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Describing the population experiencing COVID-19 vaccine breakthrough following second vaccination in England: A cohort study from OpenSAFELY

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Abstract:	Background While the vaccines against COVID-19 are highly effective, COVID-19 vaccine breakthrough is possible despite being fully vaccinated. With SARS-CoV-2 variants still circulating, describing the characteristics of individuals who have experienced COVID-19 vaccine breakthroughs could be hugely important in helping to determine who may be at greatest risk. Methods With the approval of NHS England we conducted a retrospective cohort study using routine clinical data from the OpenSAFELY-TPP database of fully vaccinated individuals, linked to secondary care and death registry data, and described the characteristics of those experiencing COVID-19 vaccine breakthroughs. Results As of 01 st November 2021, a total of 15,501,550 individuals were identified as being fully vaccinated against COVID-19, with a median follow-up time of 149 days (IQR: 107-179). From within this population, a total of 579,780 (<4%) individuals reported a positive SARS-CoV-2 test. For every 1,000 years of patient follow-up time, the corresponding incidence rate (IR) was 98.06 (95% CI 97.93-98.19). There were 28,580 COVID-19-related hospital admissions, 1,980 COVID-19-related critical care admissions and 6,435 COVID-19-related deaths; corresponding IRs 4.77 (95% CI 4.74-4.80), 0.33 (95% CI 0.32-0.34) and 1.07 (95% CI 1.06-1.09), respectively. The highest rates of breakthrough COVID-19 were seen in those in care homes and in patients with chronic kidney disease, dialysis, transplant, haematological malignancy or who were immunocompromised. Conclusion While the majority of COVID-19 vaccine breakthrough cases in England were mild, some differences in rates of breakthrough cases have been identified in several clinical groups. While it is important to note that these findings are simply descriptive and cannot be used to answer why certain groups have higher rates of COVID-19 breakthrough than others, the emergence of the Omicron variant of COVID-19 coupled with the number of positive SARS-CoV-2 tests still occurring is concerning and as numbers of fully vaccinated (and boosted) individuals increases and as follow-up time lengthens, so too will the number of COVID-19 breakthrough cases. Additional analyses, to assess vaccine waning and rates of breakthrough COVID-19 between different variants, aimed at identifying individuals at higher risk, are needed.
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Response to Reviewers:	Please note, when uploading our files we were unable to upload our revised manuscript as the *manuscript type as when uploaded as a file of this type, the file type become blank and the only options were table/figure/supplementary. So in order to submit our revision we had to include the old manuscript. We hope this does not include any confusion. Re: Describing the population experiencing COVID-19 vaccine breakthrough following second vaccination in England: A cohort study from OpenSAFELY 4th March 2022 Dear Dr. Lucy Dunbar, We would like to thank BMC Medicine for considering our proposal, and thank the reviewers for their informed and helpful comments. We are pleased to re-submit the manuscript (number BMED-D-21-02626) entitled “Describing the population experiencing COVID-19 vaccine breakthrough following second vaccination in England: A cohort study from OpenSAFELY” for consideration as a Research Article in BMC Medicine. We would also like to extend our sincere gratitude to the Reviewers for their positive and constructive feedback. We have carefully reviewed the reviewers’ comments and provide point-by-point responses to their comments (document attached), describing exactly what amendments have been made to the manuscript text and where these can be viewed. As a result of increasing the follow-up time (as per the reviewers suggestions) we have updated all corresponding tables, figures and numbers in the text accordingly and also added in a few additions to the discussions to reflect on this increased follow-up, these changes are detailed below, after our replies to the reviewers comments. With the increase in the numbers of outcomes, we have been able to include an additional outcome which was previously not included due to small numbers; COVID-19 related critical care admission. In addition, to help inform decisions around rollout of vaccine/booster programmes for patients at high risk of adverse outcomes we have separated out chronic kidney disease from dialysis and transplant. All changes to the manuscript are indicated in the text by yellow highlights. Due to the longer follow-up time, as expected, there has been a rise in all rates (calculated per 1000 person-years); Positive SARS-CoV-2 test from 12.33 (12.14-12.51) to 98.06 (95% CI 97.93-98.19); COVID related hospitalisation from 0.70 (0.65-0.74) to 2.31 4.77 (4.74-4.8); COVID related death from 0.12 (0.1-0.14) to 0.64 1.07 (1.06-1.09). But reassuringly, breakthrough cases seem to be remaining mild; 579,780 Positive SARS-CoV-2 tests vs 6,435 COVID-19 related deaths, with the majority (~80%) of deaths occurring in those over 70 years of age. We believe that the revised manuscript is now improved and has addressed all reviewer comments – with textual changes, and more detailed explanations of our methods and assumptions. Our manuscript continues to have important findings which we believe will be of great interest to the general medical community Thank you again for your consideration. Yours Sincerely, Amelia Green and Ben Goldacre, on behalf of the OpenSAFELY collaborative.

Describing the population experiencing COVID-19 vaccine breakthrough following second vaccination in England: A cohort study from OpenSAFELY

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Abstract

Background

While the vaccines against COVID-19 are considered to be highly effective, COVID-19 vaccine breakthrough is likely and a small number of people will still fall ill, be hospitalised, or die from COVID-19, despite being fully vaccinated. With the continued increase in numbers of positive SARS-CoV-2 tests, describing the characters of individuals who have experienced a COVID-19 vaccine breakthrough could be hugely important in helping to determine who may be at greatest risk.

Method

With the approval of NHS England we conducted a retrospective cohort study using routine clinical data from the OpenSAFELY TPP database of fully vaccinated individuals, linked to secondary care and death registry data, and described the characteristics of those experiencing a COVID-19 vaccine breakthrough.

Results

As of 30th June 2021, a total of 10,782,870 individuals were identified as being fully vaccinated against COVID-19, with a median follow-up time of 43 days (IQR: 23-64). From within this population, a total of 16,815 (0.1%) individuals reported a positive SARS-CoV-2 test. For every 1000 years of patient follow-up time, the corresponding incidence rate was 12.33 (95% CI 12.14-12.51). There were 955 COVID-19 hospital admissions and 145 COVID-19-related deaths; corresponding incidence rates of 0.70 (95% CI 0.65-0.74) and 0.12 (95% CI 0.1-0.14), respectively. When broken down by the initial priority group, higher rates of hospitalisation and death were seen in those in care homes. Comorbidities with the highest rates of breakthrough COVID-19 included renal replacement therapy, organ transplant, haematological malignancy, and immunocompromised.

Conclusion

The majority of COVID-19 vaccine breakthrough cases in England were mild with relatively few fully vaccinated individuals being hospitalised or dying as a result. However, some concerning differences in rates of breakthrough cases were identified in several clinical and demographic groups. While it is important to note that these findings are simply descriptive and cannot be used to answer why certain groups have higher rates of COVID-19 breakthrough than others, the continued increase in numbers of positive SARS-CoV-2 tests are concerning and, as numbers of fully vaccinated individuals increases and follow-up time lengthens, so too will the number of COVID-19 breakthrough cases. Additional analyses, aimed at identifying individuals at higher risk, are therefore required.

Keywords

COVID-19; Vaccine breakthrough; EHR data

Background

The vaccination programme for COVID-19 in the United Kingdom (UK) was started on 8 December 2020. Initially, the recipients of COVID-19 vaccines included those in care homes, those over 80 years old and frontline health and social care workers. Those aged ≥70 years or clinically extremely vulnerable were the next priority group, followed by remaining adults in order of decreasing age or at increased risk. As of September 1st, 2021 75.2% of individuals aged over 16 in England have been fully vaccinated (i.e., ≥14 days have passed since the receipt of their second dose of a COVID-19 vaccine) [1].

The vaccines against COVID-19 are considered to be highly effective and there is clear evidence that the UK's COVID-19 vaccination programme has reduced infection and severe outcomes in vaccinated individuals [2, 3]. However, as no vaccine is 100% effective, COVID-19 vaccine breakthrough is likely (i.e., a small number of people will still get sick, be hospitalised, or die from COVID-19, despite being fully vaccinated). Describing individuals who have experienced a COVID-19 vaccine breakthrough could provide the first indication that the COVID-19 vaccine is less effective in certain demographic groups and could be hugely important in helping to determine who may be at greatest risk and therefore might benefit most from booster doses of vaccine.

To that end we used the new secure data analytics platform, OpenSAFELY [4] (built by our group on behalf of NHS England to support analysis of important questions related to COVID-19) to: describe breakthrough COVID-19 among fully vaccinated individuals in England; and to describe how breakthrough COVID-19 varied between priority groups and by clinical and demographic characteristics.

Methods

Data sources

This OpenSAFELY study was conducted using the OpenSAFELY-TPP database which contains records for approximately 24 million people currently registered with GP surgeries using TPP SystmOne software (approximately 40% of the English population).

Study population

The base population consisted of all individuals aged 16 or over with records indicating that they had received two COVID-19 vaccination doses since 8 December 2020 (the earliest vaccination date in England) and who were still alive and registered 2 weeks after their second dose. Individuals were excluded if they tested positive for SARS-CoV-2 or had been hospitalised or died due to COVID-19 within the 2 weeks after their second dose. Follow up started 14 days after an individual's second dose of the COVID-19 vaccination (the point by which individuals were classified as being fully vaccinated) and individuals were followed up until 30th June 2021 (the latest date for which data were available at the time of the analysis) or until the first occurrence of: the outcome of interest; death; practice de-registration.

Outcomes

Three outcomes were assessed: positive SARS-CoV-2 swab test, via SGSS and based on swab date (we did not distinguish between symptomatic and asymptomatic infection for this outcome, nor PCR and lateral flow testing); COVID-19 hospital admissions via HES in-patient records (using both primary and non-primary diagnosis codes); and COVID-19-related death, via linked death registry records, which included individuals who died within 28-days of positive SARS-CoV-2 test or who had COVID-19 mentioned on the death certificate as one of the causes. COVID-19 hospitalisation variables were derived using ICD-10 COVID-19 diagnosis codes [5]. Outcomes were only included if they occurred 14 days or more after an individual's second dose of a COVID-19 vaccination.

Priority groups for vaccination

Individuals were classified into seven priority groups (box 1), based on the Joint Committee on Vaccination and Immunisation (JCVI) priority groups [6] using SNOMED-CT codelists and logic defined in the national COVID-19 Vaccination Uptake Reporting Specification developed by PRIMIS [7]. Individuals were assigned only to their highest priority group and not included again as part of any other priority group. In line with the national reporting specification, most criteria were ascertained using the latest available data at the time of analysis, with the exception of age which was calculated as at 31 March 2021 as recommended by Public Health England.

Box 1 – ***Priority groups for vaccination.***

JCVI Risk group	Priority group	
	Description	**Name**
1	Residents in a care home for older adults, aged 65+	Care home
2	All those 80 years of age and over	80+
	Health and social care workers	Health/Care workers
3	All those 70 years of age and over	70-79
4	Clinically extremely vulnerable individuals	CEV
5,7,8,9	All those 50 years of age and over	50-69
6	“At Risk” individuals, some misclassified health/care workers and care home residents (except those age 70+ or shielding who will be included in another group), carers, household contacts of those at increased risk, and those not in priority groups who had the vaccine opportunistically, e.g. by responding to calls to use up excess doses.	Others not in the above groups

Key demographic and clinical characteristics

Key clinical and demographic groups which were considered to have a higher possibility of experiencing a COVID-19 vaccine breakthrough were identified from previous studies [8–12]. This included age, sex, body mass index (BMI; kg/m^2), smoking status, deprivation

(measured by the Index of Multiple Deprivation (IMD) as quintiles, ethnicity, NHS region of patient's general practice, asthma, asplenia, blood pressure, cancer, diabetes mellitus, heart disease, haematological malignancy, immunocompromised, kidney disease, learning disability, liver disease, neurological diseases, respiratory disease, renal replacement therapy, severe mental illness and organ transplant. Other variables considered were time since being fully vaccinated, time between vaccinations and any evidence of a prior SARS-CoV-2 infection.

Codelists and implementation

Information on all covariates were obtained from primary care records by searching TPP SystmOne records for specific coded data. Detailed information on compilation and sources for every individual codelist is available at https://codelists.opensafely.org/ and the lists are available for inspection and re-use by the broader research community.

Missing data

Individuals with missing ethnicity, IMD and region were included as "Unknown".

Statistical methods

Simple descriptive statistics were used to summarise the counts and rates of COVID-19 vaccine breakthrough. Rates for each outcome were estimated by dividing the count by person-years, with 95% confidence intervals. Counts and rates were stratified by initial priority groups for all outcomes and by selected clinical and demographic groups.

Software and Reproducibility

Data management and analysis was performed using the OpenSAFELY software libraries, Python 3 and R version 4.0.2. All code for the OpenSAFELY platform for data management, analysis and secure code execution is shared for review and re-use under open licenses at GitHub.com/OpenSAFELY. All code for data management and analysis for this paper is shared for scientific review and re-use under open licenses on GitHub (https://github.com/opensafely/covid-19-vaccine-breakthrough).

Patient and Public Involvement

Any patient or member of the public is invited to contact us at https://opensafely.org/ regarding this study or the broader OpenSAFELY project.

Results

Study population

Out of approximately 24m patients, 10,782,870 individuals were identified as being fully vaccinated against COVID-19 and included in this study (Figure 1). The median follow-up time was 43 days (interquartile range: 23 - 64 days). Since being fully vaccinated, 1,940,917 (18%) of the base population had at least one record for a (positive/negative) SARS-CoV-2 test recorded. The total number of COVID-19 vaccine breakthrough cases was 17,030 (0.2%). Table 1 shows the number and rate of individuals fully vaccinated broken down by initial JCVI priority groups, along with the number and rate (per 1000 patient years) of each outcome.

Positive SARS-CoV-2 test

In fully vaccinated individuals, the median number of days to a positive test for SARS-CoV-2 was 29 (IQR 14 - 52 days) with a total of 16,815 (0.2%) individuals testing positive. For every 1000 years of patient follow-up time, the corresponding incidence rate was 12.33 (95% CI 12.14-12.51). Within the initial JCVI priority groups, positive SARS-CoV-2 test rates were highest in the CEV group (16.57, 95% CI 15.73-17.42) and lowest in those over 80 years (3.68, 95% CI 3.44-3.92). The overall cumulative incidence of positive SARS-CoV-2 tests at 150 days from the study start date was <0.01% (Figure 2).

When broken down into clinical/demographic groups and comorbidities (Table 2), rates of individuals testing positive for SARS-CoV-2 decreased with increasing age; 26.76 (26.16-27.36) vs 4.23 (3.98-4.48) for 16-50 year olds vs those over 80 years, respectively. Rates were higher in females than in males: 13.25 (13.00-13.51) vs 11.08 (10.81-11.35), respectively, and lower in those with a white ethnic origin than other eithnic groups: 11.90 (11.70-12.11) vs rates ranging from 12.14 (11.57-12.70) to 19.30 (18.02-20.40), respectively. Comorbidities with the highest rates of positive SARS-CoV-2 tests included renal replacement therapy, asthma and organ transplant; 21.21 (16.62-25.81), 15.46 (14.92-15.99) and 15.33 (11.04-19.63), respectively. Other comorbidities with high rates of positive SARS-CoV-2 tests included asplenia and immunocompromised. Rates of positive SARS-CoV-2 tests were highest 0-4 weeks after being fully vaccinated and decreased with time since being fully vaccinated: 32.91 (31.95-33.87) at 0-4 weeks vs 9.91 (9.51-10.30) at 12+ weeks).

COVID-19 hospital admissions

From within the fully vaccinated population, 955 had a COVID-19 hospital admission (about 1 in 11,000 or <0.01%), with median time to hospitalisation 33 days (IQR 16-66). Of those who had a COVID-19 hospital admission, 699 (73%) had a positive SARS-CoV-2 test in their records with 178 (25%) occurring prior to an individual being hospitalised, 149 (21%) occurring within the first 2 days of their hospital admission, 263 (38%) between 3 and 29 days after being hospitalised and 109 (16%) occurring 30 days or more after an individual had been hospitalised.

Rates of COVID-19 hospital admissions increased with age; 0.28 (0.22-0.34) for 16-50 year olds vs 1.88 (1.71-2.05) for those over 80 years, respectively. Rates were three times as high in those with Asian or Asian British ethnicities compared with a white ethnic origin; 1.52 (1.22-1.83) vs 0.50 (0.15-0.84), respectively. Rates were higher in those who were more deprived; most deprived IMD quintile versus least deprived IMD quintile was 1.15 (1.01-1.29) vs 0.53 (0.44-0.61), respectively. Comorbidities with the highest rates of COVID-19 hospital admissions included renal replacement therapy, organ transplant and haematological malignancy; 7.49 (4.77-10.22), 6.88 (4-9.75) and 15.33 2.76 (1.96-3.57), respectively. Other comorbidities with high rates of COVID-19 hospital admissions included kidney disease, immunocompromised and respiratory disease. Rates of hospitalisation were lowest 0-4 weeks after being fully vaccinated and increased as time since being fully vaccinated increased; 0.52 (0.4-0.64) at 0-4 weeks vs 1.16 (1.02-1.29) at 12+ weeks).

COVID-19 related death

Of those who were fully vaccinated, 145 had a COVID-19 related death (about 1 in 100,000 or <0.01%) with a median number of days to death of 40 (IQR 22-60). While the majority (63%) of deaths occurred in the 80+ JCVI priority group, COVID-19 related death rates were almost five times as high among individuals living in care homes compared to those over 80 years living in private residences; 1.84 (1.23-2.45) vs 0.38 (0.30-0.45), respectively.

There were very few deaths in those under 60 years of age with rates of COVID-19-related death increasing with increased age; 0.03 (0.01-0.06) for 60-69 year olds vs 0.48 (0.4-0.57) for those over 80 years, respectively. Rates of COVID-19-related death were over five times higher in the West Midlands compared to the South West; 0.27 (0.12-0.41) vs 0.05 (0.02-0.08), respectively. Comorbidities with the highest rates of COVID-19-related death included haematological malignancy, organ transplant, kidney disease; 0.8 (0.36-1.23), 0.41 (0.3-0.51) and 0.41 (0.31-0.52), respectively. Other comorbidities with high rates of COVID-19-related death included immunocompromised and respiratory disease.

Discussion

Summary

This descriptive analysis in over 10 million people living in England shows that COVID-19 vaccine breakthrough is occurring, however, events are currently rare and mostly mild in nature. Nevertheless, some individuals are experiencing higher rates of serious illness and death due to COVID-19, such as those in care homes, on renal replacement therapy, with organ transplants, with haematological malignancy, and who are immunocompromised. It is important to note that this analysis is a simple descriptive piece of analysis and was not designed to estimate risk factors for COVID-19 vaccine breakthrough and thus cannot be used to answer why certain groups have higher rates of breakthrough cases than others or to estimate vaccine effectiveness.

Strengths and weaknesses

This study used large-scale, routinely-collected primary care records, linked to coronavirus testing surveillance, hospital, and death registry data. This allowed us to describe a substantial proportion of the English population in rich longitudinal detail and to detect variations in COVID-19 vaccine breakthrough cases, as early as possible.

We acknowledge several important limitations of these findings. First, even though the base population consisted of over 10 million fully vaccinated individuals the numbers of COVID-19 vaccine breakthrough cases were relatively small, especially for hospitalisations and deaths. This made comparisons between outcomes, specifically at selected clinical and demographic levels difficult,meaning rates could be imprecisely estimated. Second, due to the targeted roll out of the COVID-19 vaccination programme in England, this cohort represents mostly older and vulnerable populations. In addition, follow-up time is systematically different amongst individuals included in this study and no adjustment for this has been made. Third, asymptomatic testing patterns vary between individuals. Apart from health and care workers, asymptomatic individuals without any underlying health issues or comorbidities are less likely to get tested than those with underlying health issues or

comorbidities (i.e., haemodialysis patients) who will undergo asymptomatic testing regularly. Most lateral flow tests conducted at home are not included in our data. The number of reported positive SARS-CoV-2 tests is therefore likely to be an undercount of SARS-CoV-2 among fully vaccinated individuals without any underlying health issues or comorbidities, which may have led to underestimation of the corresponding rates. Fourth, characteristics linked to COVID-19 vaccine breakthrough in fully vaccinated individuals may be reflective of higher infection rates regardless of vaccination in some groups, not because of vaccination (i.e. due to higher exposure due to behavioural differences) [13].

Findings in Context

Although COVID-19 vaccinations have demonstrated safety and efficacy in healthy volunteers [14], some people still contract COVID-19 after vaccination and are at risk of serious COVID-19 outcomes (in particular, hospital admission or death). However, with only a handful of studies investigating risk factors for post-vaccination infection [8, 11, 12], very little is known about how breakthrough COVID-19 varies between key clinical and demographic groups. Our findings on COVID-19 vaccine breakthrough are consistent with patterns observed worldwide; COVID-19 vaccine breakthrough cases are rare and mild. However, there are potentially several groups who are at higher risk of COVID-19 vaccine breakthrough including those in care-homes, on renal replacement therapy, with organ transplants or who are immunocompromised.

Conclusion

As of 30th June 2021, the majority of COVID-19 vaccine breakthrough cases in England were mild with relatively few fully vaccinated individuals being hospitalised or dying as a result. While these numbers are in line with expectations, and while follow-up time for fully vaccinated individuals is limited and variation in vaccination coverage between groups and regions will have many complex drivers, some differences in rates of breakthrough cases were identified in several clinical and demographic groups. With the continued increase in numbers of positive SARS-CoV-2 tests and as numbers of fully vaccinated individuals increases and follow-up time lengthens, so too will the number of COVID-19 breakthrough cases. Additional analyses are therefore needed to enable identification of individuals at higher risk, who would require continued strict precautions, and possibly additional vaccination.

Abbreviations

Body Mass index (BMI); Joint Committee Vaccination and Immunisation (JCVI); Index of Multiple Deprivation (IMD); United Kingdom (UK).

Declarations

Information governance and ethical approval

NHS England is the data controller; TPP is the data processor; and the key researchers on OpenSAFELY are acting with the approval of NHS England. This implementation of OpenSAFELY is hosted within the TPP environment which is accredited to the ISO 27001 information security standard and is NHS IG Toolkit compliant[17,18]; Patient data has been pseudonymised for analysis and linkage using industry standard cryptographic hashing techniques; all pseudonymised datasets transmitted for linkage onto OpenSAFELY are encrypted; access to the platform is via a virtual private network (VPN) connection, restricted to a small group of researchers; the researchers hold contracts with NHS England and only access the platform to initiate database queries and statistical models; all database activity is logged; only aggregate statistical outputs leave the platform environment following best practice for anonymisation of results such as statistical disclosure control for low cell counts[16] . The OpenSAFELY research platform adheres to the obligations of the UK General Data Protection Regulation (GDPR) and the Data Protection Act 2018. In March 2020, the Secretary of State for Health and Social Care used powers under the UK Health Service (Control of Patient Information) Regulations 2002 (COPI) to require organisations to process confidential patient information for the purposes of protecting public health, providing healthcare services to the public and monitoring and managing the COVID-19 outbreak and incidents of exposure; this sets aside the requirement for patient consent[17] . Taken together, these provide the legal bases to link patient datasets on the OpenSAFELY platform. GP practices, from which the primary care data are obtained, are required to share relevant health information to support the public health response to the pandemic, and have been informed of the OpenSAFELY analytics platform.

This study was approved by the Health Research Authority (REC reference 20/LO/0651) and by the LSHTM Ethics Board (reference 21863).

Availability of data and materials

Access to the underlying identifiable and potentially re-identifiable pseudonymised electronic health record data is tightly governed by various legislative and regulatory frameworks, and restricted by best practice. The data in OpenSAFELY is drawn from General Practice data across England where TPP is the Data Processor. TPP developers (CB, RC, JP, FH, and SH) initiate an automated process to create pseudonymised records in the core OpenSAFELY database, which are copies of key structured data tables in the identifiable records. These are linked onto key external data resources that have also been pseudonymised via SHA-512 one-way hashing of NHS numbers using a shared salt. DataLab developers and PIs (BG, LS, CEM, SB, AJW, WH, DE, PI, and CTR) holding contracts with NHS England have access to the OpenSAFELY pseudonymised data tables as needed to develop the OpenSAFELY tools. These tools in turn enable researchers with OpenSAFELY Data Access Agreements to write and execute code for data management and data analysis without direct access to the underlying raw pseudonymised patient data, and to review the outputs of this code. All code for the full data management pipeline—from raw data to completed results for this analysis—and for the OpenSAFELY platform as a whole is available for review at github.com/OpenSAFELY.

Competing interests

All authors have completed the ICMJE uniform disclosure form and declare the following: BG has received research funding from Health Data Research UK (HDRUK), the Laura and John Arnold Foundation, the Wellcome Trust, the NIHR Oxford Biomedical Research Centre, the NHS National Institute for Health Research School of Primary Care Research, the Mohn-Westlake Foundation, the Good Thinking Foundation, the Health Foundation, and the World Health Organisation; he also receives personal income from speaking and writing for lay audiences on the misuse of science. IJD holds shares in GlaxoSmithKline (GSK).

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Funders had no role in the study design, collection, analysis, and interpretation of data; in the writing of the report and in the decision to submit the article for publication.
The views expressed are those of the authors and not necessarily those of the NIHR, NHS England, Public Health England or the Department of Health and Social Care.

Authors' contributions

Contributions are as follows:
Conceptualisation: RM, CTR, KB, RME, LS, BG, BM, HJC, SJWE, KK, DH, KR
Funding acquisition: LS, BG, RME
Methodology: AG, HC, WH, EW, HMD, AW, LF, CA, LH, CM, BMK, RC, JM, AM, KB,AS,CR,AR,LF,LT, RM, AW, HF, SE, LS, BG
Formal analysis: AG, HC
Codelists: RM, LT, AS, AJW, CM, BG, WJH, SB, AM
Software: AW, CB, JC, DE, PI, CM, WH, BN, SB, HC, ND, RC, JP, FH, SH
Visualisation: AG, HC, WH, EW

Writing - original draft: AG
Writing- review & editing: ALL
Information governance: CB LS BG AM

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Guarantor

BG is guarantor.

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Figures, tables and additional files

Table 1. *Number of individuals fully vaccinated (2 doses + 2 weeks) in initial priority groups in OpenSAFELY-TPP, and number and rate with each outcome.*

Priority Group	Fully vaccinated						Positive SARS-CoV-2 test			Hospitalised with COVID-19		COVID-19 related death	
	Count*	Follow-up time, median days (IQR)	Tests conducted** (%)				Events* (PYs)	Positivity rate, %	Incidence rate per 1000 person-years (95% CI)	Events* (PYs)	Incidence rate per 1000 person-years (95% CI)	Events* (PYs)	Incidence rate per 1000 person-years (95% CI)
			0	1	2	3+							
All	10,782,870	43 (23-64)	82	7	3	7	16,815 (1,357,691)	0.24	12.33 (12.14-12.51)	955 (1,358,425)	0.70 (0.65-0.74)	145 (1,358,521)	0.12 (0.1-0.14)
Care home (priority group 1)	94,865	77 (65-84)	21	15	24	40	255 (19,015)	0.14	13.36 (11.71-15.00)	45 (19,038)	2.26 (1.58-2.93)	35 (19,042)	1.84 (1.23-2.45)
80+ (priority group 2)	1,053,455	76 (68-90)	83	7	3	7	900 (244,557)	0.24	3.68 (3.44-3.92)	455 (24,4612)	1.86 (1.69-2.03)	90 (244,675)	0.38 (0.3-0.45)
Health/care workers (priority groups 1-2)	480,840	78 (65-89)	79	9	3	9	1,205 (101,050)	0.44	11.94 (11.27-12.62)	20 (101,116)	0.21 (0.12-0.30)	<8	-
70-79 (priority groups 3-4)	1,953,015	60 (53-67)	86	7	2	5	1,265 (319,752)	0.20	3.96 (3.74-4.18)	195 (319,808)	0.61 (0.52-0.70)	20 (319821)	0.07 (0.04-0.1)
Shielding (age 16-69) (priority group 4)	676,875	49 (35-59)	78	8	4	10	1,475 (88,875)	0.32	16.57 (15.73-17.42)	115 (88,938)	1.27 (1.04-1.50)	<8	-
50 - 69 (priority groups 5-9)	4,420,060	28 (18-42)	84	6	2	8	5,620 (390,033)	0.20	14.41 (14.03-14.79)	85 (390,255)	0.22 (0.17-0.27)	<8	-
Others not in the above groups* **	2,102,620	27 (12-49)	79	7	3	11	6,015 (194,409)	0.28	30.94 (30.16-31.72)	40 (194,660)	0.20 (0.13-0.26)	<8	-

*All counts (of people and events) have been rounded to the nearest 5 and counts < 8 have been redacted

**This is a count of (positive and negative) test results and may include multiple tests for an individual person

***Others includes: others in priority groups ("At Risk"), some misclassified health/care workers and care home residents (except those age 70+ or shielding who will be included in another group), carers, household contacts of those at increased risk, and those not in priority groups who had the vaccine opportunistically, e.g. by responding to calls to use up excess doses.

Table 2 *Count and rates of breakthrough* positive SARS-CoV-2 tests *and hospitalisation and death in fully vaccinated individuals in OpenSAFELY-TPP, broken down by selected clinical and demographic groups*

Clinical/ demographic group	Category	Fully vaccinated						Positive SARS-CoV-2 test			Hospitalised with COVID-19		COVID-19 related death	
		Count*	Follow-up time, median days (IQR)	Tests conducted (%)				Events* (PYs)	Positivity rate, %	Incidence rate per 1000 person-years (95% CI)	Events* (PYs)	Incidence rate per 1000 person-years (95% CI)	Events* (PYs)	Incidence rate per 1000 person-years (95% CI)
				0	1	2	3+							
Age	16 - 50	2658445	34 (15-61)	79	8	3	11	7680 (286923)	0.31	26.76 (26.16-27.36)	80 (287254)	0.28 (0.22-0.34)	<8	-
	50 - 59	2687930	24 (13-41)	83	6	3	9	4415 (227734)	0.23	19.39 (18.81-19.96)	75 (227907)	0.33 (0.26-0.41)	<8	-
	60 - 69	2333900	39 (27-50)	84	6	2	7	2225 (259546)	0.17	8.57 (8.22-8.93)	105 (259643)	0.4 (0.32-0.47)	10 (259649)	0.03 (0.01-0.06)
	70 - 79	1977395	60 (53-68)	85	7	3	5	1320 (324576)	0.20	4.07 (3.85-4.29)	205 (324638)	0.63 (0.54-0.71)	25 (324652)	0.07 (0.04-0.1)
	80 +	1124065	76 (68-90)	79	8	4	9	1095 (258911)	0.22	4.23 (3.98-4.48)	485 (258983)	1.88 (1.71-2.05)	125 (259049)	0.48 (0.4-0.57)
Sex	Female	5864565	48 (25-68)	79	7	3	10	10335 (779686)	0.21	13.25 (13-13.51)	450 (780195)	0.58 (0.52-0.63)	75 (780243)	0.09 (0.07-0.12)
	Male	4917165	40 (21-61)	85	6	3	6	6405 (578004)	0.33	11.08 (10.81-11.35)	500 (578230)	0.87 (0.79-0.94)	85 (578279)	0.15 (0.12-0.18)
BMI (kg/m2)	Not obese	8052760	44 (22-66)	82	7	3	8	12355 (1017048)	0.24	12.15 (11.93-12.36)	695 (1017585)	0.68 (0.63-0.73)	125 (1017659)	0.12 (0.1-0.14)
	Obese (>30)	2728970	42 (26-62)	82	7	3	8	4380 (340643)	0.25	12.86 (12.48-13.24)	255 (340840)	0.75 (0.66-0.84)	35 (340862)	0.11 (0.07-0.14)
Smoking	Non-smoker and unknown	4983435	41 (21-64)	81	7	3	9	8540 (615700)	0.26	13.87 (13.57-14.16)	360 (616059)	0.59 (0.53-0.65)	60 (616099)	0.1 (0.08-0.13)

	Current and former	5798295	46 (25-64)	83	7	3	8	8200 (741991)	0.23	11.05 (10.81-11.29)	590 (742366)	0.79 (0.73-0.86)	100 (742422)	0.13 (0.11-0.16)
Ethnicity	White	8602570	46 (25-66)	81	7	3	9	13240 (1112238)	0.24	11.9 (11.7-12.11)	830 (1112804)	0.75 (0.7-0.8)	145 (1112891)	0.13 (0.11-0.15)
	Asian or Asian British	508665	40 (21-64)	86	6	2	5	1190 (61655)	0.50	19.3 (18.2-20.4)	95 (61723)	1.52 (1.22-1.83)	10 (61731)	0.19 (0.08-0.3)
	Black or Black British	134865	40 (21-63)	81	7	3	9	235 (16056)	0.22	14.7 (12.82-16.57)	10 (16068)	0.5 (0.15-0.84)	<8	-
	Mixed/other ethnic groups	198955	36 (19-62)	83	7	3	7	315 (22808)	0.26	13.72 (12.2-15.24)	10 (22820)	0.39 (0.14-0.65)	<8	-
	Unknown	1336680	34 (18-59)	86	5	2	7	1760 (144934)	0.21	12.14 (11.57-12.7)	10 (145009)	0.06 (0.02-0.09)	<8	-
IMD quintile	1 (least deprived)	1680180	41 (22-62)	84	6	3	8	3115 (203126)	0.29	15.34 (14.8-15.88)	235 (203276)	1.15 (1-1.29)	35 (203297)	0.18 (0.12-0.24)
	2	1940500	42 (23-63)	82	7	3	8	3125 (240878)	0.24	12.97 (12.52-13.43)	185 (241026)	0.78 (0.66-0.89)	35 (241041)	0.15 (0.1-0.19)
	3	2327605	45 (24-65)	82	7	3	8	3265 (295832)	0.22	11.03 (10.65-11.41)	175 (295981)	0.58 (0.5-0.67)	25 (296000)	0.08 (0.05-0.12)
	4	2336025	46 (24-66)	82	7	3	8	3310 (298957)	0.23	11.07 (10.69-11.45)	180 (299092)	0.6 (0.51-0.69)	35 (299110)	0.12 (0.08-0.16)
	5 (most deprived)	2255405	46 (23-66)	81	7	3	8	3420 (288976)	0.24	11.84 (11.45-12.24)	150 (289104)	0.53 (0.44-0.61)	20 (289123)	0.08 (0.04-0.11)
	Unknown	242015	42 (22-63)	81	7	3	8	500 (29922)	0.32	16.74 (15.28-18.21)	25 (29946)	0.87 (0.53-1.2)	<8	-
Region	London	481650	42 (21-63)	81	9	3	7	815 (59132)	0.38	13.78 (12.84-14.73)	40 (59167)	0.66 (0.45-0.87)	10 (59170)	0.14 (0.04-0.23)
	East of England	2492925	44 (23-66)	81	7	3	9	2615 (314729)	0.15	8.32 (8-8.63)	195 (314865)	0.62 (0.54-0.71)	35 (314891)	0.12 (0.08-0.16)
	East Midlands	1950180	41 (21-61)	84	6	3	8	2605 (231453)	0.23	11.25 (10.81-11.68)	155 (231573)	0.68 (0.57-0.78)	25 (231587)	0.1 (0.06-0.15)

	North East	521180	46 (23-67)	84	6	3	7	865 (66383)	0.33	13.06 (12.19-13.93)	65 (66418)	0.95 (0.71-1.18)	10 (66425)	0.12 (0.04-0.2)
	North West	991585	43 (23-66)	82	7	3	8	2695 (126663)	0.43	21.29 (20.49-22.1)	110 (126763)	0.88 (0.72-1.05)	15 (126772)	0.13 (0.07-0.2)
	South East	757435	46 (25-67)	81	7	3	9	870 (98102)	0.15	8.88 (8.29-9.47)	45 (98145)	0.48 (0.34-0.62)	15 (98151)	0.15 (0.08-0.23)
	South West	1676975	46 (25-63)	81	7	3	9	1930 (214756)	0.16	9 (8.6-9.4)	75 (214846)	0.34 (0.27-0.42)	10 (214852)	0.05 (0.02-0.08)
	West Midlands	384265	41 (24-64)	84	6	3	8	810 (48632)	0.40	16.64 (15.49-17.78)	80 (48663)	1.6 (1.25-1.96)	15 (48672)	0.27 (0.12-0.41)
	Yorkshire and The Humber	1521640	47 (25-67)	83	7	3	8	3520 (197355)	0.36	17.84 (17.25-18.43)	185 (197498)	0.93 (0.8-1.07)	30 (197514)	0.14 (0.09-0.19)
	Unknown	3890												
Asthma		1651165	42 (25-63)	80	8	3	9	3190 (206525)	0.28	15.46 (14.92-15.99)	170 (206663)	0.83 (0.7-0.95)	30 (206680)	0.14 (0.09-0.19)
Asplenia		101345	48 (34-63)	79	8	3	10	185 (13905)	0.27	13.45 (11.52-15.38)	10 (13912)	0.58 (0.18-0.97)	<8	-
Blood pressure	Normal	1892585	40 (20-63)	79	8	3	10	4010 (226182)	0.27	17.72 (17.18-18.27)	165 (226354)	0.72 (0.61-0.84)	35 (226370)	0.15 (0.1-0.2)
	Elevated/high	2540955	41 (22-62)	82	7	3	8	3840 (310579)	0.24	12.36 (11.97-12.75)	220 (310748)	0.71 (0.62-0.81)	40 (310770)	0.13 (0.09-0.16)
	Unknown	6348190	46 (25-66)	83	7	3	8	8890 (820929)	0.24	10.83 (10.6-11.05)	565 (821323)	0.69 (0.63-0.74)	90 (821382)	0.11 (0.09-0.13)
Cancer (non-haematological)		842935	58 (42-71)	79	9	4	9	895 (135642)	0.20	6.61 (6.18-7.05)	165 (135685)	1.23 (1.04-1.42)	35 (135703)	0.26 (0.17-0.34)
Diabetes		1389570	51 (35-67)	83	7	3	7	2015 (202992)	0.30	9.94 (9.5-10.37)	320 (203078)	1.57 (1.4-1.74)	50 (203105)	0.25 (0.18-0.32)
Heart disease		1674700	58 (41-74)	81	8	4	8	1975 (273317)	0.24	7.23 (6.91-7.55)	460 (273409)	1.68 (1.53-1.83)	90 (273460)	0.33 (0.26-0.39)

Haematological malignancy		98995	58 (46-70)	77	9	4	10	175 (16279)	0.37	10.81 (9.21-12.41)	45 (16285)	2.76 (1.96-3.57)	15 (16289)	0.8 (0.36-1.23)
Immunocompromised		476855	54 (40-68)	78	9	4	9	915 (72343)	0.33	12.66 (11.84-13.48)	120 (72382)	1.66 (1.36-1.95)	25 (72393)	0.33 (0.2-0.46)
Kidney disease		774045	65 (51-77)	80	8	4	9	865 (142828)	0.25	6.06 (5.65-6.46)	290 (142873)	2.02 (1.79-2.26)	60 (142905)	0.41 (0.31-0.52)
Learning disability		92545	40 (27-55)	74	9	6	11	110 (10658)	0.15	10.13 (8.22-12.04)	10 (10662)	1.03 (0.42-1.64)	<8	-
Liver disease		315180	42 (27-60)	82	8	3	7	465 (38944)	0.30	11.99 (10.9-13.08)	60 (38964)	1.54 (1.15-1.93)	<8	-
Neurological disease		821165	54 (36-70)	77	8	5	10	1145 (125513)	0.23	9.14 (8.61-9.67)	205 (125565)	1.62 (1.4-1.85)	55 (125588)	0.42 (0.31-0.54)
Respiratory disease		559080	58 (46-70)	81	8	3	8	675 (92341)	0.26	7.29 (6.74-7.84)	165 (92374)	1.76 (1.49-2.04)	35 (92389)	0.39 (0.26-0.52)
Renal replacement therapy		23205	58 (48-70)	62	9	4	24	80 (3865)	0.35	21.21 (16.62-25.81)	30 (3871)	7.49 (4.77-10.22)	<8	-
Severe mental illness		158185	39 (25-57)	81	7	4	8	185 (18352)	0.25	10.14 (8.68-11.59)	20 (18359)	1.14 (0.65-1.63)	<8	-
Organ transplant		20065	56 (48-67)	74	10	4	12	50 (3196)	0.56	15.33 (11.04-19.63)	20 (3198)	6.88 (4-9.75)	<8	-
Time since being fully vaccinated	0-4 weeks	3353065	15 (9-22)	89	5	2	4	4530 (137643)	0.65	32.91 (31.95-33.87)	70 (137712)	0.52 (0.4-0.64)	55 (137714)	0.41 (0.3-0.51)
	4 - 8 weeks	3601190	42 (35-49)	83	7	3	7	4955 (414232)	0.30	11.96 (11.63-12.29)	220 (414380)	0.53 (0.46-0.6)	60 (414391)	0.14 (0.1-0.18)
	8 - 12 weeks	3004920	68 (61-76)	77	8	4	12	4830 (561123)	0.17	8.61 (8.36-8.85)	375 (561365)	0.67 (0.6-0.73)	40 (561394)	0.07 (0.05-0.09)
	12+ weeks	822560	96 (89-116)	68	9	4	19	2425 (244692)	0.15	9.91 (9.51-10.3)	285 (244968)	1.16 (1.02-1.29)	10 (245024)	0.03 (0.01-0.06)
Time between vaccinations	6 weeks or less	311705	157 (77-160)	72	10	4	14	1250 (101011)	0.24	12.37 (11.69-13.06)	235 (101186)	2.3 (2.01-2.6)	55 (101232)	0.52 (0.38-0.66)

	6-12 weeks	*9548165*	*43 (23-64)*	*82*	*7*	*3*	*8*	*14390 (1160600)*	*0.24*	*12.4 (12.19-12.6)*	*635 (1161123)*	*0.55 (0.51-0.59)*	*90 (1161168)*	*0.08 (0.06-0.09)*
	12 weeks or more	*921860*	*39 (21-54)*	*84*	*6*	*3*	*7*	*1100 (96080)*	*0.24*	*11.44 (10.76-12.11)*	*80 (96116)*	*0.83 (0.65-1.01)*	*20 (96121)*	*0.19 (0.1-0.27)*
Prior COVID-19	*Between 1st and 2nd vaccination*	*63060*	*68 (45-83)*	*62*	*9*	*6*	*23*	*265 (10973)*	*0.20*	*24.24 (21.33-27.15)*	*40 (10997)*	*3.55 (2.43-4.66)*	*25 (11002)*	*2.09 (1.24-2.94)*
	Before 1st vaccination	*568995*	*37 (19-62)*	*75*	*8*	*4*	*13*	*735 (65244)*	*0.11*	*11.27 (10.45-12.08)*	*75 (65303)*	*1.18 (0.92-1.44)*	*35 (65312)*	*0.57 (0.38-0.75)*

Figure 1 - *Inclusion/exclusion flowchart*

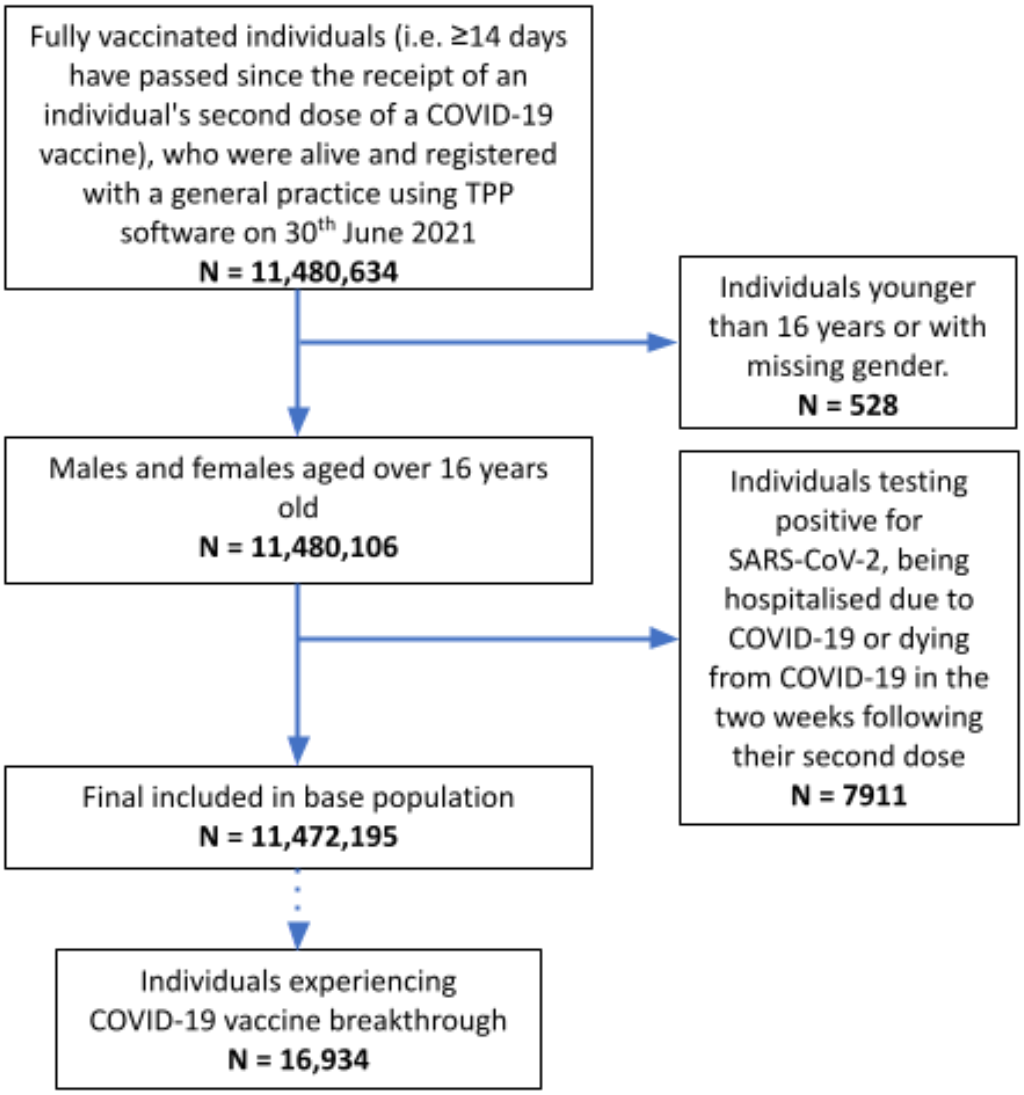
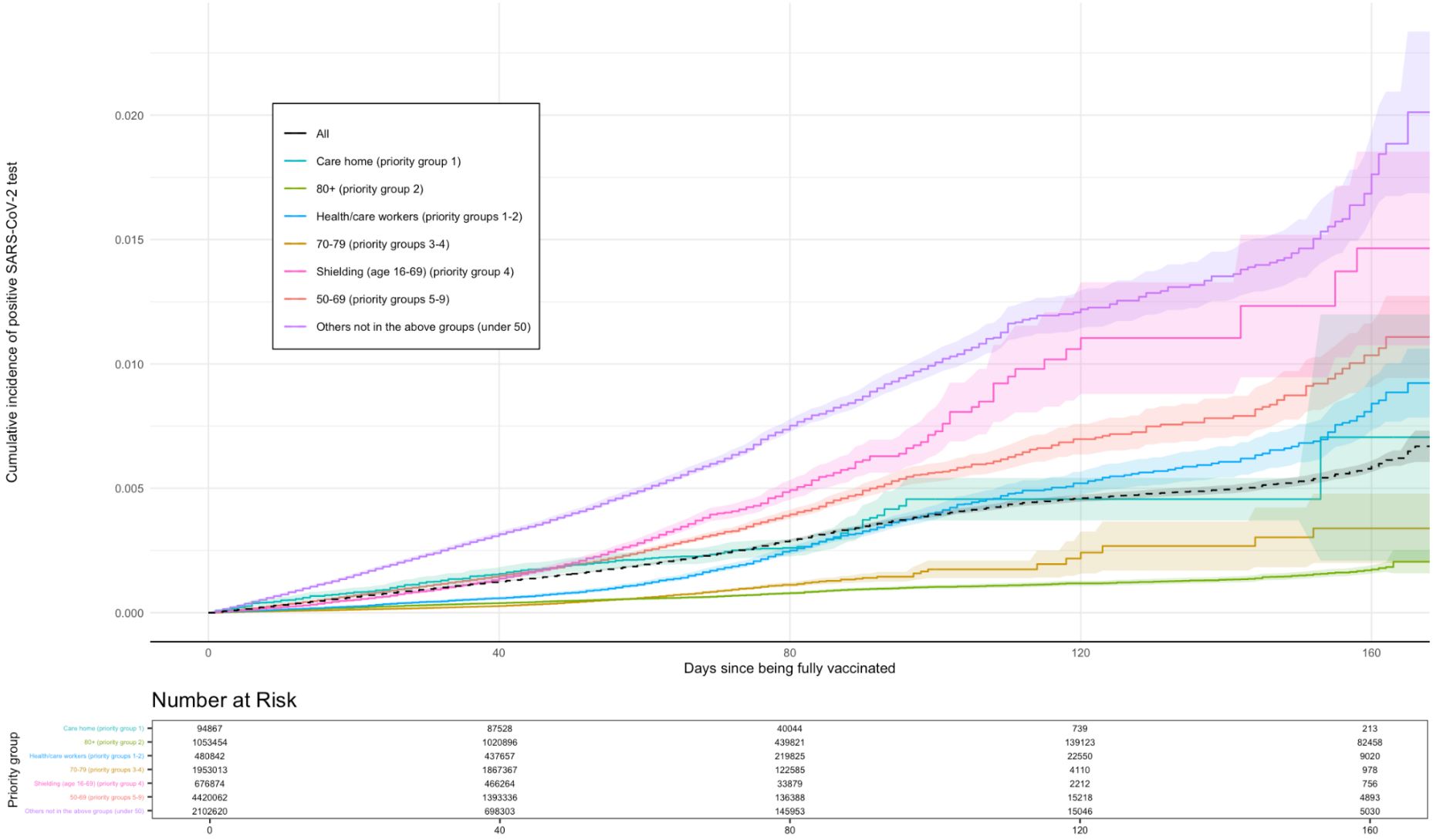


Figure 2 *Kaplan-Meir plot for positive SARS-CoV-2 test over time, by priority group*



Re: Describing the population experiencing COVID-19 vaccine breakthrough following second vaccination in England: A cohort study from OpenSAFELY

4th March 2022

Dear Dr. Lucy Dunbar,

We would like to thank BMC Medicine for considering our proposal, and thank the reviewers for their informed and helpful comments. We are pleased to re-submit the manuscript (number BMED-D-21-02626) entitled "***Describing the population experiencing COVID-19 vaccine breakthrough following second vaccination in England: A cohort study from OpenSAFELY***" for consideration as a Research Article in BMC Medicine. We would also like to extend our sincere gratitude to the Reviewers for their positive and constructive feedback.

We have carefully reviewed the reviewers' comments and provide point-by-point responses to their comments below, describing exactly what amendments have been made to the manuscript text and where these can be viewed. As a result of increasing the follow-up time (as per the reviewers suggestions) we have updated all corresponding tables, figures and numbers in the text accordingly and also added in a few additions to the discussions to reflect on this increased follow-up, these changes are detailed below, after our replies to the reviewers comments. With the increase in the numbers of outcomes, we have been able to include an additional outcome which was previously not included due to small numbers; COVID-19 related critical care admission. In addition, to help inform decisions around rollout of vaccine/booster programmes for patients at high risk of adverse outcomes we have separated out chronic kidney disease from dialysis and transplant. All changes to the manuscript are indicated in the text by yellow highlights.

Due to the longer follow-up time, as expected, there has been a rise in all rates (calculated per 1000 person-years); Positive SARS-CoV-2 test from 12.33 (12.14-12.51) to 98.06 (95% CI 97.93-98.19); COVID related hospitalisation from 0.70 (0.65-0.74) to 2.31 4.77 (4.74-4.8); COVID related death from 0.12 (0.1-0.14) to 0.64 1.07 (1.06-1.09). But reassuringly, breakthrough cases seem to be remaining mild; 579,780 Positive SARS-CoV-2 tests vs 6,435 COVID-19 related deaths, with the majority (~80%) of deaths occurring in those over 70 years of age.

We believe that the revised manuscript is now improved and has addressed all reviewer comments – with textual changes, and more detailed explanations of our methods and assumptions. Our manuscript continues to have important findings which we believe will be of great interest to the general medical community

Thank you again for your consideration.

Yours Sincerely,

Amelia Green and Ben Goldacre, on behalf of the OpenSAFELY collaborative.

Reviewer(s)' Comments to Author:

Reviewer: 1

Comments to the Author

I believe this manuscript provides a good analysis of the risk profile for breakthrough infections, and highlights the decreased risk of severe illness with a robust data approach. I will defer to a statistical reviewer for any questions as to whether the time-risk is adequately analyzed (e.g. number of events versus days at risk), and the 43 day follow up is a short interval, but given that this manuscript was looking at breakthrough of fully vaccinated rather than analysis of effects of waning, I think this is appropriate. Ideally, I'd see the short follow up acknowledged as one of the limitations, as well as the fact that the time period predates current strains (e.g. this is pre- Delta). But these are minor points.

Overall, the question of breakthroughs is of interest to clinicians, but is not as novel as it was, particularly given the pre-delta population. Extending to include a longer follow up, and include the Delta era and stratify accordingly, would be useful. The work is well written, referenced, and has appropriate logic. The biggest weakness of this methodology is the lack of a comparator- e.g. there was no control of breakthroughs among fully vaccinated/non boosted, though this is a descriptive work, and thus controls are not strictly necessary. The conclusions are reasonable based on the data shown.

6. Are the methods appropriate and well described?
7. Does the work include the necessary controls?
8. Are the conclusions drawn adequately supported by the data shown?

Response: We thank the reviewer for these positive comments and agree the initial short follow-up was a limitation. We have since extended the follow-up period, and the study now includes data from December 2020 until November 2021 (we chose not to go further than this due to the roll out of booster vaccinations), during which two different variants of SARS-COV-2 were dominating in England at different times; the Alpha variant (B.1.1.7) between January 2021 and May 2021, and the Delta variant (B.1.617.2) after June 2021[1]. Given the longer follow-up, stratifying results by the two variants and comparing the rates would be useful, however accurately determining the presence of certain variants of concern is only possible if an individual's SARS-CoV-2 test is sequenced, which only occurs in a small minority of cases. The completeness and accuracy of data that we have access to which would allow us to compare breakthrough rates between the two variants is therefore limited. In addition, to the issue of vaccine waning, which would need to be accounted for in order to sensibly compare rates, due to the different time periods that the variants dominated, the characteristics of people vaccinated will be different and thus susceptibility to breakthrough infection.

We have acknowledged this as one of the limitations, and have added the following to the bottom of the limitations section of the discussion section on page 8:

This study includes data from December 2020 until November 2021, during which time two different variants of SARS-COV-2 were dominating in England at different times; the Alpha

variant (B.1.1.7) between January 2021 and May 2021, and the Delta variant (B.1.617.2) after June 2021[1]. These have since been supplanted by other variants, in particular the Omicron variant. This is a descriptive study and does not aim to quantify the contribution of vaccine breakthrough due to the change in dominant variant from Alpha to Delta or the extent of waning in the months immediately following vaccination. Further studies are needed to assess vaccine waning and rates of breakthrough COVID-19 between different variants and in newer, more prevalent variants, such as Omicron (B.1.1.529).

We also agree that having a comparator group (i.e. unvaccinated) would be useful for public health messaging but the focus of this study was on describing the population experiencing COVID-19 vaccine breakthrough following second vaccination, for example to inform service use and identify those who remain at high-risk of severe COVID outcomes. The primary aim is to identify those at highest risk among people who have completed the vaccination programme. The study was not intended to compare rates of outcomes between different vaccinated and unvaccinated individuals as such analyses are difficult to conduct robustly given the many complex biases at play, and are being considered by our group in other work.

Reviewer: 2

Comments to the Author

This study includes a large number of individuals who are fully vaccinated and provides descriptive information about those with vaccine breakthroughs. It does not utilize any complex statistics, however there are a number issues that need to be clarified throughout the paper. This includes providing more background information, improving definitions used, and consideration of further discussion related to waning immunity.

Major issues to be addressed:
- The finding that rates of positive SARS-CoV-2 tests were highest 0-4 weeks after full vaccination and decreased with time since being fully vaccinated is confusing. Is it possible that the study included patients that had a positive SARS-CoV-2 test in recent proximity to vaccine dose 2 and the finding of a positive test was co-incidental? Would it be better to exclude anyone with a positive SARS-CoV-2 tests obtained since first vaccination through 2 weeks after dose 2?

Response: we agree that the trend in time since being fully vaccinated rates are confusing and that the rates for 0-4 weeks are higher than expected. As it is possible to continue testing positive for weeks or even months after having the virus, the study does potentially include some patients whose positive SARS-CoV-2 test was related to a previous infection pre second vaccination. However, given that (1) individuals with COVID-19 who have symptoms should wait to be vaccinated until they have recovered from their illness before getting vaccinated and (2) individuals were excluded if they tested positive for SARS-CoV-2 or had been hospitalised or died due to COVID-19 within the two weeks after their second dose (as stated in the second sentence of the study population sub-section of the methods section on page 4), we felt that the 14 day period was long enough to exclude the majority of people whose positive SARS-CoV-2 test was unrelated to the vaccination event.

We agree that excluding anyone with a positive SARS-CoV-2 test obtained since first vaccination through to two weeks after their second dose could help to exclude individuals whose positive SARS-CoV-2 test was coincidental, but given COVID re-infection is increasingly common and that time between first and second vacation could be up to 12+ weeks, excluding anyone with a positive SARS-CoV-2 test obtained since first vaccination could end up excluding a large number of individuals (especially as there a high amount of repeated screening in some of the highest risk groups, i.e., dialysis patients and those in care homes), some of whom may just be more prone to re-infection, which would bias findings.

We have added the following to the limitations section of the discussion on page 8:

While individuals were excluded if they tested positive for SARS-CoV-2 or had been hospitalised or died due to COVID-19 within the two weeks after their second dose, we acknowledge that there is still the potential that some patients will have been included whose outcome was related to a previous infection pre second vaccination, in particular in some of the highest risk groups such as dialysis patients and those in care homes where there a high amount of repeated screening in, resulting in a potential increase in rates.

- It would be helpful to know the predominant circulating SARS-CoV-2 variant(s) during the study period and if breakthrough infections varied based on the predominant variant of the time.

Response: our study now includes data from December 2020 until November 2021 (we choose not to go further than this due to the roll out of booster vaccinations), during which two different variants of SARS-COV-2 were dominating in England at different times; the Alpha variant (B.1.1.7) between January 2021 and May 2021, and the Delta variant (B.1.617.2) after June 2021[1]. Given the longer follow-up, stratifying results by the two variants and comparing the rates would be useful, however accurately determining the presence of certain variants of concern is only possible if an individual's SARS-CoV-2 test is sequenced, which only occurs in a small minority of cases. The completeness and accuracy of data that we have access to which would allow us to compare breakthrough rates between the two variants is therefore limited. In addition, to the issue of vaccine waning, which would need to be accounted for in order to sensibly compare rates, due to the different time periods that the variants dominated, the characteristics of people vaccinated will be different and thus susceptibility to breakthrough infection.

We have acknowledged this as one of the limitations, and have added the following to the bottom of the limitations section of the discussion section on page 7:

This study includes data from December 2020 until November 2021, during which time two different variants of SARS-COV-2 were dominating in England at different times; the Alpha variant (B.1.1.7) between January 2021 and May 2021, and the Delta variant (B.1.617.2) after June 2021[1]. These have since been supplanted by other variants, in particular the Omicron variant. This is a descriptive study and does not aim to quantify the contribution of vaccine breakthrough due to the change in dominant variant from Alpha to Delta or the

extent of waning in the months immediately following vaccination. Further studies are needed to assess vaccine waning and rates of breakthrough COVID-19 between different variants and in newer, more prevalent variants, such as Omicron (B.1.1.529).

-It is curious that there is no discussion related to waning immunity and how that may impact results as one of the groups at higher risk of COVID-19 vaccine breakthrough infection resulting in hospitalization or death was individuals in care-homes who were the first priority group to receive vaccines. Some discussion about this should be added.

Response: we agree that some discussion about waning immunity should be added. We have added the following

"there are concerns that the effectiveness of the vaccines may fade over time, due to the vaccines being less effective against the delta variant, and/or the waning of the immune response"

to the Background section on page 2 and

"There is strong evidence that the UK's COVID-19 vaccination programme has reduced infection and severe outcomes in vaccinated individuals[2,3]. However, breakthrough infections after vaccination against SARS-CoV-2 are increasingly reported[4] and there are concerns that the effectiveness of the vaccines may reduce over time, due to the vaccines being less effective against the delta variant, and/or the waning of the immune response[5]. While we did find that breakthrough infections were more frequent in the earlier-vaccinated individuals, potentially due to waning vaccine efficacy or impaired immune response, further studies are needed to gain a clearer picture of the long-term effectiveness of COVID-19 vaccines."

to the Findings in Context section of the discussion on page 8:

- Please describe what COVID-19 vaccines are being administered and dosing schedule.

We have amended the first paragraph in the background section (page 2) to:

The vaccination programme for COVID-19 in the United Kingdom (UK) was started on 8 December 2020. Vaccination was in order of priority groups determined by the Joint Committee on Vaccination and Immunisation (JCVI) expert advisory group[6]: initially to people aged 80+ years, health and care workers and care home residents, people aged 70-79 and those extremely clinically vulnerable, followed by remaining adults in order of decreasing age or at increased risk. The Medicines and Healthcare products Regulatory Agency (MHRA) has so far approved four COVID-19 vaccines for use in the United Kingdom (UK), with each of the three vaccines currently in use requiring two doses to produce maximum protection[7]. To allow a higher percentage of the population to receive one vaccine dose quicker, second doses initially followed a 12-week interval from the first. This interval has since been shortened. These vaccines and their date of first administration and current second dose schedule are as follows: the Pfizer-BioNTech BNT162b2 mRNA COVID-19 vaccine (BNT162b2; first administered 8 Dec 2020, second dose at least 21 days later); the

Oxford-AstraZeneca ChAdOx1 nCoV-19 vaccine (ChAdOx1; first administered 4 Jan 2021, second dose between 4 and 12 weeks later); the Moderna mRNA-1273 vaccine (mRNA-1273; first administered 7 April 2021, second dose 28 days later); and the Janssen Ad26.COV2.S vaccine (Ad26.COV2.S; not yet administered).

- Median follow-up was only 43 days, why is median follow-up so short if vaccinations began December 8, 2020 and follow-up was through June 30, 2021? Providing more information about the COVID-19 vaccine dosing schedule used in England may inform the shorter duration of follow-up time than one would expect if vaccines were administered 21 days apart (i.e., the median follow-up time for the study is 43 days, however the study period goes from 12/8/2020 - 6/30/21, if only 21 days between vaccine administrations, I would anticipate the median follow-up to be closer to 90 days)

We agree that given the median follow-up time of 43 days when the study period was December 2020 - June 2021 seems short, and is potentially still the case even though the study period is now until November 2021; median follow up is now 149 days. However, the median follow-up time reflects the inclusion of individuals who were not part of the initial priority groups, and who received their second dose much later and thus follow-up time is systematically different amongst individuals included in this study and no adjustment for this has been made. This is reflected in the breakdown of follow-up time by priority group in table 1 and is already highlighted as the second limitation in the limitations section on page 7. In addition, when the vaccines were first rolled out, in order to allow a higher percentage of the population to receive one vaccine dose quicker, second doses followed a 12-week interval from the first. We hope that the additional information now included (as per response above) above about the COVID-19 vaccine dosing schedule used in England will help to make this clearer.

Minor issues:

- Page 4
o Line 9 - "aged over 16" please add "years" to better define age group
Added “years”

o Line 46 - "age 16 or over" - please add "years" - "age 16 years or over". Also, please insert by what date a person must be 16 years or over.
Added “years”.
We have already started by what date a person must be 16 years or over in the last line on page 3: In line with the national reporting specification, most criteria were ascertained using the latest available data at the time of analysis, with the exception of age which was calculated as at 31 March 2021 as recommended by Public Health England.

o Line 56, remove the colon after "of"
Removed

- Page 5
o Line 4, please define HES
Now defined (Hospital Episode Statistics (HES))

o Line 11, please list actual ICD-10 codes used rather than having readers sent to a website
Added (U071, U072). Note we have left the reference as this backs up the use of these codes.

- Page 5/6 - key demographic and clinical characteristics should be combined with codelists and implementation section
The information covered in the "Codelists and implementation" subsection generically describes the derivation of all variables in the study, including inclusion/exclusion criteria and outcomes. It therefore relates to the entire methods section, not just the "covariates" subsection.

We have changed "covariates" to "variables" in this section to reflect this.

- Page 6
o Line 1 - missing ending parenthesis
Removed unnecessary parenthesis rather than adding one.

Additional updates due to extended follow-up time:

Abstract, page 1

Background section

- To reduce word count:
    - Changed “While the vaccines against COVID-19 are considered to be highly effective, COVID-19 vaccine breakthrough is likely and a small number of people will still fall ill, be hospitalised, or die from COVID-19, despite being fully vaccinated. With the continued increase in numbers of positive SARS-CoV-2 tests, describing the characters of individuals who have experienced a COVID-19 vaccine breakthrough could be hugely important in helping to determine who may be at greatest risk.” to “While the vaccines against COVID-19 are highly effective, COVID-19 vaccine breakthrough is possible despite being fully vaccinated. With SARS-CoV-2 variants still circulating, describing the characteristics of individuals who have experienced COVID-19 vaccine breakthroughs could be hugely important in helping to determine who may be at greatest risk.”

Results section

- Added in COVID-19-related critical care admission outcome
- To reduce word count:
    - The last two sentences have been changed from “*when broken down by the initial priority group, higher rates of hospitalisation and death were seen in those in care homes. Comorbidities with the highest rates of breakthrough COVID-19 included renal replacement therapy, organ transplant, haematological malignancy, and immunocompromised*” to “*The highest rates of breakthrough COVID-19 were seen in those in care homes, and in patients with chronic kidney disease, dialysis, transplant, haematological malignancy, or who were immunocompromised*”

Conclusion:

- Added in
    - the emergence of the Omicron variant of COVID-19 coupled with the number of positive SARS-CoV-2 tests still occurring is concerning
    - and boosted
    - to assess vaccine waning and rates of breakthrough COVID-19 between different variants

Results, page 5

Added in

- Testing behaviours varied between priority groups with individuals in care homes testing more regularly than other groups; 91% of care home residents had 3+ SARS-CoV-2 tests since being fully vaccinated vs 41%-73% in other groups.
- COVID-19-related critical care admission outcome
- Updated all numbers in text

Discussion, page 7

Added in

- While it is possible to adjust rates (as demonstrated for patients with chronic kidney disease in Supplementary Table S1) to help inform decisions around rollout of vaccine/booster programme for patients at high risk of adverse outcomes
- the emergence of the Omicron variant of COVID-19 coupled with the number of positive SARS-CoV-2 tests still occurring is concerning
- and boosted
- to assess vaccine waning and rates of breakthrough COVID-19 between different variants

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Describing the population experiencing COVID-19 vaccine breakthrough following second vaccination in England: A cohort study from OpenSAFELY

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Abstract

Background

While the vaccines against COVID-19 are highly effective, COVID-19 vaccine breakthrough is possible despite being fully vaccinated. With SARS-CoV-2 variants still circulating, describing the characteristics of individuals who have experienced COVID-19 vaccine breakthroughs could be hugely important in helping to determine who may be at greatest risk.

Method

With the approval of NHS England we conducted a retrospective cohort study using routine clinical data from the OpenSAFELY-TPP database of fully vaccinated individuals, linked to secondary care and death registry data, and described the characteristics of those experiencing COVID-19 vaccine breakthroughs.

Results

As of 01st November 2021, a total of 15,501,550 individuals were identified as being fully vaccinated against COVID-19, with a median follow-up time of 149 days (IQR: 107-179). From within this population, a total of 579,780 (<4%) individuals reported a positive SARS-CoV-2 test. For every 1,000 years of patient follow-up time, the corresponding incidence rate (IR) was 98.06 (95% CI 97.93-98.19). There were 28,580 COVID-19-related hospital admissions, 1,980 COVID-19-related critical care admissions and 6,435 COVID-19-related deaths; corresponding IRs 4.77 (95% CI 4.74-4.80), 0.33 (95% CI 0.32-0.34) and 1.07 (95% CI 1.06-1.09), respectively. The highest rates of breakthrough COVID-19 were seen in those in care homes and in patients with chronic kidney disease, dialysis, transplant, haematological malignancy or who were immunocompromised.

Conclusion

While the majority of COVID-19 vaccine breakthrough cases in England were mild, some differences in rates of breakthrough cases have been identified in several clinical groups. While it is important to note that these findings are simply descriptive and cannot be used to answer why certain groups have higher rates of COVID-19 breakthrough than others, the emergence of the Omicron variant of COVID-19 coupled with the number of positive SARS-CoV-2 tests still occurring is concerning and as numbers of fully vaccinated (and boosted) individuals increases and as follow-up time lengthens, so too will the number of COVID-19 breakthrough cases. Additional analyses, to assess vaccine waning and rates of breakthrough COVID-19 between different variants, aimed at identifying individuals at higher risk, are needed.

Keywords

COVID-19; Vaccine breakthrough; EHR data

Background

The vaccination programme for COVID-19 in the United Kingdom (UK) was started on 8 December 2020. Vaccination was in order of priority groups determined by the Joint Committee on Vaccination and Immunisation (JCVI) expert advisory group [1]: initially to people aged 80+ years, health and care workers and care home residents, people aged 70-79 and those extremely clinically vulnerable, followed by remaining adults in order of decreasing age or at increased risk. The Medicines and Healthcare products Regulatory Agency (MHRA) has so far approved four COVID-19 vaccines for use in the United Kingdom (UK), with each of the three vaccines currently in use requiring two doses to produce maximum protection [2]. To allow a higher percentage of the population to receive one vaccine dose quicker, second doses initially followed a 12-week interval from the first. This interval has since been shortened. These vaccines and their date of first administration and current second dose schedule are as follows: the Pfizer-BioNTech BNT162b2 mRNA COVID-19 vaccine (BNT162b2; first administered 8 Dec 2020, second dose at least 21 days later); the Oxford-AstraZeneca ChAdOx1 nCoV-19 vaccine (ChAdOx1; first administered 4 Jan 2021, second dose between 4 and 12 weeks later); the Moderna mRNA-1273 vaccine (mRNA-1273; first administered 7 April 2021, second dose 28 days later); and the Janssen Ad26.COV2.S vaccine (Ad26.COV2.S; not yet administered). As of November 1st, 2021 78.7% of individuals aged over 16 years in England had been fully vaccinated (i.e., ≥14 days have passed since the receipt of their second dose of a COVID-19 vaccine) [3].

The vaccines against COVID-19 are considered to be highly effective and there is strong evidence that the UK's COVID-19 vaccination programme has reduced infection and severe outcomes in vaccinated individuals [4, 5][4, 6], [4, 5]. However, breakthrough infections after vaccination against SARS-CoV-2 are increasingly reported [7] and there are concerns that the effectiveness of the vaccines may fade over time, due to the vaccines being less effective against the delta variant, and/or the waning of the immune response [8]. In addition, as no vaccine is 100% effective, COVID-19 vaccine breakthrough is likely (i.e., a small number of people will still get sick, be hospitalised, or die from COVID-19, despite being fully vaccinated). Describing individuals who have experienced a COVID-19 vaccine breakthrough could provide the first indication that the COVID-19 vaccine is less effective in certain groups and could be hugely important in helping to determine who may be at greatest risk and therefore might benefit most from booster doses.

To that end we used the new secure data analytics platform, OpenSAFELY [9] (built by our group on behalf of NHS England to support analysis of important questions related to COVID-19) to: describe breakthrough COVID-19 among fully vaccinated individuals in England; and to describe how breakthrough COVID-19 varied between priority groups and by clinical and demographic characteristics.

Methods

Data sources

This OpenSAFELY study was conducted using the OpenSAFELY-TPP database which contains records for approximately 24 million people currently registered with GP surgeries using TPP SystmOne software (approximately 40% of the English population).

Study population

The base population consisted of all individuals aged 16 years or over with records indicating that they had received two COVID-19 vaccination doses since 8 December 2020 (the earliest vaccination date in England) and who were still alive and registered 2 weeks after their second dose. Individuals were excluded if they tested positive for SARS-CoV-2 or had been hospitalised or died due to COVID-19 within the 2 weeks after their second dose. Follow up started 14 days after an individual's second dose of the COVID-19 vaccination (the point by which individuals were classified as being fully vaccinated) and individuals were followed up until 01st November 2021 or until the first occurrence of the outcome of interest; death; practice de-registration.

Outcomes

Four outcomes were assessed: positive SARS-CoV-2 swab test, via SGSS and based on swab date (we did not distinguish between symptomatic and asymptomatic infection for this outcome, nor PCR and lateral flow testing); COVID-19 related hospital admissions via Hospital Episode Statistics (HES) in-patient records (using both primary and non-primary diagnosis codes); COVID-19 related critical care admissions via HES and COVID-19-related death, via linked death registry records, which included individuals who died within 28-days of positive SARS-CoV-2 test or who had COVID-19 mentioned on the death certificate as one of the causes. COVID-19 hospitalisation variables were derived using two ICD-10 COVID-19 diagnosis codes; U071, U072 [10]. Outcomes were only included if they occurred 14 days or more after an individual's second dose of a COVID-19 vaccination.

Priority groups for vaccination

Individuals were classified into seven priority groups (box 1), based on the Joint Committee on Vaccination and Immunisation (JCVI) priority groups [11] using SNOMED-CT codelists and logic defined in the national COVID-19 Vaccination Uptake Reporting Specification developed by PRIMIS [12]. Individuals were assigned only to their highest priority group and not included again as part of any other priority group. In line with the national reporting specification, most criteria were ascertained using the latest available data at the time of analysis, with the exception of age which was calculated as at 31 March 2021 as recommended by Public Health England.

Box 1 – *Priority groups for vaccination.*

JCVI Risk group	Priority group	
	Description	**Name**
1	Residents in a care home for older adults, aged 65+	Care home
2	All those 80 years of age and over	80+
	Health and social care workers	Health/Care workers
3	All those 70 years of age and over	70-79
4	Clinically extremely vulnerable individuals	CEV
5,7,8,9	All those 50 years of age and over	50-69
6	"At Risk" individuals, some misclassified health/care workers and care home residents (except those age 70+ or shielding who will be included in another group), carers, household contacts of those at increased risk, and those not in priority groups who had the vaccine opportunistically, e.g. by responding to calls to use up excess doses.	Others not in the above groups

Key demographic and clinical characteristics

Key clinical and demographic groups which were considered to have a higher possibility of experiencing a COVID-19 vaccine breakthrough were identified from previous studies [13–17]. This included age, sex, body mass index (BMI; kg/m^2), smoking status, deprivation (measured by the Index of Multiple Deprivation (IMD) as quintiles, ethnicity, NHS region of patient's general practice, asplenia, asthma, blood pressure, cancer, chronic kidney disease, diabetes mellitus, dialysis, heart disease, haematological malignancy, immunocompromised, learning disability, liver disease, neurological diseases, respiratory disease, severe mental illness and transplant. Other variables considered were time since being fully vaccinated, time between vaccinations and any evidence of a prior SARS-CoV-2 infection.

Codelists and implementation

Information on all variables were obtained from primary care records by searching TPP SystmOne records for specific coded data. Detailed information on compilation and sources for every individual codelist is available at https://codelists.opensafely.org/ and the lists are available for inspection and re-use by the broader research community.

Missing data

Individuals with missing ethnicity, IMD and region were included as "Unknown".

Statistical methods

Simple descriptive statistics were used to summarise the counts and rates of COVID-19 vaccine breakthrough. Rates for each outcome were estimated by dividing the count by

person-years, with 95% confidence intervals. Counts and rates were stratified by initial priority groups for all outcomes and by selected clinical and demographic groups.

Software and Reproducibility

Data management and analysis was performed using the OpenSAFELY software libraries, Python 3 and R version 4.0.2. All code for the OpenSAFELY platform for data management, analysis and secure code execution is shared for review and re-use under open licenses at GitHub.com/OpenSAFELY. All code for data management and analysis for this paper is shared for scientific review and re-use under open licenses on GitHub (https://github.com/opensafely/covid-19-vaccine-breakthrough).

Patient and Public Involvement

Any patient or member of the public is invited to contact us at https://opensafely.org/ regarding this study or the broader OpenSAFELY project.

Results

Study population

Out of approximately 24 million patients, 15,501,550 individuals were identified as being fully vaccinated against COVID-19 and included in this study (Figure 1). The median follow-up time was 149 days (interquartile range: 107 - 179 days). Since being fully vaccinated, 8,370,837 (54%) of the base population had at least one record for a (positive/negative) SARS-CoV-2 test recorded, with a positivity rate of 3.17%. Testing behaviours varied between priority groups with individuals in care homes testing more regularly than other groups; 91% of care home residents had 3+ SARS-CoV-2 tests since being fully vaccinated vs 41%-73% in other groups. The total number of COVID-19 vaccine breakthrough cases was 590,279 (<4%). Table 1 shows the number and rate of individuals fully vaccinated broken down by initial JCVI priority groups, along with the number and rate (per 1,000 patient years) of each outcome.

Positive SARS-CoV-2 test

In fully vaccinated individuals, the median number of days to a positive test for SARS-CoV-2 was 99 (IQR 63 - 134 days) with a total of 579,780 individuals testing positive for SARS-CoV-2 (about 1 in 25 or <4%). For every 1,000 years of patient follow-up time, the corresponding incidence rate was 98.06 (95% CI 97.93-98.19). Within the initial JCVI priority groups, positive SARS-CoV-2 test rates were highest in the CEV group (107.84, 95% CI 107.27-108.42) and lowest in those over 80 years of age (26.69, 95% CI 26.48-26.90). The overall cumulative incidence of positive SARS-CoV-2 tests at 275 days from the study start date was <0.1% (Figure 2).

When broken down into clinical/demographic groups and comorbidities (Table 2), rates of individuals testing positive for SARS-CoV-2 were highest in 40-40 year olds (179.96, 95% CI 179.50-180.42) and lowest in individuals over 80 years of age (28.90, 95% CI 28.69-29.11). Rates were higher in females than in males: 102.60 (95% CI 102.42-102.78) vs 92.76 (95% CI 92.58-92.95), respectively. Comorbidities with the highest rates of positive SARS-CoV-2

tests included kidney transplant, dialysis and immunocompromised; 143.51 (95% CI 136.46-150.93), 134.75 (95% CI 124.32-146.06), 91.53 (95% CI 90.91-92.15), respectively. Rates of positive SARS-CoV-2 tests were lowest 4-8 weeks after being fully vaccinated and highest at 12+ weeks; 48.65 (95% CI 47.97-49.33) vs 100.3 (95% CI 100.16-100.43), respectively.

COVID-19 related hospital admission

From within the fully vaccinated population, 28,580 had a COVID-19 related hospital admission (about 1 in 550 or 0.18%), with a median time to hospitalisation of 143 days (IQR 102-174). Of those who had a COVID-19 related hospital admission, 18,800 (66%) had a positive SARS-CoV-2 test in their records; 9,170 (49%) occurred prior to an individual being hospitalised, 7030 (37%) occurred within the first 2 days of their hospital admission, 2365 (13%) occurred between 3 and 29 days after being hospitalised and 235 (1%) occurred 30 days or more after an individual had been hospitalised.

Rates of COVID-19 related hospital admissions increased with age; 1.09 (1.84-1.96) for 16-29 year olds vs 12.75 (12.61-12.89) for those over 80 years, respectively. Rates were higher in those who were more deprived; most deprived IMD quintile versus least deprived IMD quintile was 7.32 (7.23-7.41) vs 3.55 (3.5-3.61), respectively. Comorbidities with the highest rates of COVID-19 related hospital admissions included kidney transplant, dialysis, and chronic kidney disease; 76.08 (95% CI 71.03-81.49), 70.73 (95% CI 63.34-78.99), 49.49 (95% CI 45.33-54.02), respectively.

COVID-19 related critical care admission

Of the 28,580 COVID-19 related hospital admission, 1,980 needed to be admitted to critical care (about 1 in 1000 of fully vaccinated people or 1 in 14 of hospitalised patients), with a median time to critical care admission of 136 days (IQR 94-166). For every 1,000 years of patient follow-up time, the corresponding incidence rate was 0.33 (95% CI 0.32-0.34). Within the initial JCVI priority groups, COVID-19 related critical care admissions rates were highest in the CEV group (1.73, 95% CI 1.66-1.80) and lowest in health care workers 0.10 (95% CI 0.08-0.12).

Rates of COVID-19 related critical care admissions were higher in males than females and in; 0.45 (95% CI 0.44-0.46) vs 0.23 (95% CI 0.22-0.24), respectively. Rates were higher in those who were obese compared to not obese; BMI >30 (kg/m2) versus BMI <30 (kg/m2) was 0.68 (0.66-0.71) vs 0.22 (0.21-0.23), respectively. Comorbidities with the highest rates of COVID-19 related critical care admissions included dialysis, kidney transplant and chronic kidney disease; 19.74 (95% CI 16.03-24.32), 17.86 (95% CI 15.5-20.57) and 5.31 (95% CI 4.06-6.93), respectively.

COVID-19 related death

Of those who were fully vaccinated, 6,435 had a COVID-19 related death (about 1 in 2500 or 0.04%) with a median number of days to death of 165 (IQR 129-188). While the majority (43%) of deaths occurred in the 80+ JCVI priority group, COVID-19 related death rates were three times as high among individuals living in care homes compared to those over 80 years living in private residences; 13.37 (95% CI 12.86-13.91) vs 4.64 (95% CI 4.56-4.73), respectively.

There were very few deaths in those under 30 years of age with rates of COVID-19-related death increasing with increased age; 0.02 (95% CI 0.02-0.03) for 16-29 year olds vs 5.26 (95% CI 5.17-5.35) for those over 80 years, respectively. Comorbidities with the highest rates of COVID-19-related death included dialysis, transplant and chronic kidney disease; 25.71 (95% CI 21.42-30.86), 18.9 (95% CI 16.47-21.68), and 17.81 (95% CI 15.40-20.61), respectively.

Discussion

Summary

This descriptive analysis in over 15 million people living in England shows that COVID-19 vaccine breakthrough is occurring, however, events are currently rare and mostly mild in nature. Nevertheless, some individuals are experiencing higher rates of serious illness and death due to COVID-19, such as those in care homes, with chronic kidney disease, on dialysis, with a transplant or who are immunosuppressed. It is important to note that this analysis is a simple descriptive piece of analysis. While it is possible to adjust rates (as demonstrated for patients with chronic kidney disease in Supplementary Table S1) to help inform decisions around rollout of vaccine/booster programme for patients at high risk of adverse outcomes, it is important to stress that this study was not designed to estimate risk factors for COVID-19 vaccine breakthrough and thus cannot be used to answer why certain groups have higher rates of breakthrough cases than others or to estimate vaccine effectiveness.

Strengths and weaknesses

This study used large-scale, routinely-collected primary care records, linked to coronavirus testing surveillance, hospital, and death registry data. This allowed us to describe a substantial proportion of the English population in rich longitudinal detail and to detect variations in COVID-19 vaccine breakthrough cases, as early as possible.

We acknowledge several important limitations of these findings. First, even though the base population consisted of over 15 million fully vaccinated individuals the numbers of COVID-19 vaccine breakthrough cases were relatively small, especially for hospitalisations and deaths. This made comparisons between outcomes, specifically at selected clinical and demographic levels difficult, meaning rates could be imprecisely estimated. Second, due to the targeted roll out of the COVID-19 vaccination programme in England, this cohort represents mostly older and vulnerable populations. In addition, follow-up time is systematically different amongst individuals included in this study and no adjustment for this has been made. Third, asymptomatic testing patterns vary between individuals. Apart from health and care workers, asymptomatic individuals without any underlying health issues or comorbidities are less likely to get tested than those with underlying health issues or comorbidities (i.e., haemodialysis patients) who will undergo asymptomatic testing regularly. Most lateral flow tests conducted at home are not included in our data. The number of reported positive SARS-CoV-2 tests is therefore likely to be an undercount of SARS-CoV-2 among fully vaccinated individuals without any underlying health issues or comorbidities,

which may have led to underestimation of the corresponding rates. Fourth, individuals were excluded if they tested positive for SARS-CoV-2 or had been hospitalised or died due to COVID-19 within the two weeks after their second dose, we acknowledge that there is still the potential that some patients will have been included whose outcome was related to a previous infection pre second vaccination, in particular in some of the highest risk groups such as dialysis patients and those in care homes where there a high amount of repeated screening in, resulting in a potential increase in rates. Fifth, characteristics linked to COVID-19 vaccine breakthrough in fully vaccinated individuals may be reflective of higher infection rates regardless of vaccination in some groups, not because of vaccination (i.e. due to higher exposure due to behavioural differences) [18]. Finally, this study includes data from December 2020 until November 2021, during which time two different variants of SARS-COV-2 were dominating in England at different times; the Alpha variant (B.1.1.7) between January 2021 and May 2021, and the Delta variant (B.1.617.2) after June 2021[19]. These have since been supplanted by other variants, in particular the Omicron variant. This is a descriptive study and does not aim to quantify the contribution of vaccine breakthrough due to the change in dominant variant from Alpha to Delta or the extent of waning in the months immediately following vaccination. Further studies are needed to assess vaccine waning and rates of breakthrough COVID-19 between different variants and in newer, more prevalent variants, such as Omicron (B.1.1.529).

Findings in Context

There is strong evidence that the UK's COVID-19 vaccination programme has reduced infection and severe outcomes in vaccinated individuals[4, 5]. However, breakthrough infections after vaccination against SARS-CoV-2 are increasingly reported[7] and there are concerns that the effectiveness of the vaccines may reduce over time, due to the vaccines being less effective against the delta variant, and/or the waning of the immune response[8]. While we did find that breakthrough infections were more frequent in the earlier-vaccinated individuals, potentially due to waning vaccine efficacy or impaired immune response, further studies are needed to gain a clearer picture of the long-term effectiveness of COVID-19 vaccines. In addition, with only a handful of studies investigating risk factors for post-vaccination infection [13, 16, 17], very little is known about how breakthrough COVID-19 varies between key clinical and demographic groups. Our findings on COVID-19 vaccine breakthrough are consistent with patterns observed worldwide; COVID-19 vaccine breakthrough cases are rare and mild. However, there are potentially several groups who are at higher risk of COVID-19 vaccine breakthrough including those in care-homes, with chronic kidney disease, on dialysis, with transplants or who are immunocompromised.

Conclusion

As of 1st November 2021, the majority of COVID-19 vaccine breakthrough cases in England were mild with relatively smaller numbers of fully vaccinated individuals being hospitalised or dying as a result of COVID-19. While these numbers are in line with expectations, and while follow-up time is systematically different amongst fully vaccinated individuals and variation in vaccination coverage between groups and regions will have many complex drivers, some differences in rates of breakthrough cases were identified in several clinical groups. the emergence of the Omicron variant of COVID-19 coupled with the number of positive SARS-CoV-2 tests still occurring is concerning and as numbers of fully vaccinated (and

boosted) individuals increases and as follow-up time lengthens, so too will the number of COVID-19 breakthrough cases. Additional analyses are therefore, to assess vaccine waning and rates of breakthrough COVID-19 between different variants, and to enable identification of individuals at higher risk, who would require continued strict precautions, and additional vaccination.

Abbreviations

Body Mass index (BMI); Joint Committee Vaccination and Immunisation (JCVI); Index of Multiple Deprivation (IMD); United Kingdom (UK).

Declarations

Information governance and ethical approval

NHS England is the data controller; TPP is the data processor; and the key researchers on OpenSAFELY are acting with the approval of NHS England. This implementation of OpenSAFELY is hosted within the TPP environment which is accredited to the ISO 27001 information security standard and is NHS IG Toolkit compliant[17,18]; Patient data has been pseudonymised for analysis and linkage using industry standard cryptographic hashing techniques; all pseudonymised datasets transmitted for linkage onto OpenSAFELY are encrypted; access to the platform is via a virtual private network (VPN) connection, restricted to a small group of researchers; the researchers hold contracts with NHS England and only access the platform to initiate database queries and statistical models; all database activity is logged; only aggregate statistical outputs leave the platform environment following best practice for anonymisation of results such as statistical disclosure control for low cell counts[16] . The OpenSAFELY research platform adheres to the obligations of the UK General Data Protection Regulation (GDPR) and the Data Protection Act 2018. In March 2020, the Secretary of State for Health and Social Care used powers under the UK Health Service (Control of Patient Information) Regulations 2002 (COPI) to require organisations to process confidential patient information for the purposes of protecting public health, providing healthcare services to the public and monitoring and managing the COVID-19 outbreak and incidents of exposure; this sets aside the requirement for patient consent[17] . Taken together, these provide the legal bases to link patient datasets on the OpenSAFELY platform. GP practices, from which the primary care data are obtained, are required to share relevant health information to support the public health response to the pandemic, and have been informed of the OpenSAFELY analytics platform.

This study was approved by the Health Research Authority (REC reference 20/LO/0651) and by the LSHTM Ethics Board (reference 21863).

Availability of data and materials

Access to the underlying identifiable and potentially re-identifiable pseudonymised electronic health record data is tightly governed by various legislative and regulatory frameworks, and restricted by best practice. The data in OpenSAFELY is drawn from General Practice data across England where TPP is the Data Processor. TPP developers (CB, RC, JP, FH, and SH) initiate an automated process to create pseudonymised records in the core OpenSAFELY database, which are copies of key structured data tables in the identifiable records. These are linked onto key external data resources that have also been pseudonymised via SHA-512 one-way hashing of NHS numbers using a shared salt. DataLab developers and PIs (BG, LS, CEM, SB, AJW, WH, DE, PI, and CTR) holding contracts with NHS England have access to the OpenSAFELY pseudonymised data tables as needed to develop the OpenSAFELY tools. These tools in turn enable researchers with OpenSAFELY Data Access Agreements to write and execute code for data management and data analysis without direct access to the underlying raw pseudonymised patient data, and to review the outputs of this code. All code for the full data management pipeline—from raw data to completed results for this analysis—and for the OpenSAFELY platform as a whole is available for review at github.com/OpenSAFELY.

Competing interests

All authors have completed the ICMJE uniform disclosure form and declare the following: BG has received research funding from Health Data Research UK (HDRUK), the Laura and John Arnold Foundation, the Wellcome Trust, the NIHR Oxford Biomedical Research Centre, the NHS National Institute for Health Research School of Primary Care Research, the Mohn-Westlake Foundation, the Good Thinking Foundation, the Health Foundation, and the World Health Organisation; he also receives personal income from speaking and writing for lay audiences on the misuse of science. IJD holds shares in GlaxoSmithKline (GSK).

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Funders had no role in the study design, collection, analysis, and interpretation of data; in the writing of the report and in the decision to submit the article for publication.
The views expressed are those of the authors and not necessarily those of the NIHR, NHS England, Public Health England or the Department of Health and Social Care.

Authors' contributions

Contributions are as follows:
Conceptualisation: RM, CTR, KB, RME, LS, BG, BM, HJC, SJWE, KK, DH, KR
Funding acquisition: LS, BG, RME
Methodology: AG, HC, WH, EW, HMD, AW, LF, CA, LH, CM, BMK, RC, JM, AM, KB,AS,CR,AR,LF,LT, RM, AW, HF, SE, LS, BG
Formal analysis: AG, HC
Codelists: RM, LT, AS, AJW, CM, BG, WJH, SB, AM
Software: AW, CB, JC, DE, PI, CM, WH, BN, SB, HC, ND, RC, JP, FH, SH
Visualisation: AG, HC, WH, EW

Writing - original draft: AG
Writing- review & editing: ALL
Information governance: CB LS BG AM

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Guarantor

BG is guarantor.

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Figures, tables and additional files

Table 1. *Number of individuals fully vaccinated (2 doses + 2 weeks) in initial priority groups in OpenSAFELY-TPP, and number and rate with each outcome.*

Priority Group	Fully vaccinated						Positive SARS-CoV-2 test †			COVID-19-related hospital admission †		COVID-19-related critical care admission †		COVID-19 related death †	
	Count*	Follow-up time, medium days (IQR)	Tests conducted (%)				Positivity (%)	Events* (PYs)	Incidence rate per 1000 person-years (95% CI)	Events* (PYs)	Incidence rate per 1000 person-years (95% CI)	Events* (PYs)	Incidence rate per 1000 person-years (95% CI)	Events* (PYs)	Incidence rate per 1000 person-years (95% CI)
			0	1	2	3+									
All	15501550	149 (107-179)	46	19	10	19	579780 (5912498)	3.17	98.06 (97.93-98.19)	28580 (5993535)	4.77 (4.74-4.8)	1980 (5996007)	0.33 (0.32-0.34)	6435 (5996178)	1.07 (1.06-1.09)
Care home (priority group 1)	98400	200 (180-207)	9	5	4	82	3110 (48207)	0.90	64.51 (63.37-65.68)	755 (48600)	15.58 (15.02-16.15)	REDACTED	REDACTED	650 (48674)	13.37 (12.86-13.91)
80+ (priority group 2)	1073145	200 (191-213)	59	14	7	20	15945 (597368)	1.96	26.69 (26.48-26.9)	7545 (598868)	12.60 (12.45-12.74)	180 (599613)	0.30 (0.28-0.32)	2785 (599626)	4.64 (4.56-4.73)
Health/care workers (priority groups 1-2)	555820	200 (182-211)	27	21	14	39	30045 (282813)	3.31	106.23 (105.62-106.84)	440 (287822)	1.53 (1.46-1.60)	30 (287862)	0.10 (0.08-0.12)	20 (287866)	0.07 (0.05-0.08)
70-79 (priority groups 3-4)	1990755	184 (176-191)	56	17	8	19	41325 (985544)	2.16	41.93 (41.73-42.14)	6875 (990497)	6.94 (6.86-7.03)	525 (991111)	0.53 (0.51-0.56)	1640 (991147)	1.66 (1.62-1.70)
CEV (age 16-69) (priority group 4)	725045	171 (157-181)	42	18	10	30	34820 (322885)	2.92	107.84 (107.27-108.42)	4560 (327932)	13.90 (13.7-14.11)	565 (328308)	1.73 (1.66-1.80)	785 (328361)	2.39 (2.31-2.48)
50 - 69 (priority groups 5-9)	4730155	151 (138-166)	47	18	9	26	184890 (1946451)	2.27	94.99 (94.77-95.21)	5075 (1973346)	2.57 (2.54-2.61)	515 (1973743)	0.26 (0.25-0.27)	495 (1973791)	0.25 (0.24-0.26)
Others not in the above groups* **	15501550	149 (107-179)	46	19	10	19	579780 (5912498)	3.17	98.06 (97.93-98.19)	28580 (5993535)	4.77 (4.74-4.80)	1980 (5996007)	0.33 (0.32-0.34)	6435 (5996178)	1.07 (1.06-1.09)

† Calculated as of 01st November 2021

*All counts (of people and events) have been rounded to the nearest 5 and counts < 8 have been redacted

**This is a count of (positive and negative) test results and may include multiple tests for an individual person

***Others includes: others in priority groups ("At Risk"), some misclassified health/care workers and care home residents (except those age 70+ or shielding who will be included in another group), carers, household contacts of those at increased risk, and those not in priority groups who had the vaccine opportunistically, e.g. by responding to calls to use up excess doses.

Table 2 *Count and rates of breakthrough* positive SARS-CoV-2 tests *and hospitalisation and death in fully vaccinated individuals in OpenSAFELY-TPP, broken down by selected clinical and demographic groups*

Clinical/ demographic group	Category	Fully vaccinated						Positive SARS-CoV-2 test			Hospitalised with COVID-19		COVID-19-related critical care admission		COVID-19 related death	
		Count*	Follow-up time, medium days (IQR)	Tests conducted (%)				Positivity (%)	Events* (PYs)	Incidence rate per 1000 person-years (95% CI)	Events* (PYs)	Incidence rate per 1000 person-years (95% CI)	Events* (PYs)	Incidence rate per 1000 person-years (95% CI)	Events* (PYs)	Incidence rate per 1000 person-years (95% CI)
				0	1	2	3+									
Age	16 - 29	2227120	66 (47-129)	45	21	11	22	63620 (516289)	5.47	123.22 (122.74-123.71)	1000 (527073)	1.90 (1.84-1.96)	40 (527145)	0.07 (0.06-0.08)	10 (527150)	0.02 (0.01-0.02)
	30 - 39	2289165	94 (72-145)	42	21	12	25	93375 (660313)	4.50	141.41 (140.95-141.88)	1550 (673014)	2.30 (2.25-2.36)	80 (673118)	0.12 (0.10-0.13)	35 (673127)	0.05 (0.04-0.06)
	40 - 50	2459075	126 (103-155)	40	20	11	29	153210 (851368)	3.86	179.96 (179.5-180.42)	2320 (871625)	2.66 (2.61-2.72)	210 (871799)	0.24 (0.22-0.26)	120 (871821)	0.14 (0.12-0.15)
	50 - 59	2942440	146 (135-163)	43	19	10	28	136470 (1188958)	2.49	114.78 (114.47-115.09)	3850 (1209351)	3.18 (3.13-3.23)	420 (1209663)	0.35 (0.33-0.37)	370 (1209705)	0.31 (0.29-0.32)
	60 - 69	2421245	163 (150-174)	49	18	9	24	72735 (1064063)	1.94	68.36 (68.1-68.61)	4715 (1074117)	4.39 (4.33-4.45)	530 (1074498)	0.49 (0.47-0.52)	845 (1074542)	0.78 (0.76-0.81)
	70 - 79	2016365	184 (176-191)	56	17	8	19	42075 (998433)	2.11	42.14 (41.93-42.34)	7050 (1003480)	7.03 (6.94-7.11)	530 (1004114)	0.53 (0.51-0.55)	1720 (1004149)	1.71 (1.67-1.76)
	80 +	1146150	200 (191-213)	55	14	7	24	18295 (633074)	1.72	28.9 (28.69-29.11)	8095 (634874)	12.75 (12.61-12.89)	180 (635670)	0.29 (0.27-0.31)	3345 (635683)	5.26 (5.17-5.35)
Sex	Female	8072115	155 (116-184)	43	19	10	28	326565 (3182819)	2.69	102.6 (102.42-102.78)	13500 (3228984)	4.18 (4.14-4.22)	740 (3230164)	0.23 (0.22-0.24)	2655 (3230233)	0.82 (0.81-0.84)
	Male	7429435	144 (99-174)	50	19	10	21	253215 (2729679)	4.04	92.76 (92.58-92.95)	15080 (2764551)	5.46 (5.41-5.50)	1250 (2765843)	0.45 (0.44-0.46)	3780 (2765945)	1.37 (1.34-1.39)
BMI (kg/m2)	Not obese	12078955	145 (98-178)	46	19	10	25	429315 (4498201)	3.20	95.44 (95.3-95.59)	18330 (4558086)	4.02 (3.99-4.05)	1010 (4559694)	0.22 (0.21-0.23)	4475 (4559783)	0.98 (0.97-1.00)
	Obese (>30)	3422600	159 (135-181)	46	19	10	26	150465 (1414297)	3.07	106.39 (106.11-106.66)	10255 (1435449)	7.14 (7.07-7.21)	980 (1436313)	0.68 (0.66-0.71)	1965 (1436395)	1.37 (1.34-1.40)
Smoking	Non-smoker and unknown	7833690	143 (91-176)	45	19	10	26	291000 (2835776)	3.19	102.62 (102.43-102.81)	9960 (2876640)	3.46 (3.43-3.50)	675 (2877506)	0.24 (0.23-0.24)	1860 (2877571)	0.65 (0.63-0.66)
	Current and former	7667865	156 (125-182)	47	19	10	24	288780 (3076722)	3.14	93.86 (93.68-94.03)	18620 (3116894)	5.97 (5.93-6.02)	1310 (3118501)	0.42 (0.41-0.43)	4575 (3118607)	1.47 (1.45-1.49)

Clinical/ demographic group	Category	Fully vaccinated						Positive SARS-CoV-2 test			Hospitalised with COVID-19		COVID-19-related critical care admission		COVID-19 related death	
		Count*	Follow-up time, medium days (IQR)	Tests conducted (%)				Positivity (%)	Events* (PYs)	Incidence rate per 1000 person-years (95% CI)	Events* (PYs)	Incidence rate per 1000 person-years (95% CI)	Events* (PYs)	Incidence rate per 1000 person-years (95% CI)	Events* (PYs)	Incidence rate per 1000 person-years (95% CI)
				0	1	2	3+									
Ethnicity	White	11895195	154 (119-182)	44	19	10	26	466170 (4688366)	3.08	99.43 (99.29-99.58)	25500 (4753382)	5.36 (5.33-5.40)	1760 (4755592)	0.37 (0.36-0.38)	5905 (4755742)	1.24 (1.23-1.26)
	Mixed	151275	129 (76-164)	44	20	11	25	4980 (50030)	3.78	99.56 (98.16-100.98)	195 (50764)	3.82 (3.56-4.11)	20 (50779)	0.35 (0.28-0.45)	25 (50780)	0.51 (0.42-0.62)
	Asian or Asian British	901520	134 (81-170)	55	19	10	17	29830 (309199)	4.24	96.48 (95.92-97.04)	1735 (313404)	5.54 (5.40-5.67)	120 (313565)	0.39 (0.36-0.43)	300 (313577)	0.95 (0.90-1.01)
	Black or Black British	224740	138 (87-172)	49	18	9	23	5930 (78696)	2.98	75.37 (74.39-76.35)	415 (79581)	5.20 (4.95-5.46)	25 (79614)	0.34 (0.28-0.41)	50 (79616)	0.63 (0.55-0.72)
	Other ethnic groups	242335	122 (79-159)	50	19	10	20	5970 (78690)	3.66	75.85 (74.88-76.84)	295 (79509)	3.69 (3.48-3.91)	30 (79531)	0.38 (0.31-0.45)	55 (79534)	0.67 (0.58-0.76)
	Unknown	2086480	135 (82-164)	53	18	9	21	66900 (707517)	3.36	94.56 (94.19-94.92)	445 (716894)	0.62 (0.59-0.65)	30 (716926)	0.04 (0.03-0.05)	105 (716928)	0.14 (0.13-0.16)
IMD quintile	1 (most deprived)	2519265	146 (100-176)	54	18	9	20	96800 (927354)	3.56	104.39 (104.05-104.72)	6890 (941680)	7.32 (7.23-7.41)	460 (942314)	0.49 (0.46-0.51)	1535 (942355)	1.63 (1.59-1.67)
	2	2871570	148 (101-178)	49	19	9	23	105430 (1074696)	3.30	98.10 (97.80-98.4)	5860 (1089699)	5.38 (5.31-5.45)	410 (1090201)	0.38 (0.36-0.39)	1310 (1090236)	1.20 (1.17-1.23)
	3	3318680	150 (109-180)	46	19	10	25	119680 (1274137)	3.06	93.93 (93.66-94.2)	5595 (1290631)	4.33 (4.28-4.39)	390 (1291108)	0.30 (0.29-0.32)	1265 (1291143)	0.98 (0.95-1.01)
	4	3274460	151 (113-181)	44	19	10	27	121740 (1272731)	3.07	95.65 (95.38-95.93)	5210 (1289336)	4.04 (3.98-4.10)	380 (1289775)	0.29 (0.28-0.31)	1195 (1289806)	0.92 (0.90-0.95)
	5 (least deprived)	3115025	152 (115-181)	41	19	11	29	120245 (1220876)	2.98	98.49 (98.21-98.77)	4395 (1237218)	3.55 (3.50-3.61)	310 (1237580)	0.25 (0.24-0.26)	1020 (1237606)	0.82 (0.80-0.85)
	Unknown	402555	139 (87-173)	43	20	11	26	15885 (142704)	3.64	111.31 (110.43-112.19)	635 (144971)	4.37 (4.20-4.55)	45 (145029)	0.30 (0.25-0.35)	120 (145032)	0.82 (0.75-0.90)
Region	London	891660	129 (83-170)	40	20	12	28	21970 (304836)	4.19	72.07 (71.59-72.56)	1100 (308097)	3.57 (3.46-3.68)	70 (308184)	0.23 (0.21-0.26)	220 (308190)	0.72 (0.67-0.77)
	East of England	3629745	149 (104-179)	44	19	10	27	113725 (1380061)	2.82	82.41 (82.16-82.65)	5105 (1394975)	3.66 (3.61-3.71)	410 (1395387)	0.29 (0.28-0.31)	1215 (1395416)	0.87 (0.84-0.89)

Clinical/ demographic group	Category	Fully vaccinated						Positive SARS-CoV-2 test			Hospitalised with COVID-19		COVID-19-related critical care admission		COVID-19 related death	
		Count*	Follow-up time, medium days (IQR)	Tests conducted (%)				Positivity (%)	Events* (PYs)	Incidence rate per 1000 person-years (95% CI)	Events* (PYs)	Incidence rate per 1000 person-years (95% CI)	Events* (PYs)	Incidence rate per 1000 person-years (95% CI)	Events* (PYs)	Incidence rate per 1000 person-years (95% CI)
				0	1	2	3+									
Region (continued)	East Midlands	2702030	150 (113-177)	48	19	10	24	108255 (1029678)	3.47	105.14 (104.82-105.46)	5480 (1044633)	5.24 (5.17-5.32)	420 (1045072)	0.4 (0.38-0.42)	1215 (1045111)	1.16 (1.13-1.20)
	North East	745775	150 (115-181)	49	20	10	22	37590 (289494)	4.54	129.85 (129.18-130.52)	2170 (294874)	7.36 (7.21-7.52)	140 (295080)	0.47 (0.43-0.51)	495 (295093)	1.68 (1.61-1.76)
	North West	1402645	150 (115-180)	49	19	9	23	63570 (541871)	3.55	117.32 (116.85-117.78)	3445 (551601)	6.24 (6.14-6.35)	265 (551937)	0.48 (0.45-0.51)	780 (551962)	1.42 (1.37-1.47)
	South East	1078015	151 (108-180)	43	19	10	27	34655 (417431)	2.65	83.02 (82.58-83.47)	1715 (422133)	4.06 (3.96-4.16)	110 (422262)	0.27 (0.24-0.29)	370 (422271)	0.88 (0.84-0.93)
	South West	2314235	152 (111-180)	45	19	10	27	83030 (896729)	2.56	92.59 (92.27-92.91)	3460 (907535)	3.81 (3.75-3.88)	185 (907805)	0.20 (0.19-0.22)	760 (907822)	0.83 (0.81-0.87)
	West Midlands	548600	149 (109-179)	52	18	9	22	21340 (208833)	3.69	102.19 (101.49-102.89)	1425 (212055)	6.73 (6.55-6.91)	105 (212201)	0.50 (0.45-0.55)	300 (212211)	1.40 (1.33-1.49)
	Yorkshire and The Humber	2179520	151 (111-181)	50	19	9	22	95360 (840635)	3.44	113.44 (113.07-113.81)	4670 (854660)	5.46 (5.38-5.54)	280 (855109)	0.33 (0.31-0.35)	1080 (855132)	1.26 (1.22-1.30)
	Unknown	9325	116 (67-164)	44	20	11	25	280 (2929)	3.85	96.27 (90.7-102.17)	15 (2969)	4.71 (3.61-6.16)	REDACTED	REDACTED	REDACTED	REDACTED
Asplenia		108350	170 (154-186)	40	19	11	30	4890 (48994)	2.62	99.79 (98.37-101.22)	280 (49718)	5.59 (5.27-5.94)	15 (49744)	0.32 (0.25-0.41)	55 (49746)	1.13 (0.98-1.29)
Asthma		2336650	151 (110-178)	42	20	11	27	105015 (893242)	3.43	117.57 (117.21-117.93)	5900 (908166)	6.5 (6.41-6.58)	425 (908684)	0.47 (0.44-0.49)	1070 (908724)	1.18 (1.14-1.21)
Blood pressure	Normal	3190995	137 (87-171)	41	20	11	28	136085 (1113098)	3.44	122.26 (121.93-122.59)	4975 (1132373)	4.4 (4.33-4.46)	260 (1132792)	0.23 (0.22-0.24)	1185 (1132816)	1.05 (1.02-1.08)
	Elevated/high	3428615	151 (122-179)	46	19	10	25	136200 (1347493)	3.08	101.08 (100.8-101.35)	6565 (1366494)	4.8 (4.74-4.86)	480 (1367064)	0.35 (0.34-0.37)	1420 (1367106)	1.04 (1.01-1.07)
	Unknown	8881945	152 (113-181)	48	19	10	24	307500 (3451907)	3.09	89.08 (88.92-89.24)	17040 (3494668)	4.88 (4.84-4.91)	1250 (3496150)	0.36 (0.35-0.37)	3830 (3496255)	1.10 (1.08-1.11)
Cancer (non-haematological)		891935	180 (160-194)	45	17	9	28	25625 (426015)	2.08	60.15 (59.77-60.52)	4065 (429286)	9.47 (9.32-9.62)	235 (429659)	0.54 (0.51-0.58)	1305 (429678)	3.04 (2.96-3.13)

Clinical/ demographic group	Category	Fully vaccinated						Positive SARS-CoV-2 test			Hospitalised with COVID-19		COVID-19-related critical care admission		COVID-19 related death	
		Count*	Follow-up time, medium days (IQR)	Tests conducted (%)				Positivity (%)	Events* (PYs)	Incidence rate per 1000 person-years (95% CI)	Events* (PYs)	Incidence rate per 1000 person-years (95% CI)	Events* (PYs)	Incidence rate per 1000 person-years (95% CI)	Events* (PYs)	Incidence rate per 1000 person-years (95% CI)
				0	1	2	3+									
Chronic kidney disease	Stage 3a	529000	187 (173-201)	53	16	8	23	12170 (268808)	2.18	45.27 (44.87-45.69)	3370 (270184)	12.48 (12.27-12.7)	190 (270500)	0.70 (0.65-0.75)	1080 (270514)	4.00 (3.88-4.12)
	Stage 3b	206450	192 (178-205)	52	14	7	27	4450 (107113)	2.16	41.56 (40.95-42.19)	2105 (107527)	19.59 (19.16-20.02)	95 (107716)	0.89 (0.80-0.99)	795 (107722)	7.39 (7.13-7.66)
	Stage 4	51210	191 (174-204)	47	13	8	33	1280 (25907)	2.19	49.41 (48.05-50.81)	780 (26000)	29.92 (28.87-31.01)	45 (26064)	1.80 (1.56-2.09)	335 (26067)	12.85 (12.17-13.57)
	Stage 5	5505	184 (164-200)	29	12	7	52	215 (2607)	1.75	82.47 (77.04-88.29)	130 (2627)	49.49 (45.33-54.02)	15 (2638)	5.31 (4.06-6.93)	45 (2638)	17.81 (15.4-20.61)
Diabetes		1476880	173 (157-191)	50	17	9	24	52540 (683694)	2.80	76.85 (76.51-77.18)	8645 (690614)	12.52 (12.39-12.65)	740 (691375)	1.07 (1.03-1.11)	2255 (691436)	3.26 (3.19-3.33)
Dialysis	Previous kidney transplant	2345	183 (172-198)	25	15	9	51	155 (1143)	2.54	134.75 (124.32-146.06)	80 (1159)	70.73 (63.34-78.99)	25 (1165)	19.74 (16.03-24.32)	30 (1167)	25.71 (21.42-30.86)
	No previous kidney transplant	10505	180 (165-199)	22	9	7	63	535 (4982)	1.38	107.19 (102.65-111.93)	230 (5048)	45.36 (42.46-48.46)	25 (5068)	5.33 (4.40-6.46)	65 (5070)	13.22 (11.7-14.93)
Heart disease		1745845	180 (163-194)	48	17	9	26	51745 (844423)	2.38	61.28 (61.01-61.55)	10590 (850928)	12.45 (12.33-12.57)	650 (851904)	0.76 (0.73-0.79)	3405 (851951)	4.00 (3.93-4.07)
Haematological malignancy		103625	180 (166-193)	42	17	9	31	3725 (49945)	2.91	74.56 (73.35-75.79)	1225 (50386)	24.35 (23.67-25.06)	140 (50481)	2.79 (2.57-3.04)	435 (50492)	8.62 (8.21-9.04)
Immunocompromised		508930	177 (159-191)	42	18	10	30	21695 (237016)	2.90	91.53 (90.91-92.15)	3950 (240002)	16.45 (16.19-16.71)	450 (240303)	1.88 (1.79-1.97)	1220 (240339)	5.08 (4.94-5.23)
Learning disability		102730	160 (146-177)	47	13	6	33	3230 (43892)	1.78	73.57 (72.28-74.87)	315 (44339)	7.06 (6.67-7.47)	30 (44367)	0.65 (0.54-0.79)	50 (44371)	1.13 (0.98-1.30)
Liver disease		348855	164 (144-182)	45	19	10	26	14020 (151587)	2.96	92.5 (91.72-93.29)	1620 (153529)	10.55 (10.29-10.81)	130 (153667)	0.85 (0.78-0.93)	360 (153678)	2.36 (2.23-2.48)
Neurological disease		874635	176 (156-193)	45	16	8	30	28410 (407866)	2.29	69.66 (69.24-70.07)	5075 (411606)	12.33 (12.16-12.51)	245 (412073)	0.59 (0.55-0.63)	1685 (412095)	4.09 (3.99-4.19)
Respiratory disease		581930	180 (166-193)	50	17	9	25	16785 (282315)	2.53	59.45 (58.99-59.91)	4900 (284321)	17.24 (16.99-17.49)	305 (284751)	1.07 (1.01-1.14)	1515 (284773)	5.32 (5.19-5.46)

Clinical/ demographic group	Category	Fully vaccinated						Positive SARS-CoV-2 test			Hospitalised with COVID-19		COVID-19-related critical care admission		COVID-19 related death	
		Count*	Follow-up time, medium days (IQR)	Tests conducted (%)				Positivity (%)	Events* (PYs)	Incidence rate per 1000 person-years (95% CI)	Events* (PYs)	Incidence rate per 1000 person-years (95% CI)	Events* (PYs)	Incidence rate per 1000 person-years (95% CI)	Events* (PYs)	Incidence rate per 1000 person-years (95% CI)
				0	1	2	3+									
Severe mental illness		181865	159 (141-177)	51	15	8	26	5135 (76184)	2.44	67.42 (66.48-68.36)	650 (76905)	8.44 (8.11-8.78)	50 (76961)	0.64 (0.55-0.73)	155 (76967)	2.01 (1.86-2.18)
Transplant	Kidney (with previous dialysis)	5745	179 (172-191)	35	18	11	37	395 (2745)	4.83	143.51 (136.46-150.93)	210 (2787)	76.08 (71.03-81.49)	50 (2800)	17.86 (15.5-20.57)	55 (2804)	18.9 (16.47-21.68)
	Kidney (without previous dialysis)	4515	179 (171-191)	36	19	11	35	280 (2160)	4.65	130.07 (122.54-138.06)	130 (2192)	58.4 (53.46-63.8)	25 (2202)	10.45 (8.48-12.87)	30 (2203)	14.52 (12.17-17.33)
	Other organ	6780	178 (170-188)	35	18	11	36	405 (3202)	3.91	127.12 (120.97-133.58)	165 (3247)	50.2 (46.42-54.29)	40 (3259)	11.66 (9.91-13.71)	55 (3262)	16.86 (14.73-19.29)
Time since being fully vaccinated	0-4 weeks	331535	16 (8-23)	63	19	7	11	1100 (13569)	5.91	81.14 (78.73-83.62)	170 (13580)	12.37 (11.45-13.36)	REDACTED	REDACTED	80 (13582)	5.74 (5.13-6.43)
	4 - 8 weeks	886870	44 (37-51)	59	20	9	12	5135 (105598)	7.09	48.65 (47.97-49.33)	335 (105819)	3.15 (2.98-3.32)	20 (105825)	0.18 (0.14-0.23)	125 (105826)	1.17 (1.07-1.28)
	8 - 12 weeks	1430095	69 (62-76)	50	22	11	17	19585 (270294)	6.32	72.45 (71.94-72.97)	610 (271783)	2.25 (2.16-2.34)	55 (271801)	0.20 (0.18-0.23)	270 (271804)	0.99 (0.93-1.05)
	12+ weeks	12853055	159 (135-184)	44	19	10	27	553960 (5523038)	2.92	100.3 (100.16-100.43)	27470 (5602353)	4.90 (4.87-4.93)	1910 (5604799)	0.34 (0.33-0.35)	5965 (5604967)	1.06 (1.05-1.08)
Time between vaccinations	6 weeks or less	499185	185 (111-283)	39	18	11	31	17760 (253744)	2.43	69.99 (69.47-70.52)	1630 (256550)	6.35 (6.20-6.51)	85 (256777)	0.34 (0.03-0.38)	450 (256788)	1.75 (1.67-1.83)
	6-12 weeks	13565570	150 (108-179)	46	19	10	25	519470 (5161343)	3.20	100.65 (100.51-100.79)	23120 (5233675)	4.42 (4.39-4.45)	1635 (5235630)	0.31 (0.03-0.32)	5005 (5235771)	0.96 (0.94-0.97)
	12 weeks or more	1436800	143 (100-170)	53	18	8	21	42550 (497411)	3.19	85.54 (85.13-85.96)	3830 (503309)	7.61 (7.49-7.73)	270 (503599)	0.53 (0.05-0.57)	980 (503619)	1.95 (1.89-2.01)
Prior COVID-19	Between 1st and 2nd vaccination	191320	65 (42-166)	48	19	9	24	1720 (49491)	1.14	34.75 (33.93-35.6)	160 (49786)	3.25 (3.01-3.52)	REDACTED	REDACTED	55 (49815)	1.08 (0.95-1.24)
	Before 1st vaccination	926960	138 (88-170)	42	19	10	29	8895 (326947)	1.19	27.21 (26.92-27.5)	755 (328374)	2.31 (2.22-2.39)	30 (328454)	0.09 (0.08-0.11)	200 (328458)	0.61 (0.57-0.66)

Figure 1 - *Inclusion/exclusion flowchart*

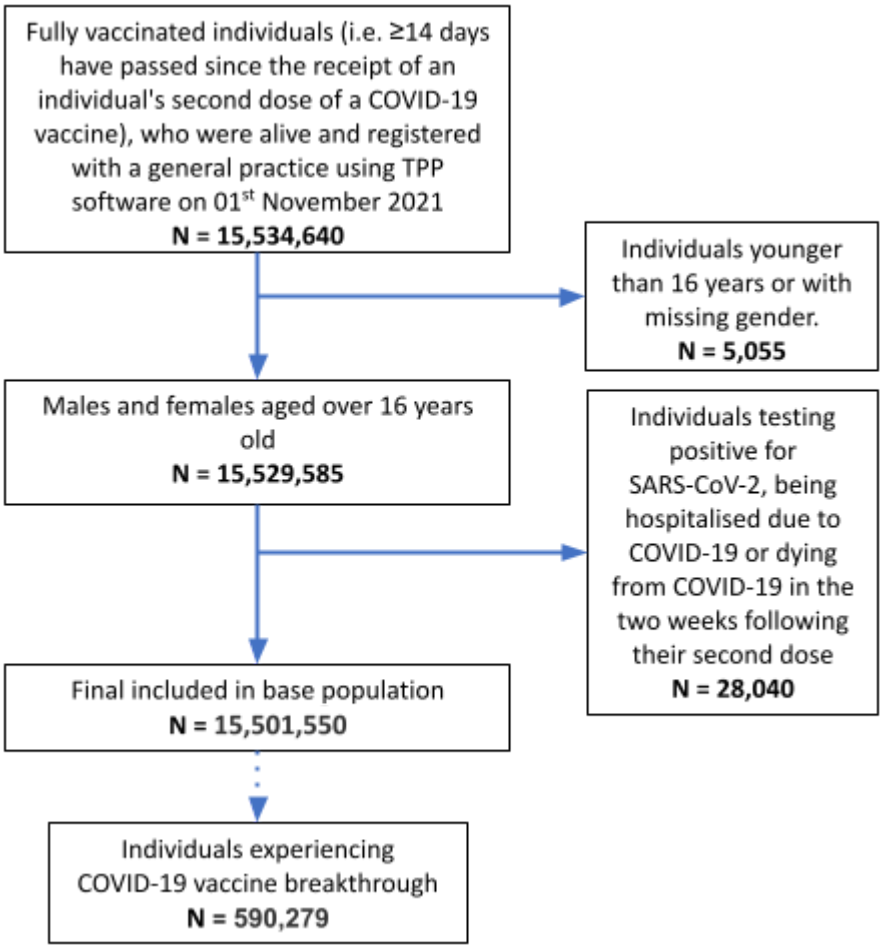

Figure 2 *Kaplan-Meir plot for positive SARS-CoV-2 test over time, by priority group*