in the logistic model and the matching process helps mitigate the influence of these omitted variables. We adjusted the case-control matching ratio from 1:6 to 1:3 based on recommendations from Pearce [19], optimizing statistical power and feasibility. Finally, we compared the performance of a simple regression model and a mixed-effects regression model through the **Receiver Operating Characteristic (**ROC) curve to further explore the protective effectiveness, defined as the probability of remaining infection-free, associated with S antibody levels across different immunity and age subgroups. [Add GitHub link here].

**Results****.**

In terms of population characteristics, the hybrid group has a younger age distribution than the vaccine group. Most hybrid (78%) and vaccine (86%) groups completed at least 3rd booster vaccines. The hybrid group had the latest event (infection/vaccine) more recently than the vaccine group. (77% had the latest immunological event within 6 months for the hybrid group vs 42% for the vaccine group). The hybrid group likely took the 4th booster less than the vaccine group (21% vs 36% -- perhaps due to the recent infection that they had).

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Table 1: Summary table of cohort study design

The trajectory plots of S antibody levels indicate that individuals in the hybrid-induced immunity group exhibit higher overall S antibody levels compared to those in the vaccine-induced group. Specifically, the hybrid group is able to maintain elevated S antibody levels (exceeding 10,000) for up to one year, whereas the S antibody levels in the vaccine-induced group decline below 5,000 within six months post-vaccination. Within the hybrid group, S antibody levels are slightly lower in individuals under 20 and over 60 compared to those aged 20-60. In contrast, there is no significant difference across age groups within the vaccine-induced group.

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Figure 2: Trajectory plot for different age groups

A graph showing the number of patients

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Figure 3: Survival Plot for Hybrid-induced and Vaccine-induced Groups

The Kaplan-Meier survival analysis (Figure 3) demonstrates the survival probabilities, interpreted as the likelihood of remaining free from COVID-19 infection, over time for populations with vaccine-induced and hybrid-induced immunity. The analysis reveals substantial differences in survival probabilities between these two types of immunity across various age groups. Individuals with hybrid-induced immunity consistently exhibit higher survival probabilities, maintaining a rate of 98% over one year, compared to those with vaccine-induced immunity, whose probabilities decrease to 50-60% over the same period. The probability of infection risk is notably observed after the sixth month following the last immunological event for the vaccine group, with a more rapid decline in those over 60 and a greater magnitude of decline in those under 20 compared to the hybrid group.

Collectively, the S antibody decay after 6 months is about 2 times greater for the hybrid group compared to the vaccine group and remains relatively constant by and after 1 year (Fig 2); this translated into the infection events survival reduced by about 10% by 6 months, but 40-50% by 12 months. Consequently, this translated into the risk probability by S antibody for vaccine group is 10-45% lower than hybrid group across age subgroups (Fig 3).

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Description automatically generatedTable 2: Cox Proportional Hazards Regression Results

The hazard ratio (exp(coef)) for hybrid group is significantly low as 0.09, indicating hybrid-induced immunity reduces the risk to approximately 9% of that for vaccine-induced immunity. For the, a hazard ratio of age groups>20 show 42-69% lower risk of infection than age <20 group with increasing risk trends with older age groups.

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Figure 4: Regression line comparison for vaccine-induced (left) and hybrid-induced (right) groups

Our results show that S antibody levels greater than 250,000, 20,000, and 15,000 for <20, >60, and 40-60 age groups are associated with >80% probability of remaining infection-free in the vaccine group. However, the hybrid group maintains over 95% of remaining infection-free regardless of the S antibody levels and age groups, similar to the results of the survival analyses.

# **Discussion**

Our study examined the protective effectiveness of COVID-19 infection across age groups between hybrid and vaccine-induced immunity in the general population based on community-based nationwide surveillance. In this study, we utilized nationwide community-based surveillance data (large sample sizes and wide age spectrums) from South Ko- rea, involving 10,000 participants, with detailed demographic information and serological assessment twice after an epidemic wave of omicron variants [20]. Our results show that hybrid immunity maintained about 2 times higher antibody levels (~10,000) at 12 months from the last immunological events compared to the vaccine group, conferring a substantially lower (9%) hazard ratio compared to vaccine immunity for COVID-19 re-infection with the Omicron variant. Although the antibody decay trend was similar across age groups, the protection effectiveness against infection was more quickly decreased for the>60 age group but in a greater magnitude for the <20 age group over time in the vaccine group. Considering the time to infection, >20 age group shows 42-69% lower hazard ratio of infection than <20 age group with increasing risk trends with older age groups. To expect >80% probability of remaining infection-free, different S antibody levels thresholds are estimated as >250,000, 20,000, and 15,000 for <20, >60, and 40-60 age groups. The different infection risks across age groups reflect heterogeneous individual immune responses and levels of exposure. The vaccination campaigns should be tailored according to individual immune status, and characteristics of the population risk factors to achieve optimal protection across individuals.[12]

Our study observed relatively small infection events (high protective effectiveness) among the hybrid immunity group as the study was conducted 3 months after the highest omicron epidemic peak (April 2022) and most people (77% for the hybrid group and 42% for the vaccine group) had the recent immunological events (either infection or vaccine) within 6 months. In the hybrid group, except for sex (which indicated significantly higher risk in both hybrid and vaccine groups), no clear and significant risk factors for infection (due in part to small events). Interestingly, we found that the hybrid 3rd or 4th booster showed a higher risk than the hybrid 2nd primary group; the counterintuitive result may be possible as the **recent infection** during the Omicron wave in the 2nd primary group likely conferred a more robust immune response (including natural immunity), which may have enhanced protection compared to those whose immunity had waned following earlier boosters. This suggests that the timing of infection or vaccination could be more critical than the sheer number of vaccine doses. This result also suggests that, except sex, traditional demographic or clinical factors might not be strongly associated with infection risk, but other variables, such as recent infection or immune waning, may play a larger role in this cohort.

Among vaccine groups, age, sex, and S ab level were significant risk factors. When the Omicron variant emerged, the presumed population immunity was between 80% and 85%, although nearly half of the children were estimated to have no immunity [22]. As the younger (<20) age group was less vaccinated or previously exposed due to shielding guidance, they may become more at risk with the lift of the social distancing policy. The older (>60) age group showed the second highest infection risks and the highest infection hospitalization risk among all age groups, although the hospitalization events were quite small (which limited sample size precludes more detailed statistical analysis: Appendix Table S1). This can be explained by immunosenescence, the age-related decline in the functioning of the immune system, results in a less complete immune response to novel antigens and a reduced ability to develop robust immunity after infections or vaccination [1]. Previous studies showed individuals 60 years or older had lower antibody levels after vaccination compared to younger participants and increased age has been associated with reduced vaccine responses in a number of studies irrespective of vaccine type [23]. A similar effect has been seen with antibody responses after infection.

Our study has some limitations. Firstly, we did not perform individual analyses for each vaccine and booster combination, provided that not all combinations had a large enough number of outcomes to allow for adequate comparisons. The role of vaccination and boosters’ interaction with predominant circulating variants remains an area of opportunity for future research. Given that most reinfections occurred during periods of Omicron predominance and that immunity-boosting by infection with Omicron seems to be low, real-world studies on hybrid immunity that consider the effects of immune imprinting from SARS-CoV-2 on protection against reinfection will be fundamental for determining the need of booster shots and its frequency in future vaccination waves [24]. Second, unmeasured bias in exposure may stem from the observational nature of the study. Confounding is expected to arise due to the lack of randomization, given substantial differences in the clinical backgrounds and sociodemographic characteristics of the comparison groups. Even though in the analysis, we accounted for sex, education, comorbidities, SARS-CoV-2 testing probability and SARS-CoV-2 environmental exposure risk, residual confounding is possible. Our results might be affected by differences between the groups in terms of healthcare-seeking behavior or risk aversion among participants, a possible confounder that was not assessed. While these biases might influence our estimates, they seem unlikely to have caused the clear patterns observed in this study. Number of factors on breakthrough infection [25]. Third, our infected cohort and new infection cohort did not include those who might have had a SARS-CoV-2 infection but were not tested. The effect of this bias is conservative, leading to underestimation of the true effects. Moreover, the antibody assays used in our study were developed before the emergence of Variants of Concern, raising questions about whether these assays, based on the original Wuhan-Hu-1 strain, accurately detect the S antibody activation/levels with Omicron variants which is a matter that should be evaluated in ongoing seroepidemiological studies. Potential sources of misclassification bias include the decay of neutralizing antibodies, the sensitivity and specificity of antibody testing, and the timing of testing relative to recent infection and vaccination. Finally, we measured binding antibodies rather than neutralizing antibodies, which are arguably a better surrogate for immune protection. Despite of the limitation, we argue that the relative comparison of the S antibody decay trends and the risk of breakthrough infections among different groups (hybrid and vaccine and age subgroups) are best seen as a consequence of the level of immunity at any moment in an individual, the variant to which that individual is exposed and the severity of disease being considered [25]. Further research is needed to better understand the interaction between natural and vaccine-induced immunity, the effects of variant exposure, and the timing between exposures [26][27][28][29].

Coverage with the updated COVID-19 vaccine among adults aged ≥65 years was 42% as of February 3, 2024 (*10*,*11*). Our findings highlight that children without previous infection and elderly aged >65 (who are more likely to rely upon vaccination to increase immunity and might have waned) might need more frequent vaccine doses to maintain protection [30]. These findings could support the development of **personalized vaccination schedules**, considering both recent infections and the timing of past vaccinations. As we expect an increase in the number of people with hybrid immunity with new variants, the definition or key risk factors of high-risk individuals with and without previous infection may change over time. For public health authorities, these findings highlight the need for **continuous surveillance** of infection rates post-vaccination/infection and possibly adjusting booster guidelines based on observed immune waning rather than fixed timelines. As we transition to endemicity, there is the potential need for altered vaccine formulations to track viral variants, the need to identify immune correlates of protection, and the public health challenges of using various tools to counter breakthrough infections, including boosters in an era of global vaccine shortages.

**Conclusions**

In summary, in this large cohort study, we compared the antibody responses, and their infection risks induced by different COVID-19 immunity statuses (hybrid and vaccine) across age groups. We showed that S antibody waning, and infection risk trends are highly correlated; the hybrid group resulted in at least 2 times higher and longer-lasting antibody responses and >40% higher probability of protective effectiveness against infection at 12 months from the last immunological event compared to vaccination alone. We also found similar risk factor (such as female) and different risk factors in hybrid and vaccine groups; the timing of infection or vaccination could be more critical than the sheer number of vaccine doses in hybrid group while children aged <20 years without previous infection and elderly aged >65 years (who are more likely to rely upon vaccination to increase immunity and might have waned) might be prioritized for the booster vaccine. These findings could support the development of **personalized vaccination schedules,** considering both recent infections and the timing of past vaccinations.

# **References**

[1] S. Gazit *et al.*, “Hybrid immunity against reinfection with SARS-CoV-2 following a previous SARS-CoV-2 infection and single dose of the BNT162b2 vaccine in children and adolescents: a target trial emulation,” *Lancet Microbe*, vol. 4, no. 7, pp. e495–e505, Jul. 2023, doi: 10.1016/S2666-5247(23)00103-9.

[2] M. Karachaliou *et al.*, “SARS-CoV-2 infection, vaccination, and antibody response trajectories in adults: a cohort study in Catalonia,” *BMC Med.*, vol. 20, p. 347, Sep. 2022, doi: 10.1186/s12916-022-02547-2.

[3] Y. Wei *et al.*, “Estimation of Vaccine Effectiveness of CoronaVac and BNT162b2 Against Severe Outcomes Over Time Among Patients With SARS-CoV-2 Omicron,” *JAMA Netw. Open*, vol. 6, no. 2, p. e2254777, Feb. 2023, doi: 10.1001/jamanetworkopen.2022.54777.

[4] M. Fabiani *et al.*, “Effectiveness of mRNA vaccines and waning of protection against SARS-CoV-2 infection and severe covid-19 during predominant circulation of the delta variant in Italy: retrospective cohort study,” *BMJ*, vol. 376, p. e069052, Feb. 2022, doi: 10.1136/bmj-2021-069052.

[5] N. Wu *et al.*, “Long-term effectiveness of COVID-19 vaccines against infections, hospitalisations, and mortality in adults: findings from a rapid living systematic evidence synthesis and meta-analysis up to December, 2022,” *Lancet Respir. Med.*, vol. 11, no. 5, pp. 439–452, May 2023, doi: 10.1016/S2213-2600(23)00015-2.

[6] N. Andrews *et al.*, “Covid-19 Vaccine Effectiveness against the Omicron (B.1.1.529) Variant,” *N. Engl. J. Med.*, p. NEJMoa2119451, Mar. 2022, doi: 10.1056/NEJMoa2119451.

[7] D. Cromer *et al.*, “Neutralising antibody titres as predictors of protection against SARS-CoV-2 variants and the impact of boosting: a meta-analysis,” *Lancet Microbe*, vol. 3, no. 1, pp. e52–e61, Jan. 2022, doi: 10.1016/S2666-5247(21)00267-6.

[8] G. Moncunill *et al.*, “Determinants of early antibody responses to COVID-19 mRNA vaccines in a cohort of exposed and naïve healthcare workers,” *EBioMedicine*, vol. 75, p. 103805, Jan. 2022, doi: 10.1016/j.ebiom.2021.103805.

[9] H. Ward *et al.*, “Population antibody responses following COVID-19 vaccination in 212,102 individuals,” *Nat. Commun.*, vol. 13, no. 1, p. 907, Feb. 2022, doi: 10.1038/s41467-022-28527-x.

[10] N. Bobrovitz *et al.*, “Protective effectiveness of previous SARS-CoV-2 infection and hybrid immunity against the omicron variant and severe disease: a systematic review and meta-regression,” *Lancet Infect. Dis.*, vol. 23, no. 5, pp. 556–567, May 2023, doi: 10.1016/S1473-3099(22)00801-5.

[11] “Protection of COVID-19 vaccination and previous infection against Omicron BA.1, BA.2 and Delta SARS-CoV-2 infections | Nature Communications.” Accessed: Sep. 23, 2024. [Online]. Available: https://www.nature.com/articles/s41467-022-31838-8

[12] N. Bobrovitz *et al.*, “Protective effectiveness of prior SARS-CoV-2 infection and hybrid immunity against Omicron infection and severe disease: a systematic review and meta-regression,” Oct. 24, 2022, *medRxiv*. doi: 10.1101/2022.10.02.22280610.

[13] Y. Goldberg *et al.*, “Protection and Waning of Natural and Hybrid Immunity to SARS-CoV-2,” *N. Engl. J. Med.*, vol. 386, no. 23, pp. 2201–2212, Jun. 2022, doi: 10.1056/NEJMoa2118946.

[14] G. den Hartog *et al.*, “Assessment of hybrid population immunity to SARS-CoV-2 following breakthrough infections of distinct SARS-CoV-2 variants by the detection of antibodies to nucleoprotein,” *Sci. Rep.*, vol. 13, no. 1, p. 18394, Oct. 2023, doi: 10.1038/s41598-023-45718-8.

[15] J. Han *et al.*, “Korea Seroprevalence Study of Monitoring of SARS-COV-2 Antibody Retention and Transmission (K-SEROSMART): findings from national representative sample,” *Epidemiol. Health*, vol. 45, 2023, doi: 10.4178/epih.e2023075.

[16] D. Steensels, N. Pierlet, J. Penders, D. Mesotten, and L. Heylen, “Comparison of SARS-CoV-2 Antibody Response Following Vaccination With BNT162b2 and mRNA-1273,” *JAMA*, vol. 326, no. 15, pp. 1533–1535, Oct. 2021, doi: 10.1001/jama.2021.15125.

[17] W. F. Garcia-Beltran *et al.*, “mRNA-based COVID-19 vaccine boosters induce neutralizing immunity against SARS-CoV-2 Omicron variant,” *Cell*, vol. 185, no. 3, pp. 457-466.e4, Feb. 2022, doi: 10.1016/j.cell.2021.12.033.

[18] B. Carstensen, M. Plummer, E. Laara, and M. Hills, *Epi: Statistical Analysis in Epidemiology*. (Jul. 18, 2024). Accessed: Aug. 12, 2024. [Online]. Available: https://cran.r-project.org/web/packages/Epi/index.html

[19] N. Pearce, “Analysis of matched case-control studies,” *BMJ*, vol. 352, p. i969, Feb. 2016, doi: 10.1136/bmj.i969.

[20] “Seroprevalence of SARS-CoV-2 antibodies in the community based on participants in the 2020 Korea National Health and Nutrition Examination Survey.” Accessed: Sep. 04, 2024. [Online]. Available: https://www.e-epih.org/journal/view.php?number=1276

[21] M. Karachaliou *et al.*, “SARS-CoV-2 infection, vaccination, and antibody response trajectories in adults: a cohort study in Catalonia,” *BMC Med.*, vol. 20, no. 1, p. 347, Sep. 2022, doi: 10.1186/s12916-022-02547-2.

[22] E. J. Jang *et al.*, “Presumed population immunity to SARS-CoV-2 in South Korea, April 2022,” *Osong Public Health Res. Perspect.*, vol. 13, no. 5, pp. 377–381, Oct. 2022, doi: 10.24171/j.phrp.2022.0209.

[23] N. Eliakim-Raz *et al.*, “Three-month follow-up of durability of response to the third dose of the SARS-CoV-2 BNT162b2 vaccine in adults aged 60 years and older: a prospective cohort study,” *BMJ Open*, vol. 12, no. 8, p. e061584, Aug. 2022, doi: 10.1136/bmjopen-2022-061584.

[24] J. A. Montes-González *et al.*, “Protection of hybrid immunity against SARS-CoV-2 reinfection and severe COVID-19 during periods of Omicron variant predominance in Mexico,” *Front. Public Health*, vol. 11, Apr. 2023, doi: 10.3389/fpubh.2023.1146059.

[25] M. Lipsitch, F. Krammer, G. Regev-Yochay, Y. Lustig, and R. D. Balicer, “SARS-CoV-2 breakthrough infections in vaccinated individuals: measurement, causes and impact,” *Nat. Rev. Immunol.*, vol. 22, no. 1, pp. 57–65, Jan. 2022, doi: 10.1038/s41577-021-00662-4.

[26] L. J. Abu-Raddad, H. Chemaitelly, and R. Bertollini, “Effectiveness of mRNA-1273 and BNT162b2 Vaccines in Qatar,” *N. Engl. J. Med.*, p. NEJMc2117933, Jan. 2022, doi: 10.1056/NEJMc2117933.

[27] N. Andrews *et al.*, “Duration of Protection against Mild and Severe Disease by Covid-19 Vaccines,” *N. Engl. J. Med.*, p. NEJMoa2115481, Jan. 2022, doi: 10.1056/NEJMoa2115481.

[28] S. K. Yoon *et al.*, “Protection with a Third Dose of mRNA Vaccine against SARS-CoV-2 Variants in Frontline Workers,” *N. Engl. J. Med.*, p. NEJMc2201821, Apr. 2022, doi: 10.1056/NEJMc2201821.

[29] M. Šmíd *et al.*, “Protection by vaccines and previous infection against the Omicron variant of SARS-CoV-2,” *J. Infect. Dis.*, p. jiac161, Apr. 2022, doi: 10.1093/infdis/jiac161.

[30] “Hybrid immunity against reinfection with SARS-CoV-2 following a previous SARS-CoV-2 infection and single dose of the BNT162b2 vaccine in children and adolescents: a target trial emulation - The Lancet Microbe.” Accessed: Sep. 04, 2024. [Online]. Available: https://www.thelancet.com/journals/lanmic/article/PIIS2666-5247(23)00103-9/fulltext

**Appendix**

1. **Cox hazard model**

Below is the equation of cox-hazard model, describing the relative risk of the COVID-19 infection since the latest immunology events.

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1. **Logistic regression model across various risk factors by the immune groups**

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Figure S: Forest plot displaying characteristic patterns. Top: Vaccine-induced group. Bottom: Hybrid-induced group. Key variables include immune\_gap (time since the latest immunological event), vac\_dose (number of vaccine doses), and S ab (S antibody level at the first surveillance).

Based on the key demographic characteristics (Table 1), we conducted logistic regression to determine specific risk factors on infection events for hybrid and vaccine groups, respectively. All available characteristics were converted to categorical variables, with the first subgroup designated as the reference category. This al- lowed for the calculation of log odds ratios, where a higher log odds ratio indicates a greater infection risk compared to the reference group. A log odds ratio of zero signifies equal risk with the reference group.

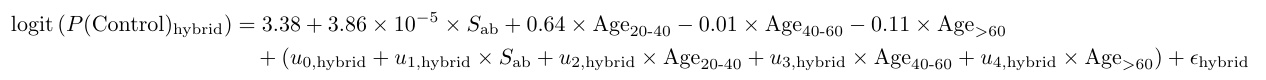
Among all characteristics, age and S antibody level demonstrated the most significant association with individual infection status, exhibiting clear patterns and non-overlapping confidence intervals. (Figure S1) Notably, the youngest group exhibited the highest individual infection risks. Except for the youngest group, there was a positive correlation between age and infection risk, indicating that risk increases with age.

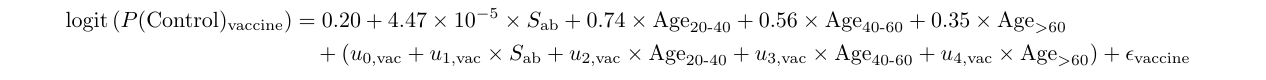
1. **Simple regression model and mixed effect regression model**

To determine the risk probability of remaining infection-free by S antibody levels across age groups, we constructed a simple logistic regression including age only based on the finding. (Figure 4 and S2) The equation for the simple logistic regression is provided below. On the left side of each equation is the logit transformation of the probability of being in the control group, which represents the likelihood of being free from COVID-19 infection.



We also conducted the mixed effects logistic regression as the S antibody initial level and decay trends clearly differed by immune type groups. The equation for the mixed effect logistic regression is provided below.





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**A graph of a curve

Description automatically generated**

Figure S2: ROC curves for comparison between simple and mixed effect logistic regression models

The ROC curve analysis demonstrates that the mixed-effects logistic regression model (red curve) exhibits superior discriminative capability compared to the simple logistic regression model (blue curve). This conclusion is supported by the consistently higher position of the mixed-effects model’s ROC curve across all threshold levels. Moreover, the mixed-effects model achieves a higher Area Under the Curve (AUC) value of 0.82, in contrast to 0.77 for the simple logistic model. This indicates a marked improvement in the mixed-effects model’s performance in predicting the binary outcome, thereby suggesting its enhanced utility in applications requiring robust classification accuracy.

1. **Infection hospitalization risks by immunity status and age groups**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | | <20 | 20-40 | 40-60 | >60 | Total |
| Hybrid | Infections | 4 | 6 | 20 | 17 | 48 |
| Hospitalization | 0 | 0 | 0 | 2 | 2 |
| Infection hospitalization risk | **0.00** | **0.00** | **0.00** | **0.14** | **0.04** |
| Vaccine | Infections | 43 | 83 | 178 | 281 | 585 |
| Hospitalization | 1 | 1 | 3 | 11 | 16 |
| Infection hospitalization risk | **0.02** | **0.01** | **0.02** | **0.04** | **0.03** |

Table S1. Infection hospitalization risks by immunity status and age groups.