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Anti-spike antibody responses to SARS-CoV-2 mRNA vaccines in people with schizophrenia and schizoaffective disorder

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ABSTRACT

Importance: Individuals with schizophrenia are at higher risk for severe COVID-19 illness and severe breakthrough infection following vaccination. It is unclear whether immune response to vaccination differs in this population.
Objective: To assess whether anti-SARS-CoV-2 spike antibody titers after vaccination differ in people with a diagnosis of schizophrenia or schizoaffective disorder (SZ) compared to controls without a psychiatric disorder.
Design: This cohort study assessed antibody response following the first and second dose of mRNA vaccines at longitudinal timepoints, up to 7 weeks following the first dose of vaccine.
Setting: A multi-center study including psychiatric healthcare settings in the United States and Europe.
Participants: 205 adults with no history of COVID-19 infection, including 106 individuals with SZ and 99 controls without a psychiatric disorder, who received their first dose of SARS-CoV-2 mRNA vaccine between December 20, 2020 and May 27, 2021.
Main outcomes and measures: Mean SARS-CoV-2 anti-Spike IgG antibody levels within 7 weeks after the first dose of vaccination.
Results: A total of 205 individuals (mean [SD] age, 44.7 [12.0] years; 90 [43.9%] male) were included, of which 106 (51.7%) were diagnosed with SZ. SZ was associated with lower mean log antibody levels (−0.15; 95% CI, −0.27 to −0.03, $P = 0.016$) after adjusting for age, sex, body mass index, smoking, days since vaccination, and vaccine manufacturer. In secondary analyses of dose-specific responses, SZ was associated with a lower mean log antibody level after the second dose of vaccine (−0.23; 95% CI -0.39 to −0.06, $P = 0.006$), but not the first dose of vaccine (0.00; 95% CI -0.18— 0.19, $P = 0.96$).
Conclusions and Relevance: In this cohort study of individuals with SZ and a control group without psychiatric disorders, SZ was associated with lower SARS-CoV-2 anti-spike antibody levels following 2 doses of SARS-CoV-2 mRNA vaccination. This highlights the need for further studies assessing vaccine immunogenicity in individuals with schizophrenia.

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1. Introduction

Individuals with schizophrenia are among the most vulnerable groups at risk of developing a severe or fatal course of illness in the setting of COVID-19 infection. In addition to the increased prevalence of chronic medical conditions and barriers to accessing healthcare that contribute to adverse outcomes in people with schizophrenia, a diagnosis of schizophrenia has been established as an independent risk factor for COVID-19-associated mortality (Fond et al., 2021; Nemani et al., 2021; Tzur Bitan et al., 2021a; Vai et al., 2021; Toubasi et al., 2021). The high level of evidence supporting this finding prompted the Centers for Disease Control and Prevention to add schizophrenia to its list of conditions associated with higher risk for severe COVID-19 and helped inform European vaccine strategy to include individuals with severe mental illness as a priority group (De Picker et al., 2021; Vai et al., 2022).

Vaccines play a vital role in safeguarding populations at high risk of severe infection. However, lower SARS-CoV-2 anti-Spike antibody levels are found following vaccination in conditions associated with clinical vulnerability to severe COVID-19, including diabetes, obesity, hypertension and cardiac conditions (Shrotri et al., 2022; Gilboa et al., 2023). An association between lower SARS-CoV-2 anti-Spike IgG antibody titers and risk of breakthrough infection has been established at both the individual and population level (Gilboa et al., 2023; Wei et al., 2022; Bergwerk et al., 2021; Khoury et al., 2021). This suggests that (1) both vaccine immunogenicity and vaccine efficacy may be suboptimal in those at highest risk for infection and (2) there may be a common immune mechanism contributing to increased risk of severe COVID-19 and a suboptimal serologic vaccine response.

Individuals with schizophrenia who have been vaccinated are at decreased risk of severe COVID-19 infection compared to non-vaccinated individuals with schizophrenia, suggesting that COVID-19 vaccines do provide protection for this group (Tzur Bitan et al., 2021b). However, risk of severe breakthrough infection leading to hospitalization is still 3-fold higher among vaccinated patients with schizophrenia compared to the vaccinated general population—even after controlling for demographic and clinical risk factors (Tzur Bitan et al., 2022). Preliminary evidence suggested a decreased antibody response to COVID-19 vaccination in people reporting any psychiatric disorder (Karachaliou et al., 2022). It is possible that immune dysregulation in schizophrenia impairs response to infection and contributes to diminished immune response to vaccination.

Few studies have examined immune response to vaccination in people with schizophrenia. A diminished antibody response following immunization with plain pertussis vaccine in people with schizophrenia compared to controls was reported in 1947 (Vaughan et al., 1949). Subsequent studies reported an increased antibody response to cholera vaccination (Friedman et al., 1967) and typical antibody responses to vaccination against tetanus (Solomon et al., 1970) and diphtheria (Hussar et al., 1971). These studies were conducted prior to the development of the DSM-III and before the development of immunological assays such as ELISA, which improved the accuracy of antibody measurement. More recently, in a study of hospitalized patients with schizophrenia and community controls who received childhood vaccination against hepatitis B virus, seroprevalence of hepatitis B antigens was higher in the schizophrenia group—suggesting that patients with schizophrenia may be at higher risk of infection with hepatitis B even after vaccination (Wang et al., 2016).

The present study evaluated SARS-CoV-2 anti-Spike antibody responses to SARS-CoV-2 mRNA vaccines in individuals with schizophrenia or schizoaffective disorder (SZ) compared to controls without psychiatric disease. We hypothesized that antibody levels would be lower in the SZ group.

2. Methods

2.1. Study design and participants

This multi-center cohort included adults with SZ and adults without a psychiatric diagnosis who received their primary SARS-CoV-2 messenger RNA (mRNA) vaccination series with BioNTech/Pfizer (BNT162b2) or Moderna (mRNA-1273). All participants received two doses of vaccine. One or more blood samples were collected longitudinally from each individual following the first and/or second dose. Individuals with prior COVID-19 infection were excluded, including those with (1) a positive SARS-CoV-2 polymerase chain reaction test result, (2) a positive SARS-CoV-2 nucleocapsid antibody test result or (3) a prior clinical diagnosis of COVID-19 infection. The study followed the Strengthening of the Reporting of Observational Studies in Epidemiology (STROBE) reporting guidelines for cohort studies. Participants were enrolled across four study sites in the United States and Europe.

2.1.1. New York state patient cohort

Plasma samples were collected from adult inpatients with SZ hospitalized in psychiatric centers operated by the New York State Office of Mental Health (NYS-OMH), USA. Samples were derived from blood collected for routine clinical purposes between January 4, 2021 and March 31, 2021 from patients who were vaccinated with BioNTech/Pfizer or Moderna COVID-19 vaccines. Vaccination history including dates of administration and vaccine manufacturer were confirmed using a centralized vaccine registry. Infection history was confirmed using a centralized COVID-19 registry, which was implemented March 1, 2020, and included COVID-19 test results and clinical status for every patient on census; this included both RT-PCR test results (for active infection) and anti-nucleocapsid IgG antibody test results (for past infection). The study was approved by the Nathan Kline Institute Institutional Review Board with a waiver of informed consent for secondary use of biospecimens.

2.1.2. Maryland patient cohort

Participants with SZ were recruited from an established cohort of research participants receiving outpatient care in psychiatric programs affiliated with Sheppard Pratt Health System in central Maryland, USA. The control individuals without a history a psychiatric disorder were recruited from posted announcements at local healthcare facilities and universities in the same geographic area. Samples were collected between January 4, 2021 and March 31, 2021 from patients who received the BioNTech/Pfizer, Moderna, AstraZeneca, or Janssen (Johnson & Johnson) COVID-19 vaccine. Data from participants with psychiatric diagnoses other than schizophrenia/schizoaffective disorder and from participants who received AstraZeneca or Janssen vaccines were not included in the present analysis. Vaccination history and history of Covid-19 infection were obtained by self-report and confirmed by review of immunization record cards and available medical records. The study was approved by the Sheppard Pratt Institutional Review Board. All participants provided written informed consent.

2.1.3. Belgium patient cohort

Plasma samples were collected prospectively from adult inpatients with severe mental illness residing in the psychiatric long-stay facilities of The University Psychiatric Center Duffel (*UPC Duffel*) in Flanders, Belgium between February 22, 2021 and July 13, 2021 as part of a larger multi-center clinical study. Hospital staff were enrolled under the same protocol to serve as healthy controls. All eligible patients and staff who registered for vaccination at UPC Duffel were invited to participate. BioNTech/Pfizer, Moderna, or AstraZeneca (AZD1222) COVID-19 vaccines were used according to batch availability.

Data from patients with diagnoses other than SZ and from participants who were vaccinated with AstraZeneca were not included in the present analysis. Samples from participants vaccinated with BioNTech/

Pfizer or Moderna vaccines were collected (1) at baseline, prior to vaccination (2) 7 days after the first dose of vaccine, (3) on the day of the second vaccine administration, and (4) 21 days after the second dose of vaccine. Participants' infection history was confirmed through (1) participant report (patients and controls), (2) centralized medical records (patients) and (3) records of PCR tests conducted within the hospital for all new admissions as well as symptomatic individuals or close contacts of confirmed cases (patients and controls). The study was approved by the Ethics Committees of the University Hospital Antwerp and Emmaus, and all participants provided written informed consent prior to study participation.

2.1.4. France patient cohort

Participants with severe mental illness and hospital staff were enrolled at Assistance Publique–Hôpitaux de Paris (*AP-HP*) under the same study protocol as the Belgium patient cohort. All participants at this site received the BioNTech/Pfizer COVID-19 vaccine and were invited to participate in the study. The study was approved by the Comité de Protection des Personnes Sud Est V and all participants provided written informed consent.

2.2. Antibody assessment

All blood samples were sent to the John Hopkins Stanley Neurovirology Laboratory in Baltimore, Maryland under the direction of Dr. Robert Yolken. IgG antibodies to the SARS-CoV-2 spike protein were measured by solid phase enzyme immunoassay employing SARS-CoV-2 Spike S1-His Recombinant Protein as antigen (Sino Biological, Wayne PA, Catalogue number 40591- V08H16) and enzyme labelled anti-human IgG. The amount of enzymatic reactivity generated by bound IgG and enzyme substrate was measured in optical density units using a microplate colorimeter. The optical density units were converted to ratios by comparison with standard samples assayed on each microtiter plate.

2.3. Outcomes

The main outcome variable was defined as mean SARS-CoV-2 anti-Spike IgG antibody levels of all samples collected within 7 weeks of the first dose of vaccination from subjects who met study inclusion criteria. The mean natural logarithm of antibodies was compared between the SZ group and the control group.

Additional analyses were performed to evaluate potential dose-specific differences. To assess differences in response following the first dose of vaccine, mean antibody levels from samples collected prior to the second dose of vaccine were compared across groups. To examine whether a diagnosis of SZ was associated with antibody levels at their peak detection concentration, mean antibody levels from samples collected 2–4 weeks after the second dose of vaccine were compared.

2.4. Covariates

The following covariates were extracted from electronic health records or collected from participants at the time of study enrollment based on their known or hypothesized association with antibody response to vaccination: age, sex, body mass index (BMI), and smoking status. Age and BMI were coded as continuous variables. Sex was limited to a male and female binary variable. Smoking status was collapsed into a binary variable of smoker/non-smoker based on current use. Vaccine type was a binary variable according to manufacturer (BioNTech/Pfizer or Moderna). Time since vaccine dose was coded continuously as number of days. The square of time since vaccine dose was also considered in the models.

2.5. Statistical analysis

The percentage, mean, and standard deviation were computed to describe characteristics of the study population. Chi-square tests for binary variables and Wilcoxon rank sum tests for continuous variables were used to evaluate the relationship between covariates and diagnostic groups.

Mixed effects models were used to explore the relationships between diagnostic groups and mean log antibody levels over time controlling for covariates. A random effect for the number of samples per participant was included in the models. Statistical significance was defined as $\alpha < 0.05$. Wald-95% confidence intervals were constructed and Wald tests were used to evaluate hypotheses. All statistical analyses were conducted in RStudio and R (versions 2022.12.0 + 353 and 4.1.2, respectively). Given the low percentage of missing data (8 cases, accounting for 3.7% missing data on smoking, and 1 case, representing 0.5% missing data on BMI out of a total of 214 participants), a complete case analysis was performed. A sensitivity analysis using multiple imputation methods was also conducted, which revealed no changes in the results (data not shown). Local polynomial regression models were used to smooth the data in the Figures (Wasserman, 2006).

3. Results

3.1. SARS-CoV-2 anti-spike antibody levels (all samples)

A total of 205 individuals (106 with SZ and 99 controls) were eligible for inclusion in the study (eFig. 1 in the Supplement). Compared to the control group, the SZ group was younger, had a greater proportion of men, a higher BMI, a greater proportion of smokers, and a greater proportion of individuals vaccinated with Moderna (Table 1).

Mean log antibody levels were negatively associated with age and cigarette smoking. SZ was associated with lower mean log antibody levels (−0.15 [−0.27 to −0.03]; $P = 0.016$) after adjusting for age, sex, BMI, smoking, days since vaccination, and vaccine manufacturer (Table 2). Mean log antibody levels over time for each group are plotted in Fig. 1.

3.2. SARS-CoV-2 anti-spike antibody levels following first dose of vaccine

A total of 172 individuals, including 76 with SZ and 96 controls, were included in the analysis of SARS-CoV-2 anti-Spike antibody levels following the first dose of vaccine, prior to the second dose of vaccine (eTable 1 in the Supplement). Mean log antibody levels in individuals with SZ did not differ significantly from controls after adjusting for age, sex, BMI, smoking, and days since the first vaccination dose (0.00

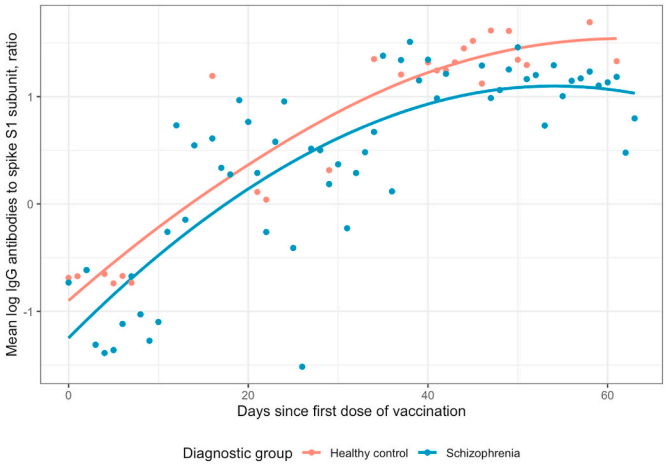

Fig. 1. SARS-CoV-2 Anti-Spike antibody levels over time (all samples).

Table 1
Demographic and clinical characteristics of individuals with at least one sample collected after the first or second dose of vaccination.

Characteristic	No. (%)			
	Overall (n = 205)	Control (n = 99)	SZ[a] (n = 106)	p-value[b]
Age, mean (SD), y	44.7 (12.0)	46.8 (11.7)	42.7 (12.1)	0.013
Sex				
Female	115 (56.1)	83 (83.8)	32 (30.2)	<0.001
Male	90 (43.9)	16 (16.2)	74 (69.8)	
Race/Ethnicity				
Asian/PI	2 (1.0)	0	2 (1.9)	<0.001
Black	29 (14.1)	0	29 (27.4)	
Hispanic	12 (5.9)	0	12 (11.3)	
Other/ Unknown[c]	2 (1.0)	0	2 (1.9)	
White	160 (78.0)	99 (100.0)	61 (57.5)	
BMI, mean (SD)	27.8 (6.2)	25.7 (5.2)	29.8 (6.4)	<0.001
Smoking[d]	58 (28.3)	13 (13.1)	45 (42.5)	<0.001
Vaccine Manufacturer				
Moderna	62 (30.2)	22 (22.2)	40 (37.7)	0.016
Pfizer	143 (69.8)	77 (77.8)	66 (62.3)	
Study Site				
Belgium or France	115 (56.1)	94 (94.9)	21 (19.8)	<0.001
New York	69 (33.7)	0	69 (65.1)	
Maryland	21 (10.2)	5 (5.1)	16 (15.1)	

[a] Schizophrenia or schizoaffective disorder.
[b] Wilcoxon rank sum test; Pearson's Chi-squared test.
[c] Included Guamanian or Chamorro, Native American, other Pacific Islander, Native Hawaiian, Samoan, unspecified or unknown race by patient report.
[d] Reference group is not smoking.

Table 2
Multivariable linear regression model of variables associated with SARS-CoV-2 anti-Spike antibody levels.

Predictors	log(SARS-CoV-2 anti-spike IgG)		
	Estimates	CI	p
(Intercept)	−0.76	−1.09–−0.42	<0.001
Diagnostic Group [SZ]	−0.15	−0.27–−0.03	0.016
Days since dose 1	0.07	0.06–0.08	<0.001
Days since dose 1^2	−0.00	−0.00–−0.00	<0.001
Age	−0.01	−0.01–−0.00	<0.001
Sex [Male]	−0.03	−0.13–0.07	0.532
Manufacturer [Pfizer]	−0.04	−0.12–0.05	0.368
BMI	0.01	−0.00–0.01	0.060
Smoking [Yes]	−0.12	−0.21–−0.02	0.017
Random Effects			
σ^2	0.21		
$\tau_{00\ visit}$	0.05		
ICC	0.18		
$N_{\ visit}$	4		
Observations	605		
Marginal R^2/Conditional R^2	0.723/0.774		

[2] Squared.

[−0.18— 0.19], $P = .96$) (Fig. 2). Lower mean log antibody levels were associated with older age and smoking (eTable 2 in the Supplement).

3.3. SARS-CoV-2 anti-spike antibody levels following second dose of vaccine

A total of 152 individuals, including 94 with SZ and 58 controls, were included in the analysis of SARS-CoV-2 anti-Spike antibody levels 2–4 weeks following the second dose of vaccine (eTable 3 in the Supplement). SZ was associated with lower mean log antibody levels (−0.23 [−0.39 to −0.06]; $P = 0.006$) after adjusting for age, sex, BMI, smoking, days since dose 2, and vaccine manufacturer (Fig. 3, Table 3).

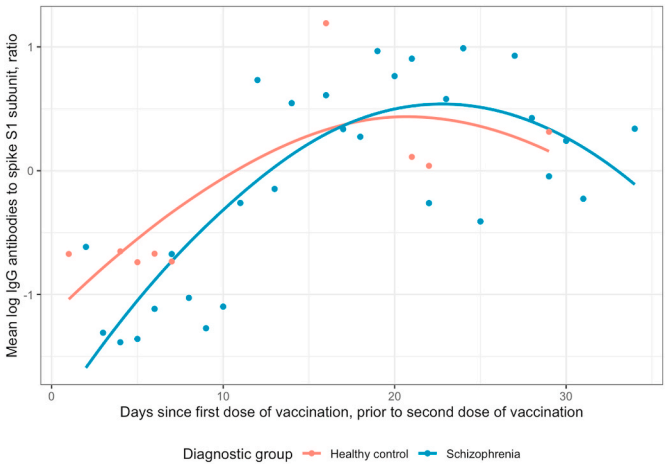

Fig. 2. SARS-CoV-2 Anti-Spike antibody levels following vaccine dose 1.

Table 3
Multivariable linear regression model of variables associated with SARS-CoV-2 anti-Spike antibody levels 14–28 days after dose 2 of vaccination.

Predictors	log(SARS-CoV-2 anti-spike IgG)		
	Estimates	CI	p
(Intercept)	1.49	0.91–2.06	<0.001
Diagnostic Group [SZ]	−0.23	−0.39–−0.06	0.006
Days since dose 2	−0.02	−0.11–0.06	0.560
Days since dose 2^2	0.00	−0.00–0.01	0.673
Age	−0.00	−0.01–0.00	0.576
Sex [Male]	0.03	−0.11–0.17	0.627
Manufacturer [Pfizer]	−0.12	−0.26–0.01	0.076
BMI	0.00	−0.01–0.01	0.583
Smoking [Yes]	0.01	−0.13–0.15	0.870
Observations	152		
R^2	−5.161		

[2] Squared.

4. Discussion

Results of this cohort study of patients with SZ and a control group without a psychiatric disorder suggests that individuals with schizophrenia mount a lower antibody response to SARS-CoV-2 mRNA vaccines. To our knowledge, this is the first large-scale study to assess immune response to COVID-19 vaccination in this population.

Findings from this study suggest a similar response to the first dose of vaccine between groups but diminished response to the second dose of

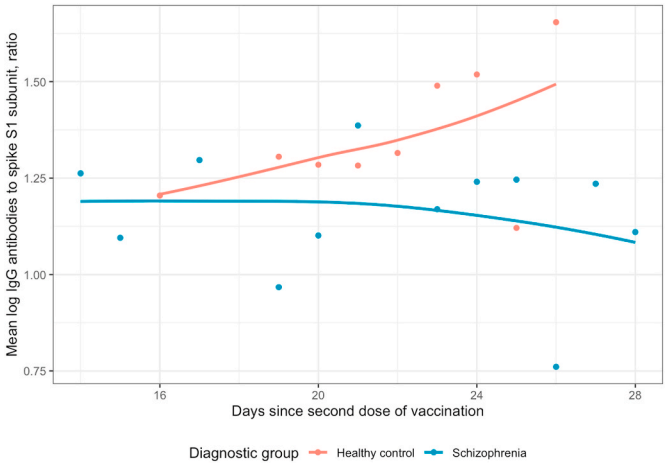

Fig. 3. SARS-CoV-2 Anti-Spike antibody levels 14–28 following vaccine dose 2.

vaccine in individuals with schizophrenia. There are several potential explanations for this finding, including immune dysfunction inherent to the disorder itself as well as external factors such as differences in diet, living conditions, physical comorbidity, and medication effects. One immune mechanism that could contribute to the pattern of response observed is a defect in the B cell memory response within germinal centers. Germinal centers are specialized structures within lymph nodes where B-cells proliferate, undergo affinity maturation, and differentiate into plasma cells; this activity is activated and regulated by $CD4^+$ T helper cells (Victora and Nussenzweig, 2012). Germinal center reactions are more prominent after the second dose of vaccine and result in high-affinity antibodies that produce sustained protection (Laidlaw and Ellebedy, 2022). These differ from extrafollicular B cell responses outside the germinal center, which are generally T cell-independent and result in the production of early antibodies with low-affinity (Elsner and Shlomchik, 2020). In individuals with severe COVID-19, antibody titers correlate with extrafollicular B cell activation rather than a germinal center response, (Kuri-Cervantes et al., 2020; Woodruff et al., 2020) possibly due to the significant decrease in T helper cell quantity (Kaneko et al., 2020). An impaired ability to generate high affinity antibodies via the germinal center response in individuals with schizophrenia might contribute to a diminished response to the second dose of vaccine and susceptibility to severe COVID-19 infection.

Interestingly, a recent study found that genetic risk variants for schizophrenia are enriched within epigenetically active sites in lymphoid cells, especially stimulated $CD4^+$ T cells and memory B cells (Lynall et al., 2022). Genetic risk variants at these active sites may modulate infection-induced activation of regulatory elements, leading to atypical T or B cell phenotypes following infection. Consistent with this, T cells from patients with schizophrenia have been reported to have a lower proliferative response to activation (Craddock et al., 2007). Based on this evidence it is conceivable that alterations in T cell or B cell activation within germinal centers may contribute to an altered response to vaccination in people with schizophrenia, but this remains to be studied.

Research in other infectious diseases suggests that baseline immune signatures prior to vaccination may predict immune response to vaccination (Tsang et al., 2020). For example, increased frequencies of proinflammatory innate immune cells at baseline correlate with lower antibody responses to Hepatitis B vaccination (Fourati et al., 2016), and higher frequencies of exhausted and activated natural killer cells are associated with lower antibody titers to the yellow fever vaccine (Muyanja et al., 2014). Multiple studies have found evidence of chronic activation of the innate immune system activation in schizophrenia, including increased monocytes (Steiner et al., 2020), proinflammatory cytokines (Halstead et al., 2023) and persistent activation of natural killer cells (Tarantino et al., 2021), which may interfere with an efficient immune response to infection or vaccination. Determining whether these baseline immune abnormalities predict antibody response to Covid-19 vaccination may inform personalized vaccination strategies in the future.

Several other mechanisms may contribute to a diminished antibody response to vaccination in people with schizophrenia. Chronic medical conditions, including diabetes and cardiovascular disease, are more prevalent in people with schizophrenia (Ali et al., 2023) and have been linked to a lower antibody response to COVID-19 vaccination (Shrotri et al., 2022; Lustig et al., 2021). In addition, treatment with antipsychotics may modulate the immune response. A decreased antibody response following immunization against pneumococcal antigen was found in mice treated with risperidone (May et al., 2020), and an association between clozapine use and reduced immunoglobulin levels were reported in a study of individuals with schizophrenia (Ponsford et al., 2018). At the same time, these antipsychotic medications have been associated with decreased risk of severe COVID-19 infection (Nemani et al., 2022). Further research is needed to understand how these medications may alter immune response to vaccination and infection.

Breakthrough infections were not assessed in this sample and the optimal antibody threshold for protection is not clear, limiting the clinical interpretation of our findings. However, data from prior research suggests a higher rate of severe breakthrough infections in vaccinated individuals with schizophrenia compared to vaccinated individuals from the general population (Tzur Bitan et al., 2022). Findings from this study suggest that a reduced antibody response to vaccination may be in part responsible for decreased vaccine efficacy. Vaccine-preventable diseases are a significant contributor to the poor health, higher hospitalization rates, and higher rates of premature death of people living with severe mental illness (Momen et al., 2020; Cunningham et al., 2014; Sara et al., 2021). Additional research is critically needed to determine whether strategies such as time interval between doses, higher doses or additional boosters should be considered in individuals with schizophrenia to optimize protection against COVID-19 and other vaccine-preventable illnesses.

4.1. Limitations

This study has limitations. The potential effects of psychopharmacologic treatment on antibody response were not assessed; all individuals in the SZ group were treated with antipsychotic medication. Additional differences between groups may have contributed to differences in antibody response; while many of these variables (including age, sex, BMI, and smoking status) were accounted for in the analysis, comorbid medical conditions and the impact of confinement in hospital were not assessed. While both inpatient and outpatients were included in the SZ cohort, representing a broad spectrum of clinical severity, the majority were recruited from inpatient facilities for patients with severe and persistent illness; additional work is needed to determine the generalizability of these findings to those with early stage and mild illness. This study assessed SARS-CoV-2 anti-Spike IgG antibodies but did not include measures of antibody function or other markers of immune response, such as cellular immune components. The duration of immune response was not assessed, which should be a focus of future investigations.

5. Conclusions

This cohort study of COVID-19-naïve adults found lower antibody titers following SARS-CoV-2 mRNA vaccination in individuals with SZ compared to a control group without psychiatric illness. To our knowledge, this is the first study to measure immune response to COVID-19 vaccines in this group. There is an urgent need for more research to assess the both the efficacy and immunogenicity of vaccines in this vulnerable population, with the goal of understanding the mechanisms that contribute to severe infection and informing strategies to mitigate risk.

CRediT authorship contribution statement

Katlyn Nemani: Conceptualization, Data curation, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing. **Livia De Picker:** Conceptualization, Data curation, Methodology, Supervision, Writing – review & editing. **Faith Dickerson:** Conceptualization, Data curation, Funding acquisition, Supervision, Writing – review & editing. **Marion Leboyer:** Conceptualization, Data curation, Supervision. **Michele Santacatterina:** Conceptualization, Data curation, Methodology, Writing – original draft. **Fumika Ando:** Writing – original draft, Writing – review & editing. **Gillian Capichioni:** Writing – original draft, Writing – review & editing. **Thomas E. Smith:** Data curation, Writing – review & editing. **Jamie Kammer:** Data curation, Investigation, Writing – review & editing. **Kawtar El Abdellati:** Conceptualization, Data curation, Investigation, Methodology, Project administration. **Manuel Morrens:**

Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing. **Violette Coppens:** Data curation, Funding acquisition, Methodology, Project administration, Resources. **Emily Katsafanas:** Investigation, Project administration, Supervision. **Andrea Origoni:** Data curation. **Sabahat Khan:** Investigation. **Kelly Rowe:** Investigation. **R.Sarah Ziemann:** Investigation. **Ryad Tamouza:** Investigation, Writing – review & editing. **Robert H. Yolken:** Conceptualization, Data curation, Investigation, Methodology, Writing – review & editing. **Donald C. Goff:** Conceptualization, Methodology, Resources, Supervision, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.bbih.2024.100802.

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