

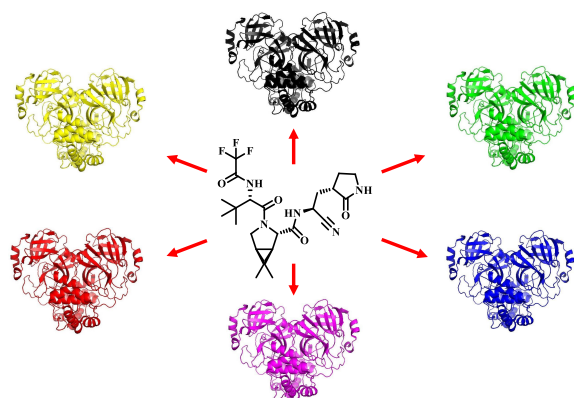
Main protease mutants of SARS-CoV-2 variants remain susceptible to PF-07321332

Sven Ullrich, Kasuni B. Ekanayake, Gottfried Otting, Christoph Nitsche*

Research School of Chemistry, Australian National University, Canberra, ACT 2601, Australia

*christoph.nitsche@anu.edu.au

Graphical Abstract



Keywords

SARS-CoV-2, main protease, variants, PF-07321332, inhibitors

Abstract

The COVID-19 pandemic continues to be a public health threat. Multiple mutations in the spike protein of emerging variants of SARS-CoV-2 appear to impact on the effectiveness of available vaccines. Specific antiviral agents are keenly anticipated but their efficacy may also be compromised in emerging variants. One of the most attractive coronaviral drug targets is the main protease (M^{pro}). A promising M^{pro} inhibitor of clinical relevance is the peptidomimetic PF-07321332. We expressed M^{pro} of five SARS-CoV-2 lineages (C.37 Lambda, B.1.1.318, B.1.2, B.1.351 Beta, P.2 Zeta), each of which carries a strongly prevalent missense mutation (G15S, T21I, L89F, K90R, L205V). Enzyme kinetics showed that these M^{pro} variants are similarly catalytically competent as the wildtype. We show that PF-07321332 has similar potency against the variants as against the wildtype. Our *in vitro* data suggest that the efficacy of specific M^{pro} inhibitors such as PF-07321332 is not compromised in current COVID-19 variants.

Since its emergence in late 2019,¹ COVID-19 has significantly impacted on societies worldwide.² More than 5 million deaths have been attributed to COVID-19, with the number of confirmed SARS-CoV-2 infections surpassing 250 million.³ The outbreak of SARS-CoV-2 prompted multiple successful vaccine development campaigns.⁴ Currently approved vaccines, such as viral vector or mRNA vaccines, successfully limited the pandemic's impact on global health.^{5, 6} Most COVID-19 vaccines function by stimulating an immune response against the SARS-CoV-2 spike protein (S)⁷⁻⁹ but, as the spike gene has gathered pronounced genetic variability,^{10, 11} it is a common concern that the effectiveness of existing vaccines may be affected by those variants of SARS-CoV-2.^{5, 6, 10, 12} At the time of writing, the World Health Organization (WHO) lists four variants of concern (VOC; Alpha, Beta, Gamma, Delta) and two variants of interest (VOI; Lambda, Mu).¹³ A possible adjustment of the vaccines to currently circulating lineages of SARS-CoV-2 is being investigated.¹⁴⁻¹⁶ It is clear that the deployment of vaccines remains the best public health measure to control the spread of SARS-CoV-2 and the severe health effects of COVID-19.^{17, 18}

Complementary to preventive vaccines, antiviral drugs are urgently needed to combat COVID-19.¹⁹ Since the discovery of SARS-CoV-1 in 2003,²⁰ several coronaviral drug targets have been identified,²¹ including the RNA-dependent RNA polymerase (RdRp, nsp12),²² the helicase (nsp13),²³ the papain-like protease (PL^{pro}, part of nsp3),²⁴ and the main protease (M^{pro}, 3CL^{pro}, nsp5).²⁵ Despite this, treatment options for COVID-19 are limited and there are currently no approved antiviral drugs specifically designed to target coronaviruses. Only very recently, in November 2021, the orally active drug molnupiravir (MK-4482, EIDD-2801, Lagevrio™) was approved in the United Kingdom. Molnupiravir targets RdRp by acting as a nucleoside analogue prodrug, but was originally developed against different RNA viruses.²⁶ Lately, the peptidomimetic PF-07321332 (Paxlovid™ as combination drug with ritonavir as booster) has also drawn attention as a potential COVID-19 therapeutic,²⁷ as the compound has entered phase 3 clinical trials (NCT04960202, NCT05011513, NCT05047601). PF-07321332 is an orally available M^{pro} inhibitor, employing a nitrile warhead to covalently bind the catalytic cysteine residue in the active site of the protease (**Figure 2a**).²⁷

SARS-CoV-2 M^{pro} is a homodimeric cysteine protease, which processes the majority of the viral polyproteins pp1a and pp1ab encoded by the ORF1a/b gene.^{25, 28} Inhibition of M^{pro} thus ultimately hinders the assembly of the replication and transcription complexes (RTCs).^{25, 29} The protease has a distinct recognition motif, with – in the Schechter-Berger notation³⁰ – preference for leucine in P₂ and especially strong preference for glutamine in P₁.^{25, 31} Human

host proteases have different substrate specificities and it is therefore anticipated that selective inhibitors have limited off-target effects.²⁵

Previous research on SARS-CoV-1 M^{pro} (which is 96% identical in amino acid sequence to SARS-CoV-2 M^{pro})²⁵ demonstrated that missense point mutations can influence protease activity. Mutants have been identified with slightly enhanced (Ser284, Thr285, Ile286)^{32, 33} or slightly or severely reduced catalytic activity (Gly11, Asn28, Ser139, Phe140, Glu166, Asn214, Arg298).^{32, 34-38} Specifically the R298A mutation has become a tool to study the protease in its monomeric form, since it inactivates the protease by disrupting the M^{pro} dimer.³⁵ The present study assesses the M^{pro} mutants of emerging SARS-CoV-2 lineages. We analysed the most widespread amino acid substitutions in SARS-CoV-2 M^{pro}, characterized them by enzyme kinetics and assessed their susceptibility to inhibition by PF-07321332.

Utilizing the Outbreak.info database by Scripps Research,³⁹ which partially operates with data provided by the GISAID Initiative,⁴⁰ we performed an analysis of the genomes of SARS-CoV-2 lineages, including the VOC and VOI. The WIV04 sequence (EPI_ISL_402124)⁴¹ acted as wildtype reference genome. Lineage comparison⁴² of VOCs and VOIs revealed two missense mutations in the M^{pro} section of the ORF1a/b gene with >20% frequency of occurrence. The mutations are G15S, which is >85% prevalent⁴³ in the Lambda VOI (or C.37, using PANGO nomenclature)⁴⁴ and K90R, which is >95% prevalent⁴⁵ in the Beta VOC (B.1.351). The Delta VOC (B.1.617.2), which is the dominant lineage at present,⁴⁶ did not display any particularly prevalent (>20%)⁴² missense mutations within the M^{pro} part of ORF1a/b at the time of writing. We additionally chose to investigate three additional abundant M^{pro} mutations to cover a larger variety of lineages: T21I, which is >90% prevalent⁴⁷ in B.1.1.318, a WHO variant under monitoring (VUM),¹³ L89F, which is >95% prevalent⁴⁸ in the B.1.2 lineage, and L205V, which is >95% prevalent⁴⁹ in the former VOI Zeta (P.2) (**Figure 1b**). Hence, we selected the five mutations G15S, T21I, L89F, K90R and L205V for further investigations.

X-ray crystal structures of wildtype (WT) SARS-CoV-2 M^{pro} (e.g. PDB: 6LU7)⁵⁰ indicate that the polar residues G15, T21 and K90 are solvent-exposed, while the hydrophobic residues L89 and L205 are buried within the protease. Except for T21I, the mutations introduce no major changes in the chemical character of the side-chains, as indicated by low, or in the case of T21S moderate, Miyata's distances.⁵¹ The mutations G15S, T21I, L89F and K90R are in domain I, while the mutation L205V is located in domain III (**Figure 1a**).²⁵

WT SARS-CoV-2 M^{pro} and the mutants G15S, T21I, L89F, K90R and L205V were expressed in *E. coli* and purified. An established Förster resonance electron transfer (FRET) *in*

vitro assay of M^{pro} activity⁵² was employed to determine initial velocities of the proteolytic activity at various substrate concentrations. The data confirmed that all mutants are enzymatically active, which was expected^{25, 53} as a dysfunctional M^{pro} would prevent replication of SARS-CoV-2. The six M^{pro} variants exhibited turnover numbers (k_{cat}) between 0.54 and 0.95 s⁻¹, and Michaelis constants (K_m) from 37 to 67 μM (**Table 1**). The catalytic efficiencies (k_{cat}/K_m) calculated for the mutants (0.009 to 0.015 s⁻¹μM⁻¹) are similar to that of WT M^{pro} (0.016 s⁻¹μM⁻¹), confirming that all M^{pro} variants are equally competent with regard to their proteolytic activities (**Figure 1c, Table 1**).

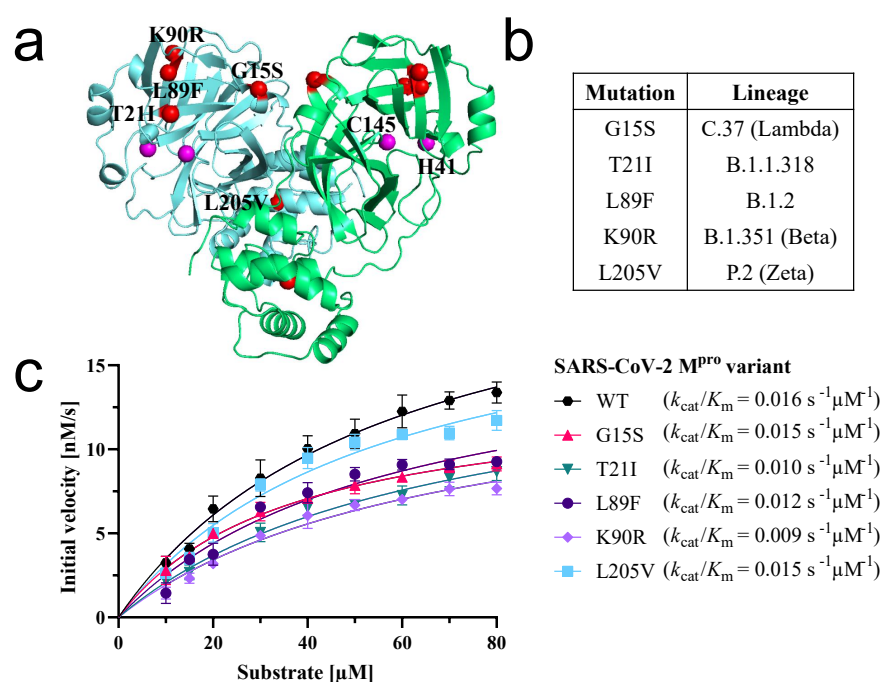


Figure 1. Comparison of M^{pro} mutations and proteolytic activities. (a) X-ray structure of SARS-CoV-2 M^{pro} (PDB: 6LU7)⁵⁰ indicating the location of mutations (red) and the catalytic dyad (purple) in the two protomers (cyan, green). (b) List of prevalent M^{pro} mutations and their corresponding SARS-CoV-2 lineage. (c) Michaelis-Menten kinetics of SARS-CoV-2 M^{pro} variants specifying their catalytic efficiency (k_{cat}/K_m).

Table 1. Michaelis-Menten parameters of SARS-CoV-2 M^{pro} variants.

Variant	k_{cat} [s ⁻¹]	K_m [μM]	k_{cat}/K_m [s ⁻¹ μM ⁻¹]
WT	0.94 ± 0.08	57 ± 9	0.016 ± 0.004
G15S	0.54 ± 0.03	37 ± 4	0.015 ± 0.002
T21I	0.64 ± 0.06	67 ± 11	0.010 ± 0.003
L89F	0.69 ± 0.08	58 ± 13	0.012 ± 0.004
K90R	0.60 ± 0.06	67 ± 12	0.009 ± 0.003
L205V	0.82 ± 0.08	55 ± 10	0.015 ± 0.004

Following the kinetic analysis of the SARS-CoV-2 M^{pro} variants, the clinical candidate PF-07321332 (**Figure 2a**) was used to assess the potential impact of M^{pro} mutations on the drug's efficacy. The inhibition constant (K_i) of PF-07321332 against SARS-CoV-2 WT M^{pro} has been reported to be 3.1 nM.²⁷ Our FRET assay confirmed that PF-07321332 inhibits the activity of M^{pro} variants at nanomolar compound concentrations. Furthermore, the extent of inhibition was similar across the different protease variants, with 5 nM compound displaying inhibition below 50%, 20 nM showing inhibition over 50% and 100 nM fully inhibiting the enzymatic activity of all mutants and the WT (**Figure 2b**).

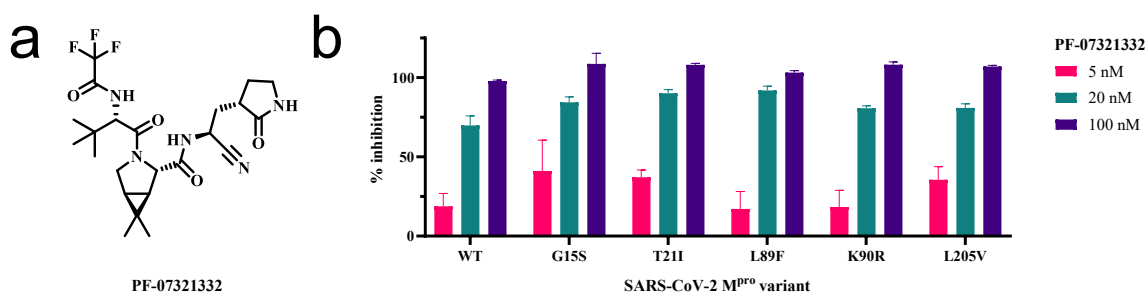


Figure 2. Inhibition of SARS-CoV-2 M^{pro} variants. (a) Chemical structure of the inhibitor PF-07321332.²⁷ (b) *In vitro* inhibition of SARS-CoV-2 M^{pro} variants by PF-07321332.

In summary, we identified the currently most prevalent M^{pro} variants (G15S, T21I, L89F, K90R, L205V) in different lineages of SARS-CoV-2 (C.37 Lambda, B.1.1.318, B.1.2, B.1.351 Beta, P.2 Zeta) and experimentally confirmed that they are equally potent as the wildtype. In addition, we confirmed that PF-07321332 maintains effective inhibition of all these M^{pro} variants. This gives hope that SARS-CoV-2 M^{pro} inhibitors at present would not be negatively affected by these virus variants. It must be noted, however, that widespread use of M^{pro} inhibitors may challenge SARS-CoV-2 to develop M^{pro} mutations that overcome these

inhibitors, as previously experienced for, e.g., HIV protease inhibitors.⁵⁴ Despite these challenges, protease inhibitors have revolutionized antiviral treatment for viral infectious diseases, including HIV and HCV.⁵⁵ It can thus be expected that M^{pro} inhibitors will have a similar impact on the future development of the COVID-19 pandemic.

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Competing Interest Declaration

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

Author Information

Sven Ullrich, ORCID: 0000-0003-4184-7024

Kasuni B. Ekanayake, ORCID: 0000-0002-3078-5895

Gottfried Otting, ORCID: 0000-0002-0563-0146

Christoph Nitsche, ORCID: 0000-0002-3704-2699

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