The Protective Effect of Coronavirus Disease 2019 (COVID-19) Vaccination on Postacute Sequelae of COVID-19: A Multicenter Study From a Large National Health Research Network

Sokratis N. Zisis,1 Jared C. Durieux,2 Christian Mouchati,1 Jamie A. Perez,2 and Grace A. McComsey1,2,3,

1School of Medicine, Case Western Reserve University, Cleveland, Ohio, USA, 2Clinical Research Center, University Hospitals Health System, Cleveland, Ohio, USA, and 3Department of Pediatrics and Medicine, Case Western Reserve University, Cleveland, Ohio, USA

Background. Coronavirus disease 2019 (COVID-19) vaccines have been proven to decrease the severity of acute-phase infection; however, little is known about their effect on postacute sequelae of COVID-19 (PASC).

Methods. Patients with confirmed COVID-19 diagnosis and minimum age of 18 years with 3-month follow-up postdiagnosis between 21 September 2020 and 14 December 2021 were identified from the TriNetX Research Network platform. The primary outcomes consisted of new-onset or persistent symptoms, new-onset diagnoses, and death and were compared between vaccine and no-vaccine groups.

Results. At baseline, 1,578,719 patients with confirmed COVID-19 were identified and 1.6% (n = 25,225) completed vaccination. After matching, there were no differences (P > .05) in demographics or preexisting comorbidities. At 28 days following COVID-19 diagnosis, the incidence of hypertension was 13.52 per 1000, diabetes was 5.98 per 1000, thyroid disease was 3.80 per 1000, heart disease was 15.41 per 1000, and mental disorders was 14.77 per 1000 in the vaccine cohort. At 90 days following COVID-19 diagnosis, the relative risk of hypertension was 0.33 (95% confidence interval [CI], 0.26–0.42), diabetes was 0.28 (95% CI, 0.20–0.38), heart disease was 0.35 (95% CI, 0.29–0.44), and death was 0.21 (95% CI, 0.16–0.27). Differences in both 28- and 90-day risk between the vaccine and no-vaccine cohorts were observed for each outcome, and there was enough evidence (P < .05) to suggest that these differences were attributed to the vaccine.

Conclusions. Our data suggest that COVID-19 vaccine is protective against PASC symptoms, new onset of health conditions, and mortality.

Keywords. COVID-19 vaccination; long COVID; PASC; postacute sequelae of COVID-19.

With >312 million infections and >5 million deaths reported globally as of 12 January 2022, the coronavirus disease 2019 (COVID-19) pandemic is still an unresolved crisis that is affecting the healthcare system worldwide [1]. Despite mitigation efforts, COVID-19 is affecting the health of patients suffering from the persistence or emergence of new symptoms and multiple complications after recovery, termed postacute sequelae of COVID-19 (PASC) [2].

PASC manifests in a wide range of persistent or new symptoms that do not resolve for many months [3–5]. Up to 70% of recovered patients report fatigue, persistent loss of taste or smell, shortness of breath, cough, headache, pain, and a wide array of serious complications affecting the cardiovascular, pulmonary, renal, endocrinological, and neurological systems [2, 6–11].

To face the pandemic, major international entities have set vaccination as their top priority [12]. Worldwide, >9 billion vaccines doses have been administered as of 12 January 2022 [1]. Immunization is effective in preventing infection [13] and decreasing its severity [14]. However, there are only a few studies that have assessed the effect of COVID-19 vaccination on the long-term sequelae of the disease [15].

In this study, using TriNetX, a large national health research network that relies on data from multiple centers across the United States, we aimed to analyze the effect of immunization on postacute sequelae of COVID-19.

METHODS

Data Collection and Definitions

We used the TriNetX database to conduct a retrospective study of adult patients aged ≥18 years with SARS-CoV-2 infection (confirmed by polymerase chain reaction) who sought care in the United States from 21 September 2020 to 14 December 2021.
The de-identified patients’ data included in this analysis belong to the TriNetX Research Network platform, a network of electronic medical records (EMRs) from 57 healthcare organizations currently involving >70 million patients across the United States.

We collected patients’ demographics, comorbidities, and COVID-19 vaccination, as well as symptoms and diagnoses prior to, at the time of, and after 3 months of SARS-CoV-2 infection. We stratified COVID-19 patients into 2 groups: (1) vaccinated patients with breakthrough infection and (2) unvaccinated patients. PASC was defined as new, continuing, or recurrent symptoms that occur 4 or more weeks after the initial SARS-CoV-2 infection; baseline comorbidities were used for matching. For the vaccinated cohort, patients diagnosed with COVID-19 after at least a week of administration of the complete vaccine were included. The primary outcomes consisted of new-onset or persistent symptoms, new-onset diagnoses, and death and were compared between the vaccine and no-vaccine groups. Data extraction and analysis were performed using a list of International Classification of Diseases, 10th Revision codes (detailed in the Supplementary Materials).

### Statistical Analysis
Characteristics of patients were described using mean ± standard deviation for continuous variables and frequency and percentage for categorical variables (Table 1). Differences between vaccine and no-vaccine groups were calculated using independent t test or χ² test. Propensity score matching (1:1) using greedy nearest-neighbor method was used to balance the 2 cohorts on age, sex, race, and comorbidities. Incidence, relative risk (RR), and attributable risk (risk difference) estimates along with 95% confidence intervals (CIs) were used as measures of risk at 28 days (Table 2) and 90 days (Table 3) following COVID-19 diagnosis. Rates were presented per 1000 and P values (α) < .05 were considered statistically significant.

### RESULTS
At baseline, 1,578,719 patients with confirmed COVID-19 were identified and 1.6% (n = 25,225) had documented COVID-19 vaccination. Among the vaccine cohort, the average age was 54.82 ± 17.77 years, 59.84% (n = 15,094) were female, and 68.45% (n = 17,266) were white. The average body mass index (BMI) was 30.20 ± 7.33 kg/m²; 47.36% (n = 11,947) had

### Table 1. Baseline Characteristics of Coronavirus Disease 2019 Patients and Vaccine Status Before and After Propensity Score Matching

| Characteristic                  | Before Matching          | After Matching           |
|--------------------------------|--------------------------|--------------------------|
|                                | Vaccine + COVID-19 (n = 25,225) | No-Vaccine + COVID-19 (n = 1,553,494) | P Value | Vaccine + COVID-19 (n = 25,225) | No-Vaccine + COVID-19 (n = 25,225) | P Value |
| Age, y, mean ± SD              | 54.82 ± 17.77            | 42.91 ± 21.84            | <.0001  | 54.82 ± 17.77            | 55.06 ± 17.96            | .13     |
|                                |                          |                          |         |                          |                          |         |
| Sex                            | Female                   | 15,094 (59.84)           | 870,301 (56.02) | <.0001 | 15,094 (59.84)           | 15,129 (59.98)           | .75     |
|                                | Male                     | 10,130 (40.16)           | 682,700 (43.95) | <.0001 | 10,130 (40.16)           | 10,095 (40.02)           | .75     |
|                                | Unknown                  | 10 (0.04)                | 493 (0.03) | .49 | 10 (0.04)                | 10 (0.04)                | 1.00     |
| Race                           | Black/African American   | 4907 (19.45)             | 287,241 (18.49) | <.0001 | 4907 (19.45)             | 4853 (19.24)             | .54     |
|                                | White                    | 17,266 (68.45)           | 965,166 (62.13) | <.0001 | 17,266 (68.45)           | 17,381 (68.90)           | .27     |
|                                | Asian                    | 860 (3.41)               | 31,290 (2.01)  | <.0001 | 860 (3.41)               | 874 (3.47)               | .73     |
|                                | American Indian/Alaska Native | 159 (0.63)       | 616,613 (0.4)   | <.0001 | 159 (0.63)               | 126 (0.50)               | .05     |
|                                | Native Hawaiian/Pacific Islander | 41 (0.16)       | 2367 (0.15)    | .66 | 41 (0.16)               | 47 (0.19)               | .52     |
|                                | Unknown                  | 1992 (7.90)             | 261,277 (16.82) | <.0001 | 1992 (7.90)             | 1944 (7.71)             | .43     |
| Comorbidities                  | Hypertension             | 11,947 (47.36)           | 435,700 (28.16) | <.0001 | 11,947 (47.36)           | 11,963 (47.43)           | .89     |
|                                | Neoplasm                 | 9487 (37.61)             | 298,980 (19.25) | <.0001 | 9487 (37.61)             | 9533 (37.79)             | .67     |
|                                | Diabetes mellitus        | 5774 (22.89)             | 214,891 (13.83) | <.0001 | 5774 (22.89)             | 5698 (22.59)             | .42     |
|                                | Asthma                   | 3818 (15.14)             | 181,145 (11.66) | <.0001 | 3818 (15.14)             | 3678 (14.58)             | .08     |
|                                | Atherosclerosis          | 3464 (13.73)             | 106,862 (6.88)  | <.0001 | 3464 (13.73)             | 3314 (13.14)             | .05     |
|                                | CKD                      | 3210 (12.73)             | 98,199 (6.32)   | <.0001 | 3210 (12.73)             | 3097 (12.18)             | .13     |
|                                | COPD                     | 1981 (7.85)              | 70,746 (4.55)   | <.0001 | 1981 (7.85)              | 1879 (7.45)              | .09     |
|                                | Transplanted organ and tissue status | 1218 (4.83) | 20,323 (1.31) | <.0001 | 1218 (4.83) | 1051 (4.17) | .0003 |
|                                | HIV                      | 209 (0.83)               | 6063 (0.39)     | <.0001 | 209 (0.83)               | 152 (0.60)               | .003    |
|                                | BMI, kg/m², mean ± SD    | 30.20 ± 7.33             | 29.16 ± 8.12    | <.0001 | 30.20 ± 7.33             | 30.68 ± 7.40             | .98     |

Data are presented as No. (%) unless otherwise indicated. Abbreviations: BMI, body mass index; CKD, chronic kidney disease; COPD, chronic obstructive pulmonary disease; COVID-19, coronavirus disease 2019; HIV, human immunodeficiency virus; SD, standard deviation.
hypertension (HTN), 22.89% (n = 5774) had diabetes mellitus (DM), and 12.73% (n = 3210) had chronic kidney disease (CKD). Among the no-vaccine cohort, the average age was 42.91 ± 21.84 years, 56.02% (n = 870301) were female, and 62.13% (n = 965566) were white. The average BMI was 29.16 ± 8.12 kg/m²; 28.16% (n = 435700) had HTN, 19.25% (n = 298980) had DM, and 6.32% (n = 98199) had CKD. After matching, there were no differences in age (P = .13), sex (P = .75), race or ethnicity (P > .05), BMI (P = .98), HTN (P = .89), DM (P = .42), or CKD (P = .13).

At 28 days following COVID-19 diagnosis (Table 2), the risk of new or persistent outcomes in the vaccine cohort was less than the risk in the no-vaccine cohort for each outcome. In the vaccine cohort, the incidence of HTN was 13.52 per 1000, DM was 5.98 per 1000, thyroid disease was 3.80 per 1000, heart disease was 15.41 per 1000, and mental disorders was 14.77 per 1000. The estimated probability (RR) of HTN was 0.45 (95% CI, .38–.54), DM was 0.43 (95% CI, .35–.54), heart disease was 0.49 (95% CI, .43–.57), and death was 0.33 (95% CI, .28–.39). The RR for respiratory symptoms (0.70 [95% CI, .67–.74]),
headache (0.56 [95% CI, .50–.63]), fatigue (0.65 [95% CI, .61–.70]), body ache (0.50 [95% CI, .42–.57]), and diarrhea or constipation (0.60 [95% CI, .55–.65]) was also <1.0.

At 90 days following COVID-19 diagnosis (Table 3), the incidence of HTN was 6.42 per 1000, DM was 2.69 per 1000, thyroid disease was 1.53 per 1000, heart disease was 7.19 per 1000, and mental disorders was 6.45 per 1000. The RR of HTN was 0.33 (95% CI, .26–.42), DM was 0.28 (95% CI, .20–.38), heart disease was 0.35 (95% CI, .29–.44), and death was 0.21 (95% CI, .16–.27). Decreases in RR were also observed in respiratory symptoms (0.54 [95% CI, .50–.57]), headache (0.39 [95% CI, .34–.45]), fatigue (0.48 [95% CI, .43–.52]), body ache (0.34 [95% CI, .28–.42]), and diarrhea or constipation (0.44 [95% CI, .40–.49]). Differences in both 28- and 90-day risk between the vaccine and no-vaccine cohorts were observed for each outcome and there was enough evidence (P < .05) to suggest that these differences were attributed to the vaccine.

**DISCUSSION**

In our study using real-time EMR data from a large national health network, we demonstrated that the vaccine was protective (ie, RR <1.0) against mortality and each incident PASC outcome and that having the vaccine is associated with a significantly lower likelihood of experiencing new or persistent PASC symptoms. This suggests that patients with COVID-19 who are not vaccinated are at greater risk of death and incident morbidity during the 90 days postinfection. In this study with data from a large-scale EHR network, we showed that individuals with COVID-19 breakthrough infections after vaccination have lower rates of PASC (or “long COVID”) symptoms/outcomes compared with propensity-matched unvaccinated COVID-19–infected people. As such, our work extends the current data on the efficacy of COVID-19 vaccination in acute COVID-19, to show that vaccination is associated with faster and better COVID-19 recovery.

In our study, vaccination against COVID-19 is associated with a lower risk of outcomes that have not been assessed in previous studies—namely, new-onset diseases including hypertension, diabetes, malignant neoplasms, heart and thyroid diseases, hypercoagulopathy or venous thromboembolism, and mental disorders, or new-onset symptoms known to be part of long COVID syndrome such as headaches, fatigue, body aches, and respiratory and gastrointestinal symptoms. We also found significant differences in postacute COVID-19 mortality rates between vaccinated and unvaccinated SARS-CoV-2–infected patients. These findings are in line with previously published data, suggesting a potential implication of immunizations in preventing the development of chronic COVID-19 symptoms [15].

The etiologic and pathophysiologic mechanisms behind PASC are not clear and the effects of vaccination status on it, in particular, are totally unclear. It is thought that factors from the acute phase such as endotheliopathy, antigen-antibody reactions, and the ability of the virus to initiate an immense inflammatory response may trigger the secondary responses in the body [16, 17]. Although previous studies have shown that immunizations are highly effective at preventing severe acute COVID-19–associated outcomes; little is known about the effect of vaccination on postacute outcomes of COVID-19 [17, 18]. However, we hypothesize that its effect on reducing the inflammatory responses during the acute phase does also explain the lower rates of all PASC outcomes observed in our study among the vaccinated group.

Moreover, it should be noted that we very carefully captured new outcomes (eg, HTN, cardiovascular disease, DM) that occurred after SARS-CoV-2 infection and not any preexisting medical conditions. On that, COVID-19 has been associated with new-onset hyperglycemia and acute decompensation of diabetes [19]. Besides drug-induced hyperglycemia from steroid use, proposed mechanisms for hyperglycemia after infection include insulin resistance as a result of the inflammatory state and insulin secretory deficits from impaired β-cell function [19, 20]. However, it is unclear whether new-onset diabetes following hospitalization for COVID-19 is permanent [19]. Markedly, even new-onset hypertension has been suggested by a study as a possible sequela of COVID-19. In particular, an enhanced angiotensin II signaling, driven by SARS-CoV-2 infection, is thought to play an important role in the renin-angiotensin system, leading to the development of hypertension in COVID-19 [21]. Nonetheless, we cannot rule out that these individuals were already predisposed to these conditions and that SARS-CoV-2 infection somehow accelerated the development of these conditions.

Apart from the above-mentioned lack of understanding in the pathophysiology of PASC, detailing the predictors of it is also essential but still unknown. Only a few studies have previously tackled the subject, with most of them revealing that long-term unfavorable outcomes (ie, PASC symptoms) were significantly more frequent in women, those with longer hospital stays, those who required intensive care unit admissions, and those with higher symptom load in the acute phase [21, 22]. Furthermore, findings of another study suggest that moderate and severe obesity (BMI ≥35 kg/m²) is associated with a greater risk of PASC. This observation can be explained not only by the underlying mechanisms of obesity, including obesity-related hyperinflammation, immune dysfunction, and comorbidities, but also the higher healthcare utilization by this portion of the population, which increases the chances of detecting and reporting any long-term complaints [23–30]. Moreover, it should be mentioned that we included post–COVID-19 follow-up results no later than 14 December 2021 to avoid the new SARS-CoV-2 variants such as Omicron, which might affect the protective effect of vaccines, since there is evidence that
variants of concerns are overrepresented in breakthrough infections [31]. Last but not least, it is possible that vaccination status was underreported in TriNetX and that a proportion of patients in the no-vaccine group may have been vaccinated. This observation would suggest that the protective effects of COVID-19 vaccine on PASC in our study may be underestimated and the true estimated decreased risk among vaccinated patients is greater than what we reported.

Despite the novelty of our findings, our study has several limitations. First, there are some inherent limitations when EHRs are used to capture data. For instance, since the data are presented as they are recorded, we cannot be sure that there has not been mis-recording of information. Second, the true prevalence of PASC among COVID-19 patients is still unknown as many asymptomatic patients have never been tested. Third, we cannot rule out the possibility that immunization status affects the probability to seek or receive medical attention, particularly for less severe outcomes. Fourth, this study is not informative on outcomes in patients infected with SARS-CoV-2 but who did not get tested nor diagnosed with COVID-19. Additionally, our vaccination rate is low and we cannot rule out that EMR documentation of vaccination may have been missed in some of the vaccinated individuals. Another potential limitation is that capturing the location where patients were seen and the difference between healthcare utilization among the 2 groups based on their concurrent morbidities, which might provide another potential explanation for the post–COVID-19 outcomes that we have described, is beyond the capacity of this database. Finally, being an observational study, causation cannot be inferred.

In summary, the present data show that prior vaccination against COVID-19 is associated with significantly lower risk of postacute COVID-19 symptoms or new onset of health conditions, referred to collectively as PASC or long COVID. These findings may raise awareness to public health on the importance of vaccination programs, by highlighting the urgent need for vaccination to prevent the long-term sequelae of COVID-19.

Supplementary Data
Supplementary materials are available at Open Forum Infectious Diseases online. Consisting of data provided by the authors to benefit the reader, the posted materials are not copypedited and are the sole responsibility of the authors, so questions or comments should be addressed to the corresponding author.

Acknowledgments
Author contributions. S. N. Z., J. C. D., C. M., J. A. P., and G. A. M. contributed to study concept and design. All authors contributed to acquisition of data. J. C. D., J. A. P., and G. A. M. contributed to analysis and interpretation of data. J. C. D. and J. A. P. contributed to statistical analysis. G. A. M. obtained funding and supervised the study. S. N. Z. and C. M. contributed to administrative, technical, or material support. S. N. Z., J. C. D., C. M., and G. A. M. drafted the manuscript, and all authors contributed to critical revision of the manuscript for important intellectual content.

Disclaimer. The contents are solely the responsibility of the authors and do not necessarily represent the official views of University Hospitals Cleveland Medical Center or the National Institutes of Health (NIH).

Financial support. This publication was made possible through funding support from the Clinical and Translational Science Collaborative of Cleveland (award number UL1TR002548), from the National Center for Advancing Translational Sciences component of the NIH and NIH Roadmap for Medical Research.

Potential conflicts of interest. G. A. M. has received grant support from Viiv, Tetraphase, Roche, Vanda, Astellas, and Genentech, and has served as a scientific advisor for Gilead, Merck, Viiv/GSK, Theratechnologies, and Janssen. All other authors report no potential conflicts of interest.

All authors have submitted the ICMJE Form for Disclosure of Potential Conflicts of Interest. Conflicts that the editors consider relevant to the content of the manuscript have been disclosed.

References
1. World Health Organization. WHO coronavirus (COVID-19) dashboard with vaccination data. https://covid19.who.int/. Accessed 12 January 2022.
2. Nalbandian A, Sehgal K, Gupta A, et al. Post-acute COVID-19 syndrome. Nat Med 2021; 27:601–15.
3. Carli A, Bernabei R, Landi F. Persistent symptoms in patients after acute COVID-19. JAMA 2020; 324:603–5.
4. Davis HE, Assaf GS, McCorkell L, et al. Characterizing long COVID in an international cohort: 7 months of symptoms and their impact. EClinicalMedicine 2021; 38:101019.
5. Huang C, Wang Y, Li X, et al. Clinical features of patients infected with 2019 novel coronavirus in Wuhan, China. Lancet 2020; 395:497–506.
6. Nasseerie T, Hittle M, Goodman SN. Assessment of the frequency and variety of persistent symptoms among patients with COVID-19: a systematic review. JAMA Netw Open 2021; 4:e2111417.
7. Kamal M, Abo Omarah M, Hussein A, Sareed H. Assessment and characterisation of post-COVID-19 manifestations. Int J Clin Pract 2021; 75:e13746.
8. Türktaş H, Oğuzülgen K. Post-COVID-19 pulmonary sequela: longterm follow up and management [in Turkish]. Tüberk Toraks 2020; 68:419–29.
9. Asly M, Hazim A. Rehabilitation of post-COVID-19 patients. Pan Afr Med J 2020; 36:1–3.
10. Davido B, Seang S, Barizien N, Tubiana R, de Truchis P. Post-COVID-19 chronic symptoms—author’s reply. Clin Microbiol Infect 2021; 27:495–6.
11. Wijeratne T, Grewther S. Post-COVID-19 neurological syndrome (PCNS): a novel syndrome with challenges for the global neurology community. J Neurol Sci 2020; 419:117197.
12. United Nations News. COVID ‘Shot for All’, not a luxury, but development priority. 2021. https://news.un.org/en/story/2021/09/1100552. Accessed 12 January 2022.
13. Polack FP, Thomas SJ, Kitchin N, et al. Safety and efficacy of the BNT162b2 mRNA Covid-19 vaccine. N Engl J Med 2020; 383:2603–15.
14. Yek C, Warner S, Wiltz JL, et al. Risk factors for severe COVID-19 outcomes among persons aged ≥18 years who completed a primary COVID-19 vaccination series—465 health care facilities, United States, December 2020–October 2021. MMWR Morb Mortal Wkly Rep 2022; 71:19–25.
15. Mahase E. Covid-19: vaccinated people are less likely to get long covid, review finds. BMJ 2022; 376:e10407.
16. Sudre CH, Murray B, Varsavsky T, et al. Attributes and predictors of long COVID. Nat Med 2021; 27:626–31.
17. Zhao Y-M, Shang Y-M, Song W-B, et al. Follow-up study of the pulmonary function and related physiological characteristics of COVID-19 survivors three months after recovery. EClinicalMedicine 2020; 25:100463.
18. Agrawal U, Katikireddi SV, McCowan C, et al. COVID-19 hospital admissions and deaths after BNT162b2 and ChAdOx1 nCoV-19 vaccinations in 2.57 million
people in Scotland (EAVE II): a prospective cohort study. *Lancet Respir Med* 2021; 9:1439–49.

19. Rubino F, Amiel SA, Zimmet P, et al. New-onset diabetes in Covid-19. *N Engl J Med* 2020; 383:789–90.

20. Paquot N, Radermecker RP. COVID-19 and diabetes. *Annu Rev Med* 2021; 75: 138–45.

21. Chen G, Li X, Gong Z, et al. Hypertension as a sequela in patients of SARS-CoV-2 infection. *PLoS One* 2021; 16:e0250815.

22. Asadi-Pooya AA, Akbari A, Emami A, et al. Risk factors associated with long COVID syndrome: a retrospective study. *Iran J Med Sci* 2021; 46:428–36.

23. Aminian A, Bena J, Pantalone KM, Burguera B. Association of obesity with post-acute sequelae of COVID-19. *Diabetes Obes Metab* 2021; 23:2183–8.

24. Popkin BM, Du S, Green WD, et al. Individuals with obesity and COVID-19: a global perspective on the epidemiology and biological relationships. *Obes Rev* 2020; 21:e13128.

25. Stefan N, Birkenfeld AL, Schulze MB. Global pandemics interconnected—obesity, impaired metabolic health and COVID-19. *Nat Rev Endocrinol* 2021; 17: 135–49.

26. Huang HK, Bukhari K, Peng CCH, et al. The J-shaped relationship between body mass index and mortality in patients with COVID-19: a dose-response meta-analysis. *Diabetes Obes Metab* 2021; 23:1701–9.

27. Gardiner J, Oben J, Sutcliffe A. Obesity as a driver of international differences in COVID-19 death rates. *Diabetes Obes Metab* 2021; 23:1463–70.

28. Smati S, Tramunt B, Wargny M, et al. Relationship between obesity and severe COVID-19 outcomes in patients with type 2 diabetes: results from the CORONADO study. *Diabetes Obes Metab* 2021; 23:391–403.

29. Peters SAE, MacMahon S, Woodward M. Obesity as a risk factor for COVID-19 mortality in women and men in the UK biobank: comparisons with influenza/pneumonia and coronary heart disease. *Diabetes Obes Metab* 2021; 23:258–62.

30. Luo X, Jiaerken Y, Shen Z, et al. Obese COVID-19 patients show more severe pneumonia lesions on CT chest imaging. *Diabetes Obes Metab* 2021; 23: 290–3.

31. McEwen AE, Cohen S, Beyson-Cahn C, et al. Variants of concern are overrepresented among post-vaccination breakthrough infections of SARS-CoV-2 in Washington State. *Clin Infect Dis* 2021; 74:1089–92.