

Striking antibody evasion manifested by the Omicron variant of SARS-CoV-2

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The B.1.1.529/Omicron variant of SARS-CoV-2 was only recently detected in southern Africa, but its subsequent spread has been extensive, both regionally and globally¹. It is expected to become dominant in the coming weeks², probably due to enhanced transmissibility. A striking feature of this variant is the large number of spike mutations³ that pose a threat to the efficacy of current COVID-19 vaccines and antibody therapies⁴. This concern is amplified by the findings of our study. Here we found that B.1.1.529 is markedly resistant to neutralization by serum not only from patients who recovered from COVID-19, but also from individuals who were vaccinated with one of the four widely used COVID-19 vaccines. Even serum from individuals who were vaccinated and received a booster dose of mRNA-based vaccines exhibited substantially diminished neutralizing activity against B.1.1.529. By evaluating a panel of monoclonal antibodies against all known epitope clusters on the spike protein, we noted that the activity of 17 out of the 19 antibodies tested were either abolished or impaired, including ones that are currently authorized or approved for use in patients. Moreover, we also identified four new spike mutations (S371L, N440K, G446S and Q493R) that confer greater antibody resistance on B.1.1.529. The Omicron variant presents a serious threat to many existing COVID-19 vaccines and therapies, compelling the development of new interventions that anticipate the evolutionary trajectory of SARS-CoV-2.

The COVID-19 pandemic continues as the causative agent SARS-CoV-2 continues to evolve. Many diverse viral variants have emerged (Fig. 1a), each characterized by mutations in the spike protein that raise concerns of both antibody evasion and enhanced transmission. The B.1.351/Beta variant was found to be highly refractory to antibody neutralization⁴ and therefore compromised the efficacy of vaccines^{5–7} and therapeutic antibodies. The B.1.1.7/Alpha variant became dominant globally in early 2021 due to having an edge in transmission⁸, only to be replaced by the B.1.617.2/Delta variant, which exhibited an even greater propensity to spread coupled with a moderate level of antibody resistance⁹. Next came the B.1.1.529/Omicron variant, which was first detected in southern Africa in November 2021 (refs. ^{3,10,11}) (Fig. 1a). Omicron has since spread rapidly in the region, as well as to over 60 countries, gaining traction even in regions in which the Delta variant is prevalent. The short doubling time (2–3 days) of Omicron cases suggests that it could soon become dominant². Moreover, its spike protein contains an alarming number of mutations (>30) (Fig. 1b and Extended Data Fig. 1), including at least 15 in the receptor-binding domain (RBD), the principal target of neutralizing antibodies. These extensive spike mutations raise the possibility that

current vaccines and therapeutic antibodies would be greatly compromised. This concern is amplified by the findings that we now report.

Serum neutralization of B.1.1.529

We first examined the neutralizing activity of serum collected in spring 2020 from patients with COVID-19, who were presumably infected with the wild-type (WT) SARS-CoV-2 (9–120 days after symptoms) (Methods and Extended Data Table 1). Samples from ten individuals were tested for neutralization against both D614G (WT) and B.1.1.529 pseudoviruses. Although robust titres were observed against D614G, a significant drop (>32-fold) in 50% infectious dose (ID₅₀) titres was observed against B.1.1.529, with only two samples showing titres above the limit of detection (LOD) (Fig. 1c and Extended Data Fig. 2a). We next assessed the neutralizing activity of sera from individuals who received one of the four widely used COVID-19 vaccines: BNT162b2 (Pfizer, 15–213 days after vaccination), mRNA-1273 (Moderna, 6–177 days after vaccination), Ad26.COV2.S (Johnson & Johnson, 50–186 days after vaccination) and ChAdOx1 nCoV-19 (AstraZeneca, 91–159

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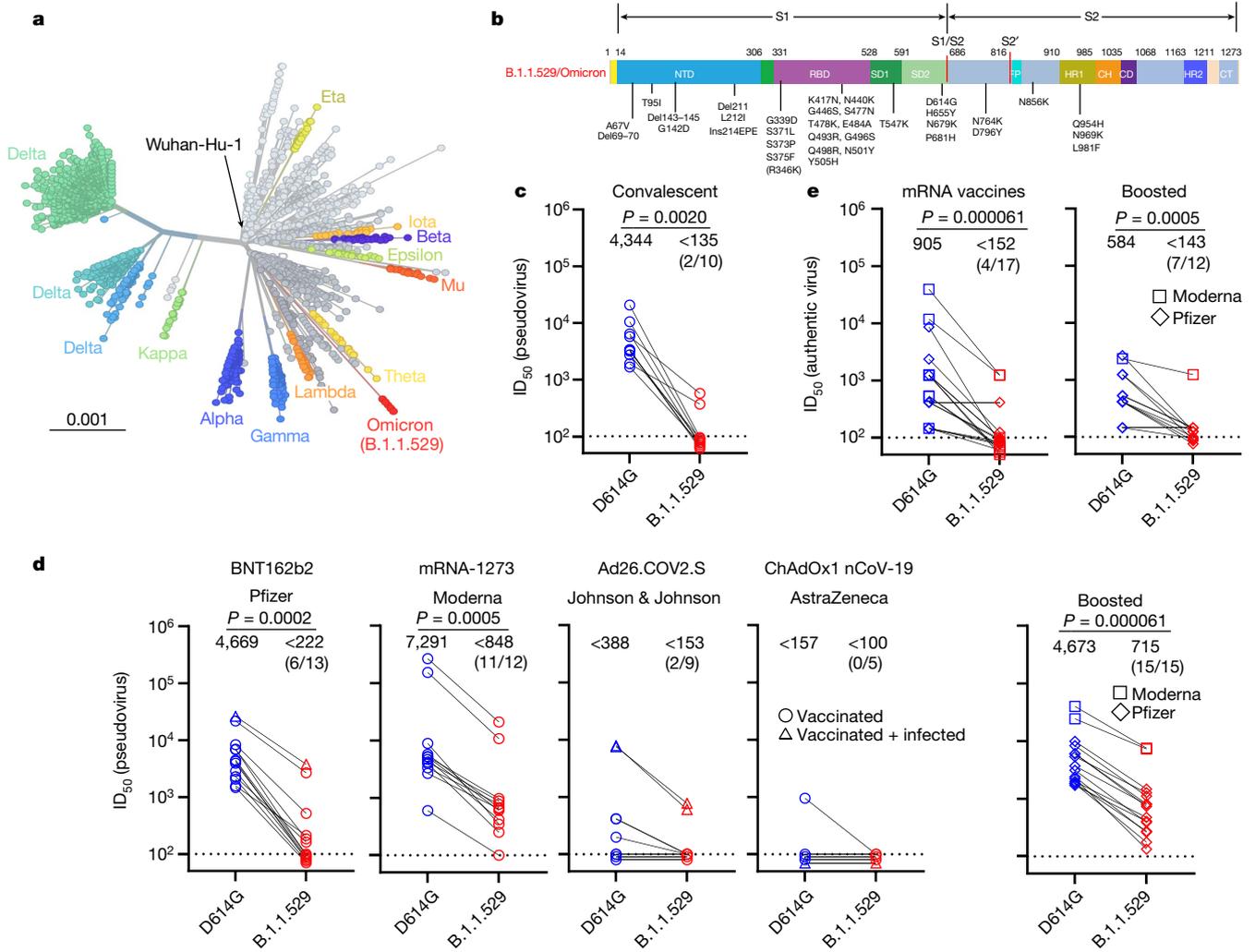


Fig. 1 | Resistance of B.1.1.529 to neutralization by sera. **a**, Unrooted phylogenetic tree of B.1.1.529 with other major SARS-CoV-2 variants. **b**, Key spike mutations found in the viruses isolated in the major lineage of B.1.1.529. Del, deletion; ins, insertion. **c**, Neutralization of D614G and B.1.1.529 pseudoviruses by convalescent patient sera. **d**, Neutralization of D614G and B.1.1.529 pseudoviruses by vaccinee sera. Within the four standard vaccination groups, individuals who were vaccinated without documented infection are denoted as circles and individuals who were both vaccinated and infected are denoted as

triangles. Within the boosted group, Moderna vaccinees are denoted as squares and Pfizer vaccinees are denoted as diamonds. **e**, Neutralization of authentic D614G and B.1.1.529 viruses by vaccinee sera. Moderna vaccinees are denoted as squares and Pfizer vaccinees are denoted as diamonds. Data represent one out of two independent experiments. For all of the panels, the values above the symbols denote the geometric mean titre and the numbers in parentheses denote the number of samples above the limit of detection. *P* values were determined by using two-tailed Wilcoxon matched-pairs signed-rank tests.

days after vaccination) (Methods and Extended Data Table 2). In all cases, a substantial loss in neutralizing potency was observed against B.1.1.529 (Fig. 1d and Extended Data Fig. 2b–f). For the two mRNA-based vaccines, BNT162b2 and mRNA-1273, a >21-fold and >8.6-fold decrease in ID_{50} was observed, respectively. Note that, for these two groups, we specifically chose samples with high titres so that the fold change in titre could be better quantified; the difference in the number of samples with titres above the LOD (6 out of 13 for BNT162b2 versus 11 out of 12 for mRNA-1273) may therefore be favourably biased. Within the Ad26.COV2.S and ChAdOx1 nCoV-19 groups, all of the samples were below the LOD against B.1.1.529, except for two Ad26.COV2.S samples from patients who had a previous history of SARS-CoV-2 infection (Fig. 1d). Collectively, these results suggest that individuals who were previously infected or fully vaccinated remain at risk for B.1.1.529 infection.

Booster shots are now routinely administered in many countries 6 months after full vaccination. We therefore also examined the serum neutralizing activity of individuals who had received three homologous mRNA vaccinations (13 with BNT162b2 and 2 with mRNA-1273,

14–90 days after vaccination). Every sample showed lower activity in neutralizing B.1.1.529, with a mean decrease of 6.5-fold compared with the WT (Fig. 1d). Although all of the samples had titres above the LOD, the substantial loss in activity may still pose a risk for B.1.1.529 infection despite the booster vaccination.

We next confirmed the above findings by testing a subset of the BNT162b2 and mRNA-1273 vaccinee serum samples using authentic SARS-CoV-2 isolates: WT and B.1.1.529. Again, a substantial decrease in the neutralization of B.1.1.529 was observed, with mean decreases of >6.0-fold and >4.1-fold for the fully vaccinated group and the boosted group, respectively (Fig. 1e).

Antibody neutralization of B.1.1.529

To understand the types of antibodies in the serum that lost neutralizing activity against B.1.1.529, we assessed the neutralization profile of 19 well-characterized monoclonal antibodies against the spike protein, including 17 directed to the RBD and 2 directed to the N-terminal

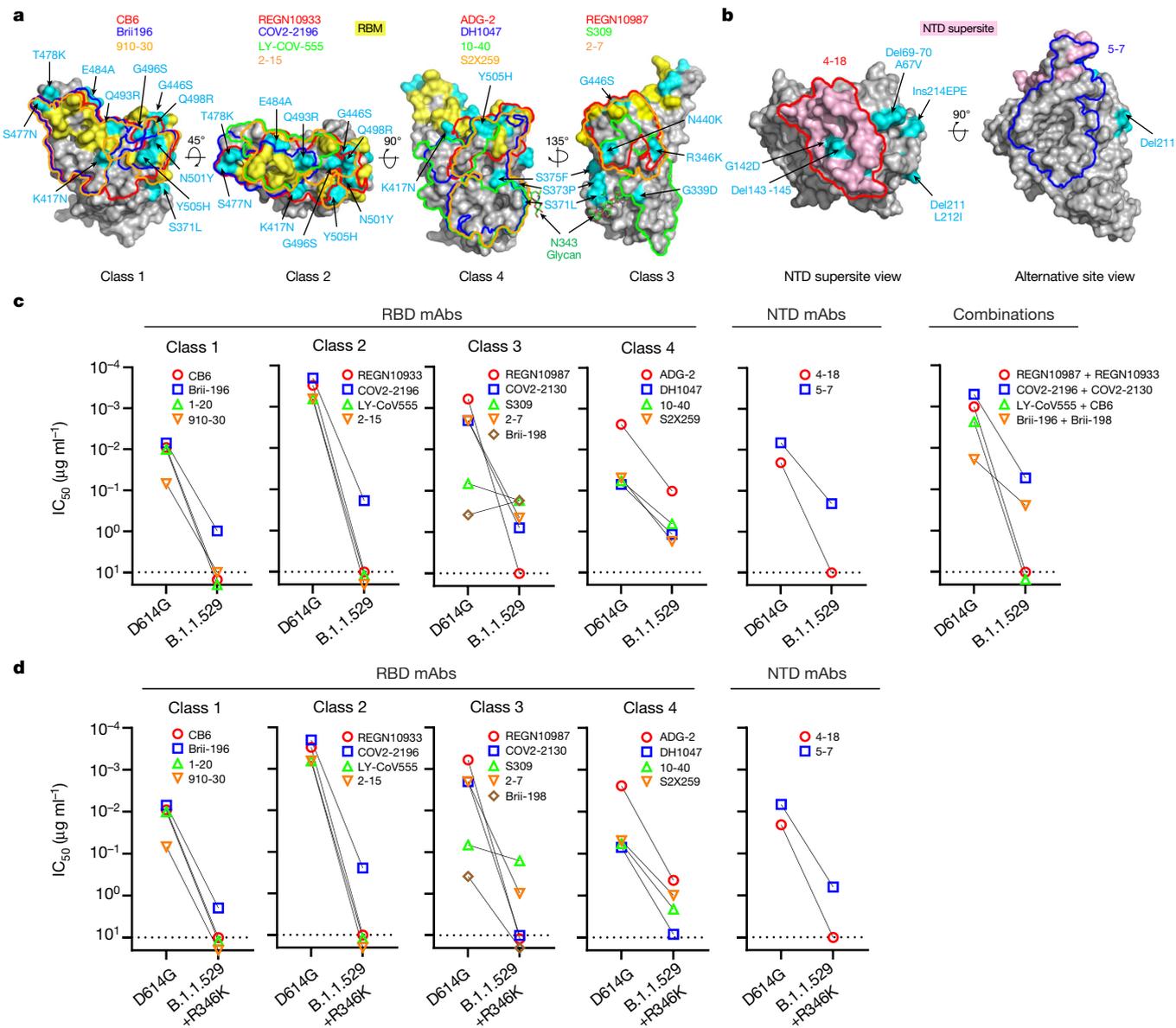


Fig. 2 | Resistance of B.1.1.529 to neutralization by monoclonal antibodies.
a, Footprints of RBD-directed antibodies. Mutations within B.1.1.529 are highlighted in cyan. Approved or authorized antibodies are shown in bold. The receptor-binding motif (RBM) residues are highlighted in yellow.
b, Footprints of NTD-directed antibodies. Mutations within B.1.1.529 are highlighted in cyan. The NTD supersite residues are highlighted in light pink.

c, Neutralization of D614G and B.1.1.529 pseudoviruses by RBD-directed and NTD-directed monoclonal antibodies (mAbs). **d**, Neutralization of D614G and B.1.1.529+R346K pseudoviruses by RBD-directed and NTD-directed monoclonal antibodies. Data represent one out of two independent experiments.

domain (NTD). We included the following monoclonal antibodies that have been authorized or approved for clinical use, either individually or in combination: REGN10987 (imdevimab)¹², REGN10933 (casirivimab)¹², COV2-2196 (tixagevimab)¹³, COV2-2130 (cilgavimab)¹³, LY-CoV555 (bamlanivimab)¹⁴, CB6 (etesevimab)¹⁵, Brie-196 (amubarvimab)¹⁶, Brie-198 (romlusevimab)¹⁶ and S309 (sotrovimab)¹⁷. We also included other monoclonal antibodies of interest: 910-30 (ref. ¹⁸), ADG-2 (ref. ¹⁹), DH1047 (ref. ²⁰), S2X259 (ref. ²¹) and our antibodies 1-20, 2-15, 2-7, 4-18, 5-7 and 10-40 (refs. ²²⁻²⁴). The footprints of monoclonal antibodies with structures available were drawn in relation to the mutations found in the B.1.1.529 RBD (Fig. 2a) and NTD (Fig. 2b). The risk to each of the four classes²⁵ of RBD monoclonal antibodies, as well as to the NTD monoclonal antibodies, was immediately apparent. Indeed, neutralization studies on B.1.1.529 pseudovirus showed that 17 out of the 19 monoclonal antibodies tested lost neutralizing activity completely or partially

(Fig. 2c and Extended Data Fig. 3). The potency of class 1 and class 2 RBD monoclonal antibodies all decreased by more than 100-fold, as did the more potent monoclonal antibodies in RBD class 3 (REGN10987, COV2-2130 and 2-7). The activities of S309 and Brie-198 were spared. All of the monoclonal antibodies in RBD class 4 lost neutralization potency against B.1.1.529 by at least tenfold, as did monoclonal antibodies directed to the antigenic supersite²⁶ (4-18) or the alternative site²³ (5-7) on the NTD. Strikingly, all four combination monoclonal antibody drugs in clinical use lost substantial activity against B.1.1.529, probably abolishing or impairing their efficacy in patients.

Approximately 10% of the B.1.1.529 viruses in the Global Initiative on Sharing All Influenza Data (GISAID)¹ also contain an additional RBD mutation, R346K, which is the defining mutation for the B.1.621/Mu variant²⁷. We therefore constructed another pseudovirus (B.1.1.529+R346K) containing this mutation for additional testing using the same panel

a

Fold change in IC ₅₀ compared with WT	RBD mAbs																	NTD mAbs	
	Class 1				Class 2				Class 3				Class 4					4-18	5-7
	CB6	Brii-196	1-20	910-30	REGN10933	COV2-2196	LY-CoV555	2-15	REGN10987	COV2-2130	S309	2-7	Brii-198	ADG-2	DH1047	10-40	SX259	4-18	5-7
B.1.1.529	<-1,000	-134	<-338	<-159	<-1,000	-140	<-1,000	<-1,000	<-1,000	-390	-2.5	-231	2.2	-43	-124	-11	-35	-125	-30
B.1.1.529+R346K	<-761	-97	<-338	<-159	<-1,000	-89	<-1,000	<-1,000	<-1,000	-988	-2.4	-109	<-32	-51	-167	-32	-16	-125	-33
A67V	1.1	1.0	-1.1	1.4	1.1	-1.0	1.1	1.1	1.1	1.2	-1.4	-1.1	-1.2	1.3	-1.3	-1.1	1.0	-1.6	-1.1
Del69-70	-1.4	-1.4	-1.6	-1.1	-1.8	-1.5	-1.4	-1.4	-1.7	-1.4	-2.2	-1.9	-2.3	-1.4	-3.3	-1.7	-1.3	-2.6	-9.4
T95I	-1.4	-2.0	-1.8	-1.7	-1.5	-1.6	-1.5	1.1	-2.0	-1.1	-2.3	-3.4	1.3	-2.5	-3.4	-1.9	-2.2	1.0	-9.5
G142D	-1.3	-1.4	-1.6	1.0	-1.6	-1.6	-1.7	-1.6	-1.9	-1.5	-2.9	-2.9	-1.5	-1.4	-2.8	-1.4	-1.5	<-125	-263
Del143-145	1.3	1.0	-1.2	1.4	1.3	1.6	1.3	1.5	1.1	-1.1	-1.9	1.2	-1.3	1.2	-2.0	-1.2	<-125	-29	
Del211	-2.4	-2.1	-1.6	-2.1	-1.5	-1.5	-1.4	-1.2	1.2	-1.2	-1.2	-1.3	-1.1	-1.9	-2.4	-1.6	-2.3	1.2	-9.1
L212I	-1.3	-1.8	-1.3	-1.6	-1.4	-1.4	-1.6	-1.3	-1.3	-1.4	-2.2	-1.9	-2.2	-1.7	-3.2	-2.0	-1.9	-7.2	-2.2
Ins214EPE	-2.4	-2.4	-2.2	-2.4	-2.8	-2.7	-2.3	-4.3	-3.0	-2.2	-3.0	-6.2	-2.7	-3.1	-2.9	-1.9	-3.3	-7.1	-15
G339D	-1.7	-1.6	-1.7	-1.4	-2.2	-1.7	-1.5	-1.4	-1.8	-1.6	-4.0	-1.9	-3.9	-1.6	-2.2	-1.5	-3.2	-4.5	-3.0
R346K	-1.5	-1.2	-1.3	1.0	-1.5	-1.3	-1.3	-1.4	-1.6	-2.9	-1.4	-1.0	-2.1	-1.1	-1.9	-1.2	-1.4	-1.4	-2.3
S371L	-19	-18	-15	-22	-10	-4.1	-2.9	-1.4	-25	-1.4	-12	-12	-17	-18	-49	-59	-23	-1.8	1.1
S373P	-1.9	-2.1	-1.6	-1.4	-1.9	-2.1	-2.0	-1.4	-1.9	-1.3	-2.3	-1.8	-2.5	-2.2	-5.1	-5.0	-2.8	-8.2	-5.0
S375F	1.7	1.6	1.6	1.5	2.1	1.9	1.9	2.6	1.2	1.5	-1.1	1.4	1.1	1.8	-1.8	-1.2	-1.6	-9.2	-1.6
K417N	<-761	-1.6	-2.3	<-158	-6.4	1.1	1.5	1.1	1.2	1.2	-1.8	1.5	-1.0	-1.1	-1.9	-1.5	-1.8	-5.3	-2.8
N440K	-1.4	-1.4	-1.6	-1.2	-1.7	-1.4	-1.4	-1.6	-246	-1.5	-2.3	-18	-1.6	1.1	-2.0	-1.3	-1.5	-4.3	-2.8
G446S	1.3	1.1	-1.1	1.2	-1.6	-1.1	-1.6	-3.0	-574	-3.7	-1.7	-50	-1.4	-1.6	-2.2	-1.4	-2.2	-3.9	-2.4
S477N	-1.8	-1.8	-1.7	-1.7	-2.4	-1.5	-1.5	-1.7	-2.9	-1.6	-1.9	-4.4	-2.4	-1.5	-2.3	-1.6	-2.2	-17	-5.1
T478K	1.2	1.1	1.4	1.6	1.3	-1.5	-1.4	-1.2	-1.6	1.1	-1.8	-2.6	-1.6	-1.2	-2.8	-1.3	-2.3	-3.3	-2.3
E484A	-2.8	-1.7	-1.8	-1.2	-4.8	-4.9	<-1,000	<-1,000	-1.6	-1.4	-1.4	-2.7	-1.9	-1.6	-1.5	-1.9	-1.9	-5.7	-2.9
Q493R	-16	-7.3	-3.2	2.9	-42	-4.2	<-1,000	-705	-1.4	-1.1	-1.2	-1.9	-2.0	-1.6	-1.6	-1.6	-1.5	-4.0	-1.3
G496S	-1.3	1.3	1.1	1.1	1.0	1.1	1.0	-9.3	-6.2	-1.3	-1.4	1.4	-1.2	-1.2	-1.6	-1.1	-1.6	-2.6	-1.6
Q498R	-1.7	-1.2	1.1	1.4	-1.5	-1.1	-1.4	-1.0	-1.6	-1.4	-1.3	1.1	-1.2	2.4	-1.3	-1.2	-1.3	-1.5	-1.8
N501Y	-9.8	-1.2	-8.4	-16	-1.4	-1.5	-1.6	-1.2	-1.2	-1.1	-1.8	-1.5	-2.7	-1.8	-2.5	-1.9	-1.9	-20	-3.9
Y505H	-1.2	1.2	-1.3	-9.6	1.1	1.0	1.0	1.1	1.4	1.0	-1.4	1.7	1.1	1.3	-1.4	1.0	-1.2	-1.2	-1.1
T547K	-1.9	-2.0	-2.0	-1.9	-1.7	-1.3	-1.6	-1.7	-2.7	-1.6	-1.6	-4.3	-1.9	-1.7	-2.6	-1.5	-1.9	-2.7	-2.7
H655Y	-2.7	-3.1	-3.5	-2.7	-3.1	-2.0	-2.2	-8.6	-8.8	-1.7	-2.3	-13	-2.4	-2.1	-3.9	-3.3	-3.9	-23	-5.3
N679K	1.0	1.2	1.1	1.1	-1.1	-1.2	-1.2	-1.2	-1.9	-1.1	-1.3	-1.8	-1.7	-1.4	-2.4	-1.7	-1.7	-2.1	-2.7
P681H	-2.3	-2.1	-2.1	1.0	-2.4	-1.8	-2.2	-1.5	-1.5	-1.0	-1.6	-1.9	-1.5	-1.3	-2.3	-1.3	-1.3	-2.3	-2.4
N764K	-1.1	-1.5	-1.3	-1.1	-1.4	-1.4	-1.4	-2.1	-2.5	-1.5	-2.2	-4.3	-1.3	-1.4	-3.3	-2.1	-2.4	-2.3	-2.1
D769Y	1.3	1.1	1.0	1.2	-1.5	-1.0	-1.4	-1.4	-2.0	-1.3	-1.9	-2.5	-1.3	-1.1	-1.7	-1.2	-1.4	-3.1	-2.5
N856K	-10	-2.8	-1.3	-12	-2.2	-3.0	-1.1	-1.0	-1.4	-1.1	-1.2	-1.3	-2.3	-1.8	-4.4	-2.1	-2.5	-1.6	-1.9
Q954H	2.7	1.9	1.5	2.6	1.2	1.0	1.2	1.1	-1.1	1.2	-1.2	-1.4	-1.1	-1.1	-2.5	-1.0	-1.1	-2.3	-2.9
N969K	-5.4	-1.6	-1.1	-4.5	-1.3	-1.8	-1.1	-1.3	-1.6	-1.1	-1.4	-2.4	-1.4	-1.1	-2.3	-2.0	-2.4	-2.5	-2.0
L981F	3.2	3.3	2.1	4.6	2.4	2.5	2.2	1.9	1.3	2.5	-1.0	-1.5	8.6	2.8	1.1	2.0	2.1	-1.3	-1.5

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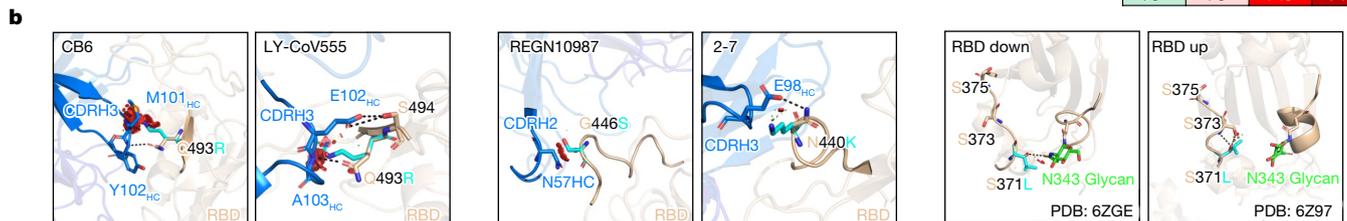


Fig. 3 | Impact of individual mutations within B.1.1.529 against monoclonal antibodies. a, Neutralization of pseudoviruses containing single mutations found within B.1.1.529 by a panel of 19 monoclonal antibodies. The fold change

relative to neutralization of D614G is denoted, with resistance coloured red and sensitization coloured green. **b**, Modelling of critical mutations in B.1.1.529 that affect antibody neutralization.

of monoclonal antibodies (Fig. 2d). The overall findings resembled those already shown in Fig. 2c, with the exception that the neutralizing activity of Brii-198 was abolished. In fact, nearly the entire panel of antibodies was essentially rendered inactive against this minor form of the Omicron variant.

The fold changes in IC₅₀ of the monoclonal antibodies against B.1.1.529 and B.1.1.529+R346K relative to D614G are summarized in the first two rows of Fig. 3a. The considerable loss of activity observed for all classes of monoclonal antibodies against B.1.1.529 suggests that perhaps the same is occurring in the serum of convalescent patients and vaccinated individuals.

Mutations conferring antibody resistance

To understand the specific B.1.1.529 mutations that confer antibody resistance, we next individually tested the same panel of 19 monoclonal antibodies against pseudoviruses for each of the 34 mutations (excluding D614G) found in B.1.1.529 or B.1.1.529+R346K. Our findings not only

confirmed the role of known mutations at spike residues 142–145, 417, 484 and 501 in conferring resistance to NTD or RBD (class 1 or class 2) antibodies⁴ but also revealed several mutations that were not previously known to have functional importance to neutralization (Fig. 3a and Extended Data Fig. 4). Q493R, which was previously shown to affect binding of CB6 and LY-CoV555 (ref.²⁸) as well as polyclonal sera²⁹, mediated resistance to CB6 (class 1) as well as to LY-CoV555 and 2-15 (class 2), findings that could be explained by the abolishment of hydrogen bonds due to the long side chain of arginine and induced steric clashes with CDRH3 in these antibodies (Fig. 3b (left)). Both N440K and G446S mediated resistance to REGN10987 and 2-7 (class 3), observations that could also be explained by steric hindrance (Fig. 3b (middle)). The most striking and perhaps unexpected finding was that S371L broadly affected neutralization by monoclonal antibodies in all four RBD classes (Fig. 3a and Extended Data Fig. 4). Although the precise mechanism of this resistance is unknown, in silico modelling suggested two possibilities (Fig. 3b (right)). First, in the RBD-down state, mutating Ser to Leu results in an interference with the N343 glycan, thereby possibly altering

Fold change in IC ₅₀ compared with WT	RBD mAbs																	NTD mAbs	
	Class 1				Class 2				Class 3				Class 4					4-18	5-7
	CB6	Brii-196	1-20	910-30	REGN10933	COV2-2196	LY-CoV555	2-15	REGN10987	COV2-2130	S309	2-7	Brii-198	ADG-2	DH1047	10-40	S2X259	4-18	5-7
B.1.1.7	-8.8	2.6	-5.2	-15	1.6	1.8	1.6	2.2	2.9	1.7	1.1	2.3	4.1	1.7	2.2	1.4	1.4	-5.1	-4.0
B.1.526	-1.0	1.1	-1.1	2.5	-4.5	-2.1	-590	-1,329	1.8	1.2	2.9	1.8	-1.1	1.5	2.9	-2.2	1.4	4.5	-2.5
B.1.429	3.0	2.3	1.4	2.5	2.5	2.8	-590	-4.6	1.6	1.1	1.9	1.6	-2.4	2.0	2.9	1.3	3.3	-39	-59
B.1.617.2	2.1	1.2	-1.1	2.5	1.2	1.4	-590	-10	-1.8	-1.7	1.2	-1.1	-8.9	1.0	1.4	-1.8	-1.4	-39	-74
P.1	-196	2.2	-16	-60	-121	-2.0	-590	-1,329	1.9	1.1	1.1	1.2	1.8	-1.0	3.0	-2.2	1.2	-39	-74
B.1.351	-196	2.0	-40	-60	-78	-2.5	-590	-1,329	1.5	1.5	1.2	1.9	-1.5	1.0	3.0	-2.9	1.2	-39	-8.4
B.1.1.529	<-1,000	-134	<-338	<-159	<-1,000	-140	<-1,000	<-1,000	<-1,000	-390	-2.5	-231	2.2	-43	-124	-11	-35	-125	-30
B.1.1.529+R346K	<-761	-97	<-338	<-159	<-1,000	-89	<-1,000	<-1,000	<-1,000	<-988	-2.4	-109	<-32	-51	-167	-32	-16	-125	-33

>3 <-3 <-10 <-100

Fig. 4 | Evolution of antibody resistance across SARS-CoV-2 variants. Neutralization of SARS-CoV-2 variant pseudoviruses by a panel of 19 monoclonal antibodies. The fold change relative to neutralization of D614G is denoted.

its conformation and affecting class 3 antibodies that typically bind to this region. Second, in the RBD-up state, S371L may alter the local conformation of the loop consisting of Ser371-Ser373-Ser375, thereby affecting the binding of class 4 antibodies that generally target a portion of this loop²⁴. It is not clear how class 1 and class 2 RBD monoclonal antibodies are affected by this mutation.

Evolution of SARS-CoV-2 to antibodies

To gain insights into the antibody resistance of B.1.1.529 relative to previous SARS-CoV-2 variants, we evaluated the neutralizing activity of the same panel of neutralizing monoclonal antibodies against pseudoviruses for B.1.1.7 (ref. ⁸), B.1.526 (ref. ³⁰), B.1.429 (ref. ³¹), B.1.617.2 (ref. ⁹), P.1 (ref. ³²) and B.1.351 (ref. ³³). It is evident from these results (Fig. 4 and Extended Data Fig. 5) that previous variants developed resistance to only NTD antibodies and class 1 and class 2 RBD antibodies. Here B.1.1.529, with or without R346K, has made a big mutational leap by becoming not only nearly completely resistant to class 1 and class 2 RBD antibodies, but also substantially resistant to both class 3 and class 4 RBD antibodies. B.1.1.529 is now the most complete ‘escapee’ from neutralization by currently available antibodies.

Discussion

The Omicron variant caused fear almost as soon as it was detected to be spreading in South Africa. The suggestion that this new variant would transmit more readily has come true in the ensuing weeks². The extensive mutations found in its spike protein raised concerns that the efficacy of current COVID-19 vaccines and antibody therapies might be compromised. Indeed, in this study, sera from convalescent patients (Fig. 1c) and vaccinees (Fig. 1d, e) showed markedly reduced neutralizing activity against B.1.1.529. Other studies have found similar losses^{34–38}. These findings are consistent with emerging clinical data on the Omicron variant demonstrating higher rates of reinfection¹¹ and vaccine breakthroughs. In fact, recent reports showed that the efficacy of two doses of BNT162b2 vaccine has dropped from over 90% against the original SARS-CoV-2 strain to approximately 40% and 33% against B.1.1.529 in the United Kingdom³⁹ and South Africa⁴⁰, respectively. Even a third booster shot may not adequately protect against Omicron infection^{39,41}, although the protection against disease still makes it advisable to administer booster vaccinations. Vaccines that elicited lower neutralizing titres^{35,42} are expected to fare worse against B.1.1.529.

The nature of the loss in serum neutralizing activity against B.1.1.529 could be discerned from our findings on a panel of monoclonal antibodies directed to the viral spike. The neutralizing activities of all four major classes of RBD monoclonal antibodies and two distinct classes of NTD monoclonal antibodies are either abolished or impaired (Fig. 2c, d). In addition to previously identified mutations that confer antibody

resistance⁴, we have uncovered four previously undescribed spike mutations with functional consequences. Q493R confers resistance to some class 1 and class 2 RBD monoclonal antibodies; N440K and G446S confer resistance to some class 3 RBD monoclonal antibodies; and S371L confers global resistance to many RBD monoclonal antibodies through mechanisms that are not yet apparent. While performing these monoclonal antibody studies, we also observed that nearly all of the currently authorized or approved monoclonal antibody drugs are rendered weak or inactive by B.1.1.529 (Figs. 2c and 3a). In fact, the Omicron variant that contains R346K renders almost all current antibody therapy for COVID-19 ineffective (Figs. 2d and 3a).

The scientific community has chased after SARS-CoV-2 variants for a year. As more and more of them appeared, our interventions directed to the spike became increasingly ineffective. The Omicron variant has now put an exclamation mark on this point. It is not too farfetched to think that this SARS-CoV-2 is now only a mutation or two away from being pan-resistant to current antibodies, either monoclonal or polyclonal. We must devise strategies that anticipate the evolutionary direction of the virus and develop agents that target better-conserved viral elements.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at <https://doi.org/10.1038/s41586-021-04388-0>.

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Article

Methods

Data reporting

No statistical methods were used to predetermine sample size. The experiments were not randomized and the investigators were not blinded to allocation during experiments and outcome assessment.

Serum samples

Convalescent plasma samples were obtained from patients with documented SARS-CoV-2 infection. These samples were collected at the beginning of the pandemic in early 2020 at Columbia University Irving Medical Center and are therefore assumed to be infection by the WT strain of SARS-CoV-2 (ref. ⁴). Sera from individuals who received two or three doses of mRNA-1273 or BNT162b2 vaccine were collected at Columbia University Irving Medical Center at least two weeks after the final dose. Sera from individuals who received one dose of Ad26.COV2.S or two doses of ChAdOx1 nCov-19 were obtained from BEI Resources. Some individuals were also infected by SARS-CoV-2 in addition to the vaccinations they received. Note that, whenever possible, we specifically chose samples with high titres against the WT strain of SARS-CoV-2 such that the loss in activity against B.1.1.529 could be better quantified and the titres observed here should therefore be considered in that context. All collections were conducted under protocols reviewed and approved by the Institutional Review Board of Columbia University. All of the participants provided written informed consent. Additional information for the convalescent samples and vaccinee samples is provided in Extended Data Tables 1 and 2, respectively.

Monoclonal antibodies

Antibodies were expressed as previously described²² by synthesis of heavy chain variable (VH) and light chain variable (VL) genes (GenScript), transfection of Expi293 cells (Thermo Fisher Scientific) and affinity purification from the supernatant by rProtein A Sepharose (GE). REGN10987, REGN10933, COV2-2196 and COV2-2130 were provided by Regeneron Pharmaceuticals; Brij-196 and Brij-198 were provided by Brij Biosciences; CB6 was provided by B. Zhang and P. Kwong (NIH); and 910-30 was provided by B. DeKosky (MIT).

Cell lines

Expi293 cells were obtained from Thermo Fisher Scientific (A14527); Vero E6 cells were obtained from the ATCC (CRL-1586); HEK293T cells were obtained from the ATCC (CRL-3216); and Vero-E6-TMPRSS2 cells were obtained from JCRB (JCRB1819). Cells were purchased from authenticated vendors and morphology was confirmed visually before use. All cell lines tested mycoplasma negative.

Variant SARS-CoV-2 spike plasmid construction

An in-house high-throughput template-guide gene synthesis approach was used to generate spike genes with single or full mutations of B.1.1.529. In brief, 5'-phosphorylated oligos with designed mutations were annealed to the reverse strand of the WT spike gene construct and extended by DNA polymerase. Extension products (forward-stranded fragments) were then ligated together by Taq DNA ligase and subsequently amplified by PCR to generate variants of interest. To verify the sequences of variants, next-generation sequencing libraries were prepared according to a low-volume Nextera sequencing protocol⁴³ and sequenced on the Illumina MiSeq platform (single-end mode with 50 bp R1). Raw reads were processed using Cutadapt v.2.1⁴⁴ with the default settings to remove adapters, and were then aligned to reference variants sequences using Bowtie2 v.2.3.4⁴⁵ with the default settings. The resulting reads alignments were then visualized in the Integrative Genomics Viewer⁴⁶ and manually inspected to verify the fidelity of variants. The sequences of the oligos used in variants generation are provided in Extended Data Table 3.

Pseudovirus production

Pseudoviruses were produced in the vesicular stomatitis virus (VSV) background, in which the native glycoprotein was replaced by that of SARS-CoV-2 and its variants, as previously described²⁴. In brief, HEK293T cells were transfected with a spike expression construct with polyethylenimine (PEI) (1 mg ml⁻¹) and cultured overnight at 37 °C under 5% CO₂, and then infected with VSV-G pseudotyped ΔG-luciferase (G*ΔG-luciferase, Kerafast) 1 day after transfection. After 2 h of infection, cells were washed three times, changed to fresh medium and then cultured for approximately another 24 h before the supernatants were collected, centrifuged and aliquoted to use in assays.

Pseudovirus neutralization assay

All viruses were first titrated to normalize the viral input between assays. Heat-inactivated sera or antibodies were first serially diluted in 96 well-plates in triplicate, starting at 1:100 dilution for sera and 10 μg ml⁻¹ for antibodies. Viruses were then added and the virus-sample mixture was incubated at 37 °C for 1 h. Vero-E6 cells (ATCC) were then added at a density of 3 × 10⁴ cells per well and the plates were incubated at 37 °C for approximately 10 h. Luciferase activity was quantified using the Luciferase Assay System (Promega) according to the manufacturer's instructions using SoftMax Pro v.7.0.2 (Molecular Devices). Neutralization curves and IC₅₀ values were derived by fitting a non-linear five-parameter dose-response curve to the data in GraphPad Prism v.9.2.

Authentic virus isolation and propagation

Authentic B.1.1.529 was isolated from a specimen from the respiratory tract of a patient with COVID-19 in Hong Kong by K.-Y. Yuen and colleagues at the Department of Microbiology, The University of Hong Kong. Isolation of WT SARS-CoV-2 was previously described⁴⁷. Viruses were propagated in Vero-E6-TMPRSS2 cells and the sequence was confirmed by next-generation sequencing before use.

Authentic virus neutralization assay

To measure neutralization of authentic SARS-CoV-2 viruses, Vero-E6-TMPRSS2 cells were first seeded in 96-well plates in cell culture medium (Dulbecco's Modified Eagle Medium (DMEM) + 10% fetal bovine serum (FBS) + 1% penicillin-streptomycin) overnight at 37 °C under 5% CO₂ to establish a monolayer. The next day, sera or antibodies were serially diluted in 96-well plates in triplicate in DMEM + 2% FBS and then incubated with 0.01 multiplicity of infection of WT SARS-CoV-2 or B.1.1.529 at 37 °C for 1 h. Sera were diluted from 1:100 dilution and antibodies were diluted from 10 μg ml⁻¹. Next, the mixture was overlaid onto cells and further incubated at 37 °C under 5% CO₂ for approximately 72 h. Cytopathic effects were then scored by plaque assay in a blinded manner. Neutralization curves and IC₅₀ values were derived by fitting a nonlinear five-parameter dose-response curve to the data in GraphPad Prism v.9.2.

Antibody footprint analysis and RBD mutagenesis analysis

The SARS-CoV-2 spike structure used for displaying epitope footprints and mutations within emerging strains was downloaded from the Protein Data Bank (PDB: 6ZGE). The structures of antibody-spike complexes were also obtained from PDB (7LSB (2-15), 6XDG (REGN10933 and REGN10987), 7L2E (4-18), 7RW2 (5-7), 7C01 (CB6), 7KMG (LY-COV555), 7CDI (Brij-196), 7KS9 (910-30), 7LD1 (DH1047), 7RAL (S2X259), 7LSS (2-7) and 6WPT (S309)). Interface residues were identified using PISA⁴⁸ using the default parameters. The footprint for each antibody was defined by the boundaries of all epitope residues. The border for each footprint was then optimized by ImageMagick v.7.0.10-31 (<https://imagemagick.org>). PyMOL v.2.3.2 was used to perform mutagenesis and to generate structural plots (Schrödinger).

Reporting summary

Further information on research design is available in the Nature Research Reporting Summary linked to this paper.

Data availability

Materials used in this study will be made available under an appropriate Materials Transfer Agreement. All the data are provided in the paper. The structures used for analysis in this study are available from PDB under accession numbers 6ZGE, 7LSB, 6XDG, 7L2E, 7RW2, 7C01, 7KMG, 7CDI, 7KS9, 7LD1, 7RAL, 7LSS and 6WPT.

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Author contributions D.D.H. conceived this project. Lihong Liu, S.I. and M.W. conducted pseudovirus neutralization experiments. J.F.-W.C., H. Chu, K.K.-H.C., T.T.-TY., C.Y., K.K.-W.T. and H. Chen conducted authentic virus neutralization experiments. Y.G. and Z.S. conducted bioinformatic analyses. Liyuan Liu and Yiming Huang constructed the spike expression plasmids. Y.L. managed the project. J.Y. expressed and purified antibodies. M.T.Y. and M.E.S. provided clinical samples. M.S.N. and Yaoxing Huang contributed to discussions. H.H.W., K.-Y.Y. and D.D.H. directed and supervised the project. Lihong Liu, S.I. and D.D.H. analysed the results and wrote the manuscript.

Competing interests Lihong Liu, S.I., M.S.N., J.Y., Yaoxing Huang and D.D.H. are inventors on patent applications (WO2021236998) or provisional patent applications (63/271,627) filed by Columbia University for a number of SARS-CoV-2 neutralizing antibodies described in this manuscript. Both sets of applications are under review. D.D.H. is a co-founder of TailMed Biologics and RenBio, consultant to WuXi Biologics and Bria Biosciences, and board director for Vicarious Surgical.

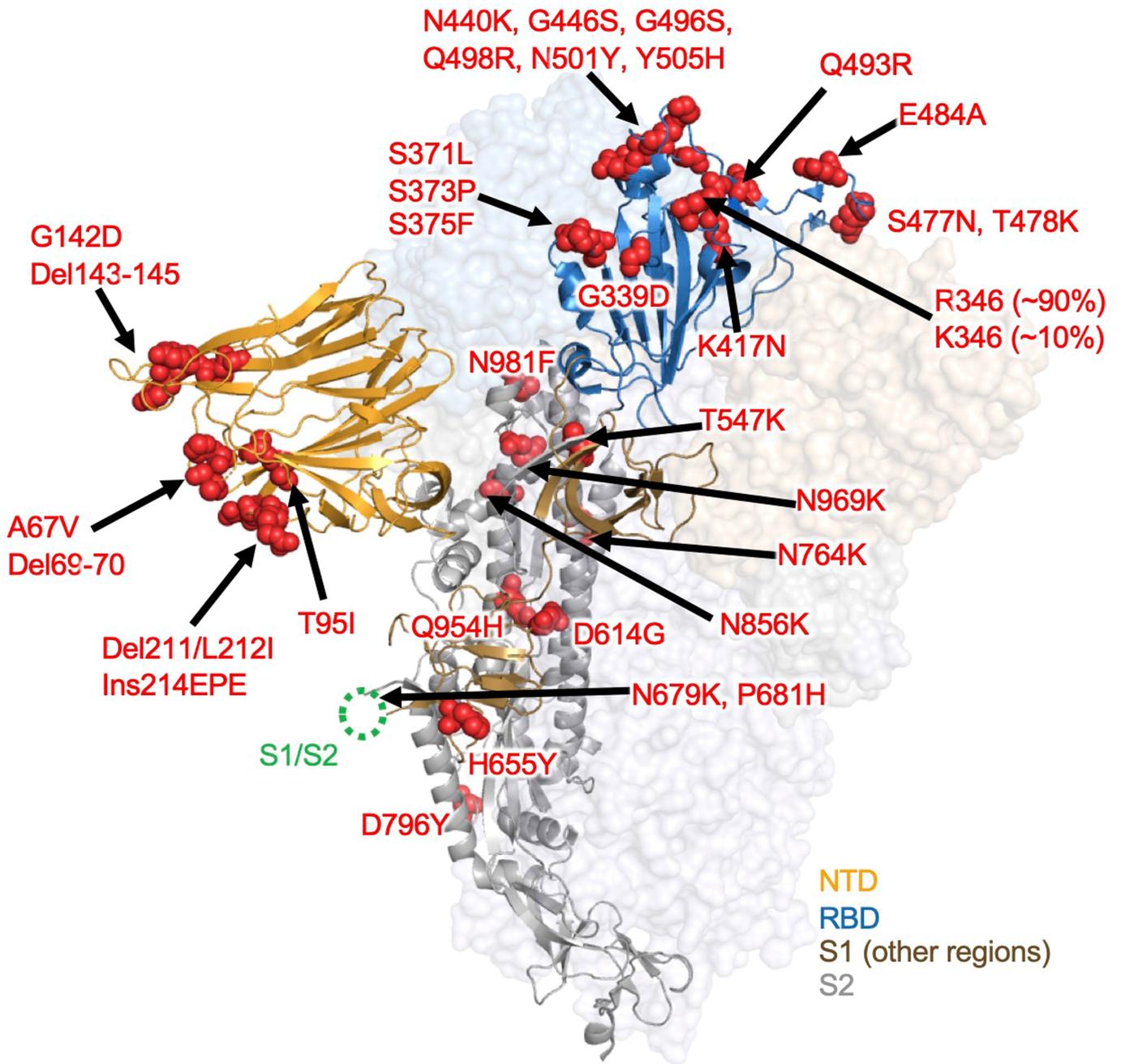
Additional information

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1038/s41586-021-04388-0>.

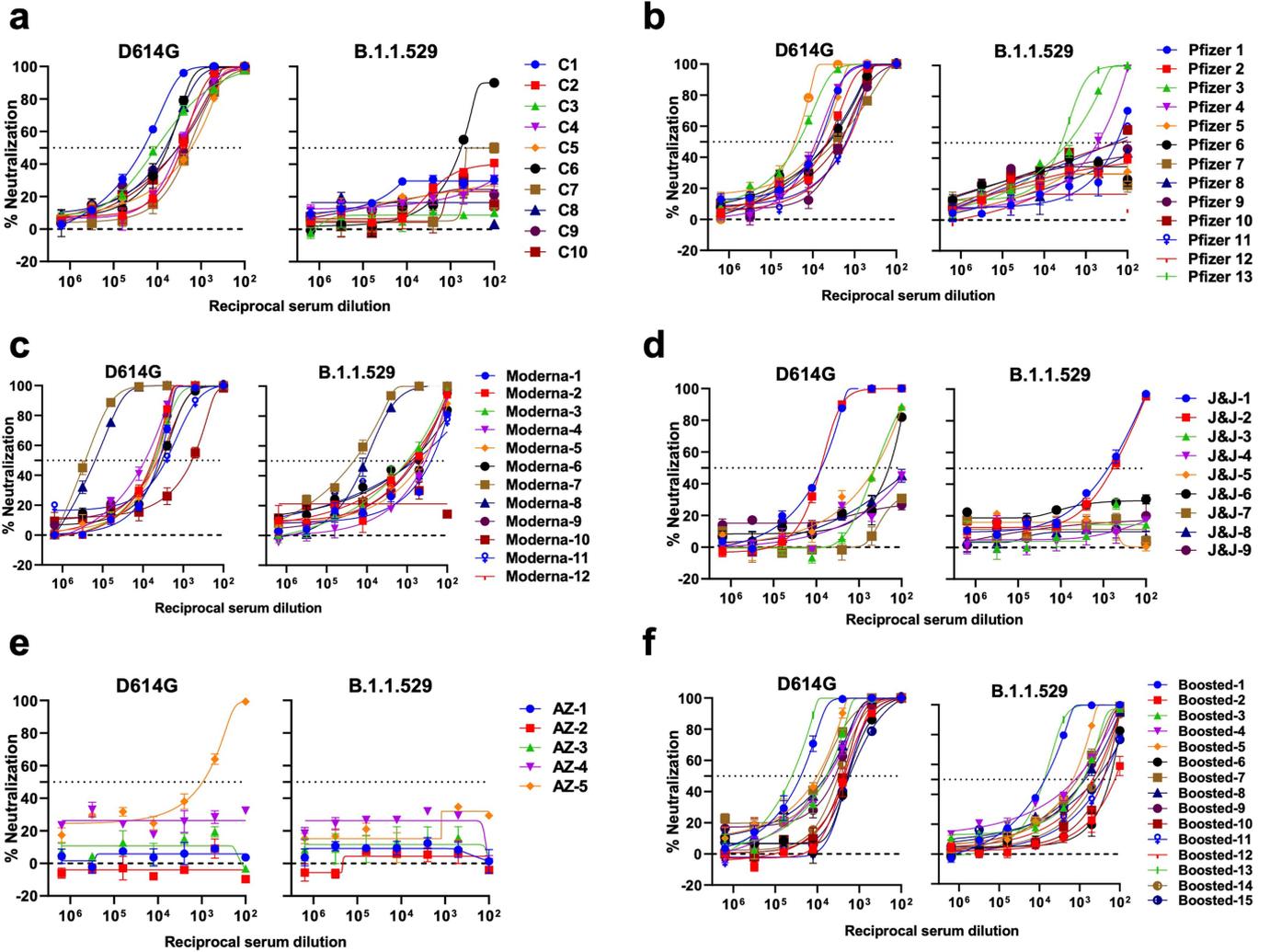
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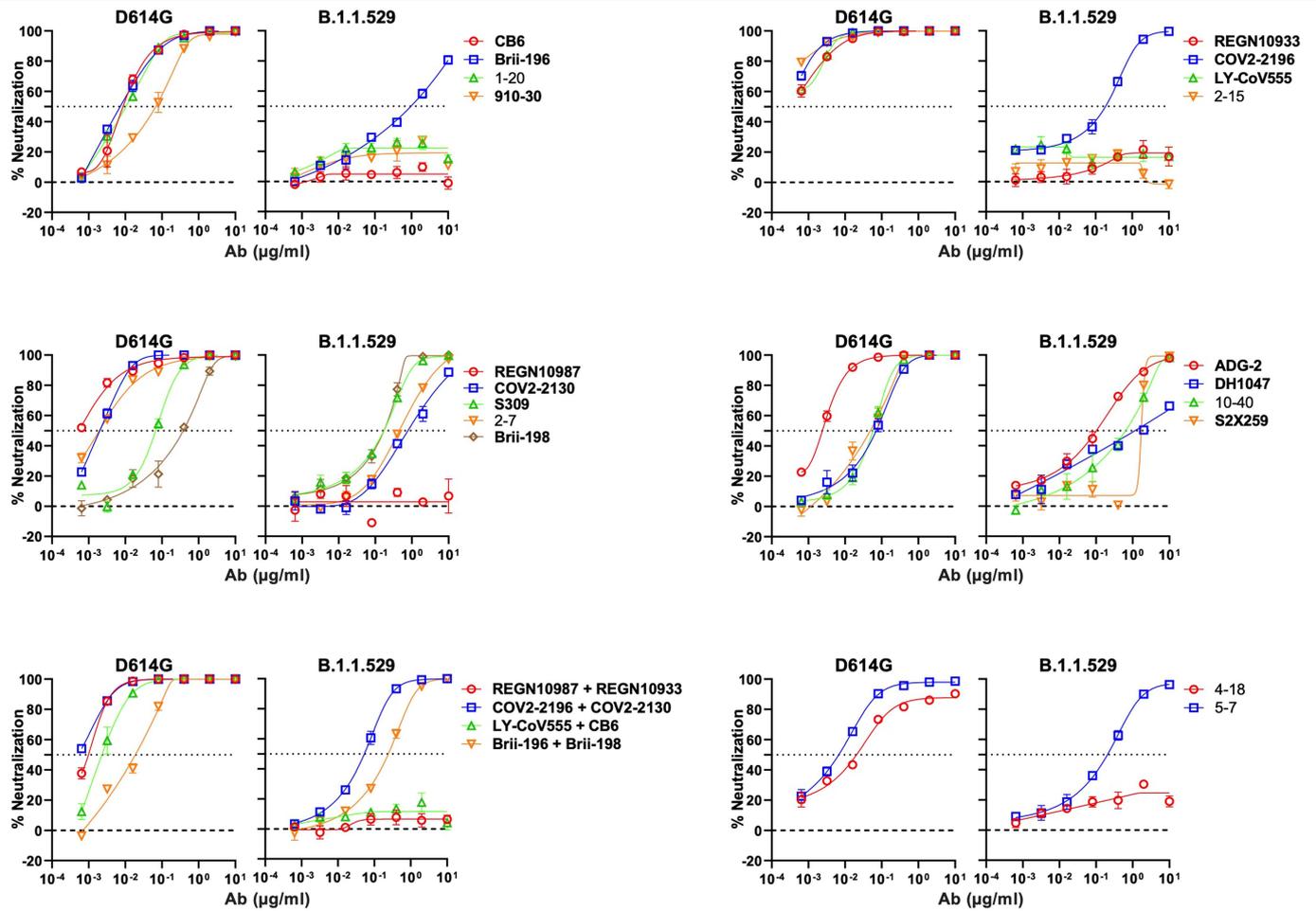
Extended Data Fig. 1 | Mutations within B.1.1.529 denoted on the full SARS-CoV-2 spike trimer. The SARS-CoV-2 spike structure was downloaded from PDB 6ZGE.



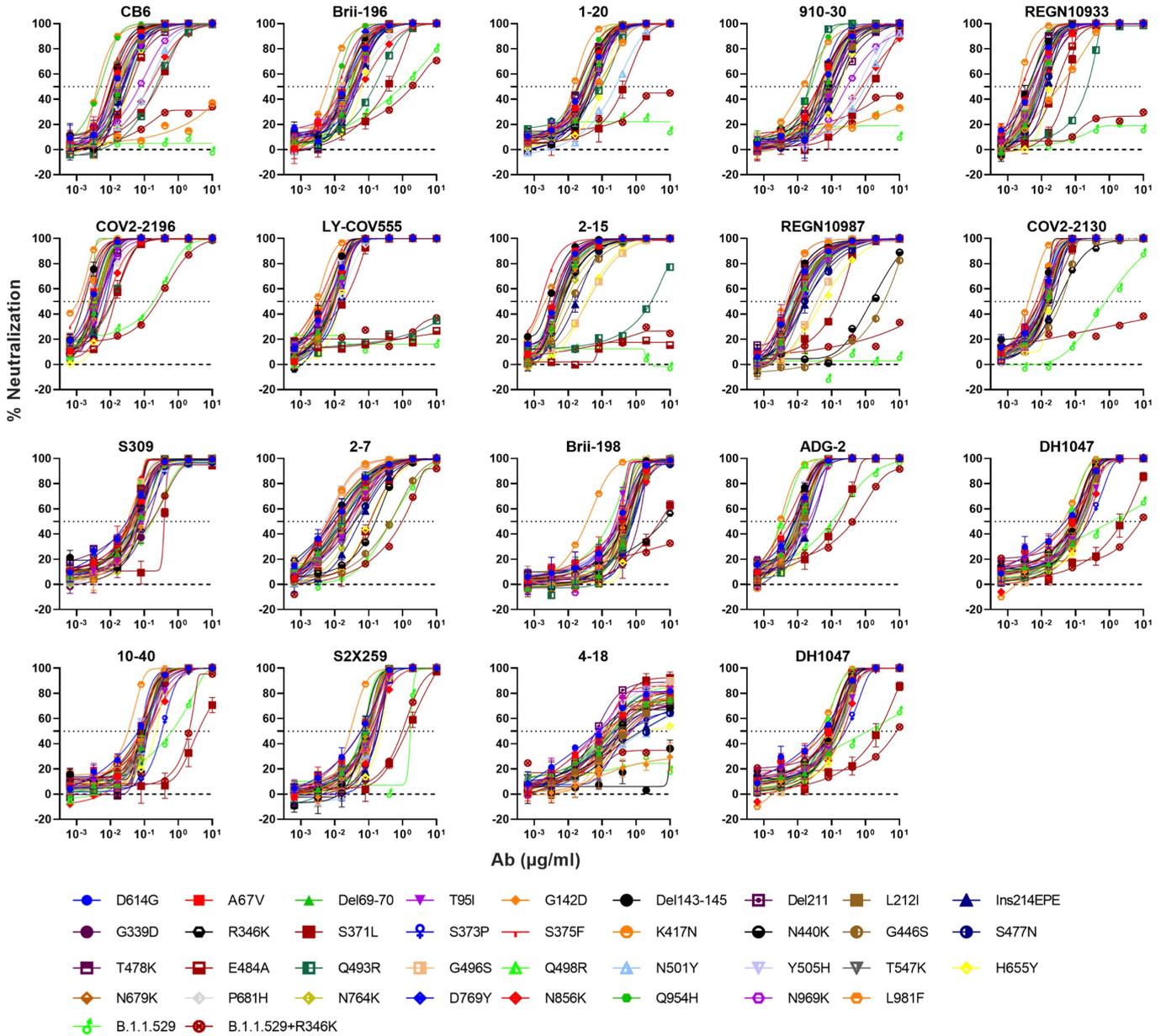
Extended Data Fig. 2 | Individual neutralization curves for pseudovirus neutralization assays by serum. Neutralization by **a**, convalescent sera. **b**, Pfizer (BNT162b2) vaccinee sera. **c**, Moderna (mRNA-1273) vaccinee sera. **d**, J&J (Ad26.COV2.S) vaccinee sera. **e**, AstraZeneca (ChAdOx1 nCoV-19)

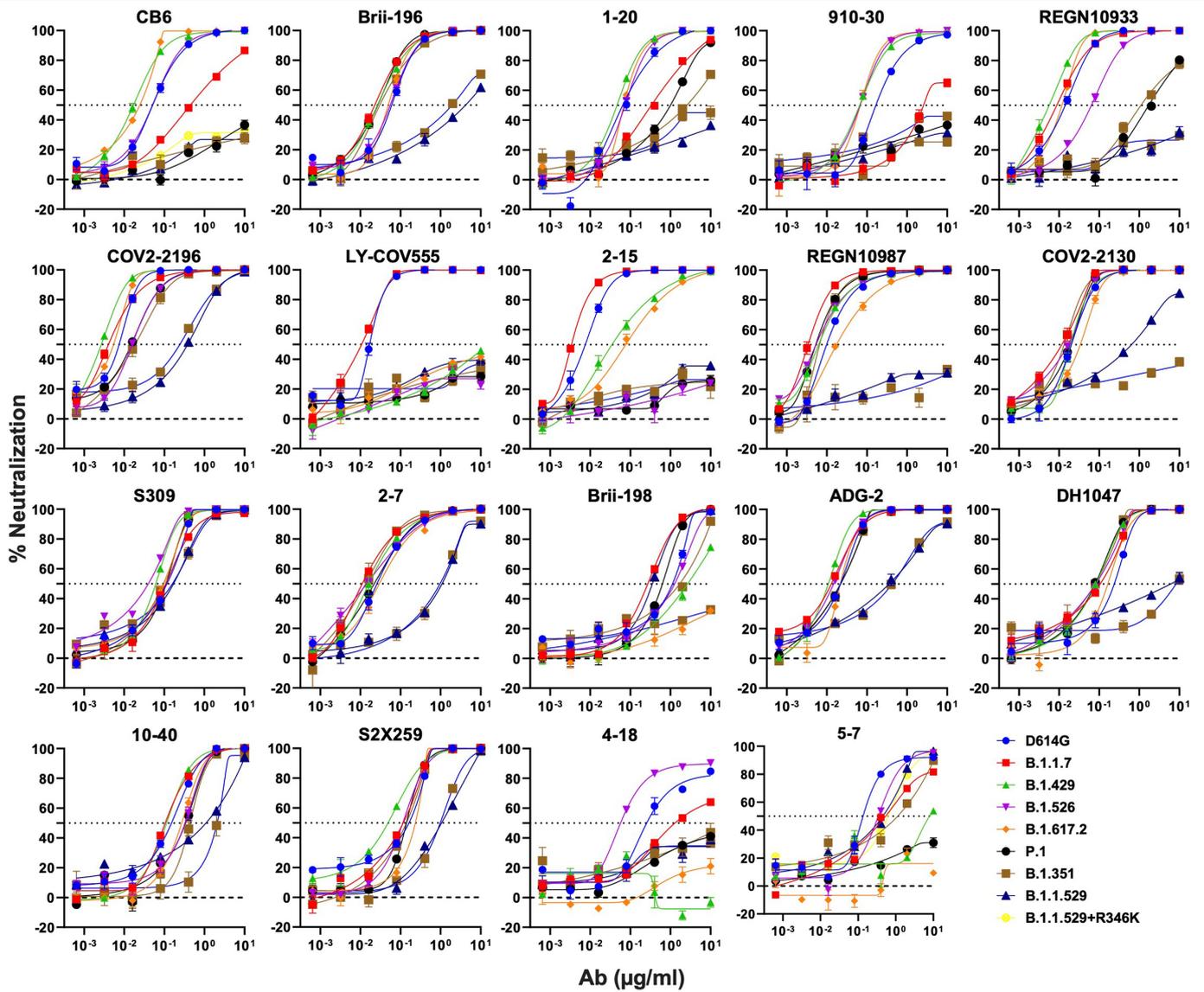
vaccinee sera. **f**, boosted (three homologous BNT162b2 or mRNA-1273 vaccinations) vaccinee sera. Error bars denote mean \pm standard error of the mean (SEM) for three technical replicates.

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Extended Data Fig. 3 | Individual neutralization curves for pseudovirus neutralization assays by monoclonal antibodies. Error bars denote mean \pm standard error of the mean (SEM) for three technical replicates.





Extended Data Fig. 5 | Individual neutralization curves for pseudovirus neutralization assays by monoclonal antibodies against SARS-CoV-2 variants. Error bars denote mean \pm standard error of the mean (SEM) for three technical replicates.

Extended Data Table 1 | Demographics and vaccination information for serum samples from convalescent patients used in this study

Convalescent Sample	Days post-symptoms	Age	Gender
C1	18	57	Female
C2	25	51	Male
C3	29	71	Female
C4	32	50	Male
C5	35	59	Male
C6	120	56	Male
C7	105	54	Female
C8	77	51	Female
C9	18	79	Male
C10	9	45	Male

Article

Extended Data Table 2 | Demographics and vaccination information for serum samples from vaccinated individuals used in this study

Vaccine Sample	Vaccine type	Days post-vaccination (after last dose)	Documented COVID Infection	Age	Gender
Moderna vaccinee #1	mRNA-1273	31	No	72	Male
Moderna vaccinee #2	mRNA-1273	19	No	38	Female
Moderna vaccinee #3	mRNA-1273	6	No	42	Male
Moderna vaccinee #4	mRNA-1273	81	No	40	Female
Moderna vaccinee #5	mRNA-1273	123	No	40	Female
Moderna vaccinee #6	mRNA-1273	177	No	40	Female
Moderna vaccinee #7	mRNA-1273	29	No	57	Female
Moderna vaccinee #8	mRNA-1273	74	No	57	Female
Moderna vaccinee #9	mRNA-1273	32	No	66	Female
Moderna vaccinee #10	mRNA-1273	72	No	63	Male
Moderna vaccinee #11	mRNA-1273	74	No	68	Female
Moderna vaccinee #12	mRNA-1273	58	No	46	Female
Pfizer vaccinee #1	BNT162b2	21	No	62	Male
Pfizer vaccinee #2	BNT162b2	36	No	62	Male
Pfizer vaccinee #3	BNT162b2	26	No	38	Male
Pfizer vaccinee #4	BNT162b2	66	No	38	Male
Pfizer vaccinee #5	BNT162b2	22	No	57	Female
Pfizer vaccinee #6	BNT162b2	61	No	57	Female
Pfizer vaccinee #7	BNT162b2	20	No	55	Male
Pfizer vaccinee #8	BNT162b2	16	No	64	Female
Pfizer vaccinee #9	BNT162b2	32	No	68	Male
Pfizer vaccinee #10	BNT162b2	20	No	35	Male
Pfizer vaccinee #11	BNT162b2	15	No	48	Female
Pfizer vaccinee #12	BNT162b2	21	No	45	Male
Pfizer vaccinee #13	BNT162b2	213	Yes	66	Male
J&J vaccinee #1 (BEI Cat. #NRH-10818)	Ad26.COVS.S	55	Yes	50	Female
J&J vaccinee #2 (BEI Cat. #NRH-10819)	Ad26.COVS.S	61	Yes	50	Female
J&J vaccinee #3 (BEI Cat. #NRH-10835)	Ad26.COVS.S	186	Unknown	43	Female
J&J vaccinee #4 (BEI Cat. #NRH-10845)	Ad26.COVS.S	69	Unknown	28	Female
J&J vaccinee #5 (BEI Cat. #NRH-10823)	Ad26.COVS.S	50	No	42	Female
J&J vaccinee #6 (BEI Cat. #NRH-10834)	Ad26.COVS.S	175	Unknown	43	Female
J&J vaccinee #7 (BEI Cat. #NRH-10839)	Ad26.COVS.S	39	No	47	Male
J&J vaccinee #8 (BEI Cat. #NRH-10844)	Ad26.COVS.S	60	Unknown	28	Female
J&J vaccinee #9 (BEI Cat. #NRH-10824)	Ad26.COVS.S	51	No	43	Male
AZ vaccinee #1 (BEI Cat. #NRH-10817)	ChAdOx1 nCoV-19	158	Unknown	73	Male
AZ vaccinee #2 (BEI Cat. #NRH-10814)	ChAdOx1 nCoV-19	152	Unknown	36	Female
AZ vaccinee #3 (BEI Cat. #NRH-10815)	ChAdOx1 nCoV-19	159	Unknown	36	Female
AZ vaccinee #4 (BEI Cat. #NRH-10811)	ChAdOx1 nCoV-19	142	Yes	26	Female
AZ vaccinee #5 (BEI Cat. #NRH-3083)	ChAdOx1 nCoV-19	91	Unknown	56	Female
Boosted sera #1	mRNA-1273/mRNA-1273	28	No	66	Female
Boosted sera #2	BNT162b2/BNT162b2	30	No	68	Male
Boosted sera #3	BNT162b2/BNT162b2	14	No	64	Female
Boosted sera #4	BNT162b2/BNT162b2	34	No	55	Male
Boosted sera #5	BNT162b2/BNT162b2	34	No	45	Male
Boosted sera #6	BNT162b2/BNT162b2	15	No	50	Female
Boosted sera #7	BNT162b2/BNT162b2	15	No	48	Female
Boosted sera #8	BNT162b2/BNT162b2	29	No	71	Male
Boosted sera #9	BNT162b2/BNT162b2	90	No	59	Male
Boosted sera #10	BNT162b2/BNT162b2	33	No	45	Male
Boosted sera #11	BNT162b2/BNT162b2	87	No	66	Female
Boosted sera #12	BNT162b2/BNT162b2	84	No	26	Male
Boosted sera #13	mRNA-1273/mRNA-1273	23	No	28	Female
Boosted sera #14	BNT162b2/BNT162b2	14	No	78	Male
Boosted sera #15	BNT162b2/BNT162b2	14	No	75	Female

Extended Data Table 3 | Oligos used to construct spike expression plasmids

Oligo name	Targeted mutations	Oligo sequence
O_single_mutant1	A67V	ATGTGACCTGGTTCCATGTGATCCATGTGTCTGGCACCAATGGCACC
O_single_mutant2	Del69-70	CTGGTTCCATGCCATCTCTGGCACCAATGGCAC
O_single_mutant3	T95I	CTTTGCCAGCATCGAGAAGAGCAACATCATC
O_single_mutant4	Del143-145	TGTAATGACCCATTCTGGGACACAAGAACAACAAGTCCTGGATG
O_single_mutant5	G142D	GTAAATGACCCATTCTGGACGTCTACTACCACAAG
O_single_mutant6	Del211	ACACACACCAATCCTGGTGAGGGACCTG
O_single_mutant7	L212I	CACACCAATCAACATCGTGAGGGACCTGCC
O_single_mutant8	Ins214EPE	ACCAATCAACCTGGTGAGGGAGCCCGAGGACCTGCCACAGGGCTT
O_single_mutant9	G339D	CTGTGTCCATTTGACGAGGTGTTCAATGCCAC
O_single_mutant10	R346K	TGTTCAATGCCACCAAGTTTGCCTCTGTCTATGCCTG
O_single_mutant11	S371F	CTCTGTGCTCTACAACCTTGCCTCCTTCAGCAC
O_single_mutant12	S371L	CTCTGTGCTCTACAACCTGGCCTCCTTCAGCAC
O_single_mutant13	S373P	CTCTACAACCTTGCCCCCTTCAGCACCTTCAAG
O_single_mutant14	S375F	CAACTCTGCCTCCTTCTTCACCTTCAAGTGTTATGG
O_single_mutant15	K417N	CCCCTGGACAAACAGGCAACATTGCTGACTACAACACTACAACTGC
O_single_mutant16	N440K	CCTGGAACAGCAACAAGCTGGACAGCAAGGTG
O_single_mutant17	G446S	GGACAGCAAGGTGAGCGGCAACTACAACACTAC
O_single_mutant18	S477N	GATTTACCAGGCTGGCAACACACCATGTAATG
O_single_mutant19	T478K	CAGGCTGGCAGCAAGCCATGTAATGGAGTGGA
O_single_mutant20	E484A	GTAATGGAGTGCCGGCTTCAACTGTTAC
O_single_mutant21	Q493R	GTTACTTTCCACTCAGATCCTATGGCTTCCAAC
O_single_mutant22	G496S	CACTCCAATCCTATAGCTTCCAACCAACCAATG
O_single_mutant23	Q498R	CAATCCTATGGCTTACAGCAACCAATGGAGTGGG
O_single_mutant24	N501Y	CTTCCAACCAACCTACGGAGTGGGCTACCAACC
O_single_mutant25	Y505H	AATGGAGTGGGCCACCAACCATACAGG
O_single_mutant26	T547K	CTTCAATGGACTGAAGGGCACAGGAGTGCTGAC
O_single_mutant27	H655Y	CTGATTGGAGCAGAGTACGTGAACAACCTCCTATG
O_single_mutant28	N679K	CCAGACCCAGACCAAGAGCCCAAGGAGGGCA
O_single_mutant29	P681H	CCCAGACCAACAGCAGAAGGAGGGCAAGGTCTGTGGC
O_single_mutant30	N764K	GTACCCAACCTAAGAGGGCTCTGACAGGC
O_single_mutant31	D769Y	GACACCTCCAATCAAGTACTTTGGAGGCTTC
O_single_mutant32	N856K	GTGCCCAGAAGTTCAAGGGACTGACAGTGCTG
O_single_mutant33	Q954H	CAAGATGTGGTGAACCAATGCCAGGCTCTG
O_single_mutant34	N969K	GCAACTTTCCAGCAAGTTTGGAGCCATCTCCTC
O_single_mutant35	L981F	GTGCTGAATGACATCTTCAGCAGACTGGACAAGGTGGAGG
O_multiple_oligo1	A67V, Del69-70	TGGTTCCATGTGATCTCTGGCACCAATGG
O_multiple_oligo2	T95I	CTTTGCCAGCATCGAGAAGAGCAAC
O_multiple_oligo3	G142D, Del143-145	GACCCATTCTGGACCACAAGAACAACAAGTC
O_multiple_oligo4	L212I, Ins214EPE	CACACACCAATCATCGTGAGGGAGCCCGAGGACCTGCCACAGGGCTTC
O_multiple_oligo5	G339D	TGTGTCCATTTGACGAGGTGTTCAATG
O_multiple_oligo6	S371L, S373P, S375F	TGTGCTCTACAACCTGGCCCCCTTCTTCACCTTCAAGTGTTATG
O_multiple_oligo7	K417N	GGACAAACAGGCAACATTGCTGACTACA
O_multiple_oligo8	N440K, G446S	GCAACAAGCTGGACAGCAAGGTGAGCGGCAACTACAA
O_multiple_oligo9	S477N, T478K, E484A	ACCAGGCTGGCAACAAGCCATGTAATGGAGTGCCGGCTTCAACTGT
O_multiple_oligo10	Q493R, G496S, Q498R, N501Y, Y505H	TACTTTCCACTCAGATCCTATAGCTTACAGCAACCTACGGAGTGGGCCACCAACCATACAGG GTGGTGGTGTCTCTCTTGA
O_multiple_oligo11	T547K	GGACTGAAGGGCACAGGAG
O_multiple_oligo12	D614G	CTCTACCAGGGCGTGAAGTGTAC
O_multiple_oligo13	H655Y	TTGGAGCAGAGTACGTGAACAACCTC
O_multiple_oligo14	N679K, P681H	CAGACCAAGAGCCACAGGAGGGCAAGG
O_multiple_oligo15	N764K	CCAACTTAAGAGGGCTCTGACAG
O_multiple_oligo16	D796Y	CCTCCAATCAAGTACTTTGGAGGCTTC
O_multiple_oligo17	N856K	CAGAAGTTCAAGGGACTGACAGTGCTG
O_multiple_oligo18	Q954H	GTGGTGAACCACAATGCCAGGCTC
O_multiple_oligo19	N969K	AACTTTCCAGCAAGTTTGGAGCCATCTCCTC
O_multiple_oligo20	L981F	AATGACATCTTCAGCAGACTGGACAAGGTGGAGGCTGAGGTCCAGATTG

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Give P values as exact values whenever suitable.
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- For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
- Estimates of effect sizes (e.g. Cohen's d , Pearson's r), indicating how they were calculated

Our web collection on [statistics for biologists](#) contains articles on many of the points above.

Software and code

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- Data collection SoftMax Pro 7.0.2 (Molecular Devices, LLC) was used to measure luminescence in the pseudovirus neutralization assays.
- Data analysis GraphPad Prism (version 9.2) was used for data visualization and for statistical tests. Cutadapt (version 2.1) was used for processing of raw reads from next-generation sequencing. Bowtie2 (version 2.3.4) was used for alignment of reads to sequences. PISA was used for identifying antibody-spike interface residues. Antibody footprints were optimized by ImageMagick 7.0.10-31. PyMOL (version 2.3.2) was used for RBD mutagenesis analysis and for visualization.

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Materials used in this study will be made available under an appropriate Materials Transfer Agreement. All the data are provided in the paper. The structures used for analysis in this study are available from PDB under IDs 6ZGE, 7L5B, 6XDG, 7L2E, 7RW2, 7C01, 7KMG, 7CDI, 7KS9, 7LD1, 7RAL, 7LSS, and 6WPT.

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Life sciences study design

All studies must disclose on these points even when the disclosure is negative.

Sample size	We used similar sample sizes as in previous work (e.g. Wang et al 2021, Nature), which we had previously determined to be sufficient sample sizes for comparisons between groups for these experiments.
Data exclusions	No data were excluded.
Replication	The key results, the resistance of R346K, S371L, B.1.1.529, and B.1.1.529+R346K to monoclonal antibodies in pseudoviruses, and serum neutralization of authentic viruses, were repeated twice independently in technical triplicate with similar results. The results that are shown are representative. Other experiments were conducted in technical triplicate and not repeated.
Randomization	As this is an observational study, randomization is not relevant.
Blinding	As this is an observational study, investigators were not blinded.

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We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

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n/a	Involved in the study
<input type="checkbox"/>	<input checked="" type="checkbox"/> Antibodies
<input type="checkbox"/>	<input checked="" type="checkbox"/> Eukaryotic cell lines
<input checked="" type="checkbox"/>	<input type="checkbox"/> Palaeontology and archaeology
<input checked="" type="checkbox"/>	<input type="checkbox"/> Animals and other organisms
<input type="checkbox"/>	<input checked="" type="checkbox"/> Human research participants
<input checked="" type="checkbox"/>	<input type="checkbox"/> Clinical data
<input checked="" type="checkbox"/>	<input type="checkbox"/> Dual use research of concern

Methods

n/a	Involved in the study
<input checked="" type="checkbox"/>	<input type="checkbox"/> ChIP-seq
<input checked="" type="checkbox"/>	<input type="checkbox"/> Flow cytometry
<input checked="" type="checkbox"/>	<input type="checkbox"/> MRI-based neuroimaging

Antibodies

Antibodies used	All of the antibodies used in this study were produced in our laboratory or received from other laboratories. 1-20, 2-15, S309, 2-7, ADG-2, DH1047, 10-40, S2X259, 4-18, and 5-7 were expressed and purified in-house as described previously in Liu et al 2020, Nature. REGN10987, REGN10933, COV2-2196, and COV2-2130 were provided by Regeneron Pharmaceuticals, Brie-196 and Brie-198 were provided by Brie Biosciences, CB6 was provided by Baoshan Zhang and Peter Kwong (NIH), and 910-30 was provided by Brandon DeKosky (MIT).
Validation	All of the antibodies have been validated in previous studies both by binding to SARS-CoV-2 spike and neutralization of SARS-CoV-2 (both pseudovirus and authentic virus), and when applicable, have been confirmed to give similar results as that described in publications by other groups. Specifically, 1-20 and 4-18 were tested in Liu et al 2020, Nature, CB6, Brie-196, 910-30, REGN10933, COV2-2196, LY-CoV555, 2-15, REGN10987, COV2-2130, S309, 2-7, Brie-198, and 5-7 were tested in Wang et al 2021, Nature, and ADG-2, DH1047, 10-40, and S2X259 were tested in Liu et al 2021, bioRxiv.

Eukaryotic cell lines

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Cell line source(s)	Expi293 cells were obtained from Thermo Fisher (Catalog #A14527), Vero E6 cells were obtained from ATCC (Catalog# CRL-1586), HEK293T cells were obtained from ATCC (Catalog# CRL-3216), and Vero-E6-TMPRSS2 cells were obtained from JCRB (Catalog# JCRB1819).
Authentication	Cell lines were purchased from authenticated vendors, and morphology was also confirmed visually prior to use.

Mycoplasma contamination Cell lines tested mycoplasma negative.

Commonly misidentified lines (See [ICLAC](#) register) No commonly misidentified cell lines were used in this study.

Human research participants

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Population characteristics Population characteristics are described in detail for each individual in Extended Data Table 1 and 2. Convalescent samples had the following ranges: 9-120 days post-symptoms, 45-79 years old, 4/10 female, 6/10 male. We presume all of these individuals were infected with the wild-type strain of SARS-CoV-2 as these samples were collected in Spring of 2020. Vaccinee samples had the following ranges: 6-213 days post-vaccination, 26-78 years old, 12/54 two mRNA-1273 vaccinations, 13/54 two BNT162b2 vaccinations, 9/54 Ad26.COVS2 vaccination, 5/54 two ChAdOx1 nCoV-19 vaccinations, 2/54 three mRNA-1273 vaccinations, 13/54 three BNT162b2 vaccinations, 4/54 previously infected, 8/54 unknown previous infection status, 42/54 uninfected, 31/54 female, 23/54 male.

Recruitment For convalescent sera, convalescing patients volunteered and were enrolled in an observational cohort study at Columbia University Irving Medical Center in Spring of 2020. For the BNT162b2 and mRNA-1273 vaccinee sera, individuals volunteered and were enrolled in an observational cohort study at Columbia University Irving Medical Center to study the immunological responses to SARS-CoV-2 in individuals who had received COVID-19 vaccines. Ad26.COVS2 and ChAdOx1 nCoV-19 vaccinee serum samples were received from BEI Resources. Self-selection biases may have affected the demographics of the enrolled population, but are not expected to have impacted the results of this study. High titer samples were specifically chosen within each of the serum groups so that fold-change in titer could be better determined, as also discussed in the manuscript.

Ethics oversight All collections were conducted under protocols reviewed and approved by the Institutional Review Board of Columbia University. All participants provided written informed consent.

Note that full information on the approval of the study protocol must also be provided in the manuscript.