

1 **Structural interactions between pandemic SARS-CoV-2 spike glycoprotein and human**
2 **Furin protease**

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14 **Keywords**

15 Coronavirus, spike glycoprotein, COVID-19, Furin, protease,

16

17 **Abstract**

18 The SARS-CoV-2 pandemic is an urgent global public health emergency and
19 warrants investigating molecular and structural studies addressing the dynamics of viral
20 proteins involved in host cell adhesion. The recent comparative genomic studies highlight
21 the insertion of Furin protease site in the SARS-CoV-2 spike glycoprotein alerting possible
22 modification in the viral spike protein and its eventual entry to host cell and presence of Furin
23 site implicated to virulence. Here we structurally show how Furin interacts with the SARS-
24 CoV-2 spike glycoprotein homotrimer at S1/S2 region, which underlined the mechanism and
25 mode of action, which is a key for host cell entry. Unravelling the structural features of
26 binding site opens the arena in rising bonafide antibodies targeting to block the Furin cleavage
27 and have great implications in the development of Furin inhibitors or therapeutics.

28

29 **Introduction**

30 The pandemic Corona Virus Disease 2019 (COVID-19) caused by Severe Acute
31 Respiratory Syndrome Coronavirus 2 (SARS-CoV-2), is an urgent public health emergency
32 and made a serious impact on global health and economy (1). To date, more than 86,000
33 deaths and 1.5 million confirmed positive cases were reported globally, making the most
34 contagious pandemic in the last decade (www.coronavirus.gov). Since the initial reports on

35 this pneumonia-causing novel coronavirus (SARS-CoV-2) in Wuhan, China , mortality and
36 morbidity are increasing exponentially around the globe despite several antiviral and
37 antibody treatments (2). Most available neutralising antibodies in use are targeting the SARS-
38 CoV-2 spike glycoprotein, which is essential for host cell adhesion via ACE2 and CD26
39 receptors (3, 4), but infection control is still insignificant. Meanwhile, several antiviral drugs
40 (Ritonavir, Lopinavir, Chloroquine, Remdesivir and others) targeting different host and viral
41 proteins are been clinically evaluating and repurposing to combat SARS-CoV-2 infection (2,
42 5). With the drastic increasing number of the positive cases around the world (www.cdc.gov),
43 moderate response to antivirals under clinical trials and poor response to antibodies targeting
44 spike SARS-CoV-2 spike glycoprotein is a serious concern and warrants detail understanding
45 of the molecular and structural features of SARS-CoV-2 structural proteins in native
46 condition and post-viral infection. This will abet in understanding the dynamics and
47 mechanism of viral action on the human cell.

48

49 In this regard, several epidemiological and evolutionary reports have highlighted the
50 several unique sequence deletions and insertions in the SARS-CoV-2 genome compare to
51 previous known SARS and Bat coronavirus (6, 7). Among the various genetic variations,
52 insertion of Furin protease cleavage site in the spike glycoprotein (aa682 – aa689) is
53 strikingly novel in SARS-CoV-2 (4, 8) and has not been found in other related coronaviruses
54 (SARS-CoV-1, Bat-CoV, Pangolin) (MERS contain pseudo binding site) (Fig. S1A). Furin
55 protease belongs to the family of calcium (Ca²⁺)-dependent proprotein/prohormone
56 convertase (PCs) which is ubiquitously expressed in humans but its levels are elevated lung
57 cystic fibrosis (9). Furin protease also cycles from trans-Golgi network (TGN) to cell
58 membrane (virus attaches) and endosomes (virus translocate in endosomes). Interestingly,
59 Furin and other related proteases are highly specific and known for cleaving different viral
60 (Influenza, HIV) envelope glycoproteins, thereby enhancing viral fusion with the host cell
61 membrane (10). Furthermore, Furin preferentially recognizes the motif R-X-K/R-R and
62 cleaves the peptide in the presence of Ca²⁺, which is physiologically connected to different
63 viral infections (10, 11). However, about SARS-CoV-2, it is elusive that how Furin could
64 bind and act on the viral spike glycoprotein. Hence to understand the interaction mode and
65 mechanism of Furin action over the spike glycoprotein warrants further structural and
66 biomolecular studies.

67

68 **Methods**

69 Considering the current public health crisis and to better understand the structural and
70 molecular mode of interactions between SARS-CoV-2 spike protein and human Furin, we
71 resolve the structure of SARS-CoV-2 spike glycoprotein in complex with Furin protease via
72 molecular dynamics and simulations. Unfortunately, the only two available SARS-CoV-2
73 spike glycoprotein Cryo-EM structures (PDB: 6VSB and 6VXX) are incomplete and has
74 several gaps in the built structure and also lacks the structure for Furin cleavage sites (3, 12).
75 As these EM structures built on molecular replacement with SARS-CoV-1 (PDB: 6ACG),
76 Furin cleavage sites in the spike protein is flexible and novel insertion only in the SARS-
77 CoV-2, the EM structures lack this important region. Hence, for the molecular dynamics and
78 simulation studies, we directed to use previously published and validated model structure of
79 full-length SARS-CoV-2 spike glycoprotein (4) and published structure of human Furin
80 (PDB: 1P8J or 1JXH) (11). The RMSD of the previously published model structure and
81 Cryo-EM structure was 0.84, which suggests overall structural accuracy even with the
82 presence of Furin cleavage sites. The binding free energies were taken into consideration for
83 selecting the best possible model. Further validation and refinement was completed by
84 ensuring that the residues occupied Ramachandran favoured positions using Coot ([www.mrc-
85 imb.cam.ac.uk/](http://www.mrc-imb.cam.ac.uk/)). The final complex structure was then compared with the initial Furin structure
86 and their overall RMSD was found to be 0.28 Å for Ca atoms.

87

88 **Results**

89 The overall complex structure shows three Furin proteases binding to the mid or
90 equatorial region (mid region of S1 and S2 domain (S1/S2)) of SARS-CoV-2 spike
91 glycoprotein homo-trimer at the off-centric and adjacent side of spike trimer (Fig. 1 and
92 S1B). The binding Furin proteases adopt a clamp-like fashion, where it clips to the cleavage
93 site of the spike glycoprotein. Furthermore, the binding of Furin protease creates a large
94 buried interface of $\sim 1,100\text{\AA}^2$ ($\sim 368\text{\AA}^2/\text{Furin}$) between the proteins, as calculated from the
95 PISA server (<https://www.ebi.ac.uk/pdbe/pisa/>). This suggests a bonafide and tight
96 interaction of Furin protease over the spike glycoprotein and Furin. The depth, shape and
97 charge of Furin protease are well known and it has canyon-like crevice and its active site
98 pocket is conserved in many species and the catalytic or substrate-binding pocket is made of
99 key amino acid residues R185, M189, D191, N192, R193, E229, V231, D233, D259, K261,
100 R298, W328 and Q346 (10, 11) (Fig. 2 and S2). Interestingly, these residues are also well-
101 positioned to interact with the viral spike protein cleavage site in our complex structure and
102 the entire substrate-binding pocket of Furin protease appears like a canyon-like crevice,

103 which can accommodate a large portion of target protein/peptide. The results show that the
104 SARS-CoV-2 spike glycoprotein amino acid residues N657 to Q690 are the prime interacting
105 residues with the Furin protease. The position and orientation of these unique residues
106 involved in Furin recognition are well exposed and organise in a flexible loop. The spike
107 protein residues N657, N658, E661, Y660, T678, N679, S680, R682, R683, R685, S689,
108 Q690 makes the strong interaction with the Furin protease (Fig. 2A). The interaction between
109 the viral spike glycoprotein and Furin protease is mediated via several van der Waals or by
110 hydrogen bonding. Furthermore, the entire cleavage loop of viral spike protein fits into the
111 canyon-like substrate-binding pocket of Furin protease. It is quite interesting to notice that
112 none of the previously known coronaviruses had this novel Furin protease cleavage site in the
113 spike glycoprotein, which accentuates the novelty and uniqueness of SARS-CoV-2. In
114 addition, previous reports on the glycosylation of spike glycoprotein show that Furin
115 cleavage site in the SARS-CoV-2 spike glycoprotein is not targeted by the glycosylation,
116 hence this cleavage loop is completely solvent-exposed (4). This further corroborates the
117 potential attack of Furin protease over the S1/S2 cleavage site in the SARS-CoV-2 spike
118 glycoprotein. Based on the Furin binding mode and structural interaction, we propose the
119 following supposition. The binding and cleaving (priming) the spike glycoprotein at S1/S2
120 region by Furin protease might cut the spike glycoprotein into N-terminal S1 domain
121 involved in host cell recognition and C-terminal S2 membrane-anchored domain involved in
122 host cell penetration and entry, thus making the SARS-CoV-2 highly virulent. In support of
123 this supposition, it is evident in infectious bronchitis virus that presence of Furin cleavage site
124 has pronounced virulence suggesting Furin cleavage increase the virulence (13).

125

126

127 **Discussion:**

128 Based on this enzyme cleavage action and separation of N- and C- terminal domain of
129 spike glycoproteins also could make the ACE2 and CD26 inhibitors of least effective, as
130 upon cleavage the N-terminal S1 domains are not required for the cell penetration. This also
131 raises a caution that while making neutralizing antibodies targeting SARS-CoV-2 spike
132 glycoprotein, these cleavage activities need to be considered. Hence, we speculate that
133 antibodies against S2 domain and drugs targeting S1 trimerization could be more promising.
134 These observations and structure-guided molecular interaction with novel Furin protease
135 guide us to suggest that SARS-CoV-2 have different infection modes with that of earlier
136 known coronaviruses. Repurposing and developing targets (inhibitors and peptide) to block

137 the Furin protease found to be another potential therapeutic option and also warrant clinical
138 investigation. This study also first to show structurally that how the human Furin interacts
139 with the coronavirus spike glycoprotein, which underlines its mechanism of action. This
140 structural and molecular dynamics study has great implications to further develop Furin
141 protease inhibitors to block the protease activity of Furin and also abet in the development of
142 bonafide antibodies targeting the S1/S2 Furin cleavage site of spike glycoprotein and
143 accenture the development of future therapeutics.

144

145 **Figures**

146 **Figure 1:** (A) Overall structure showing SARS-CoV-2 spike glycoprotein homo-trimer
147 (substrate un-bound or closed conformation) in complex with human Furin protease. The
148 three monomers of SARS-CoV-2 spike glycoprotein homo-trimer are coloured in green
149 (Chain A), pink (Chain B) and orange (Chain C) and the Furin protease is coloured in blue.
150 The spike protein cleavage site is indicated by arrow and S1/S2 domain are labelled
151 accordingly. (B) Enlarged view showing the single Furin interacting with its target cleavage
152 site (loop) of SARS-CoV-2 spike glycoprotein. Colour coding and labelling is same as
153 above. (C) Top view of Figure 1A, showing the SARS-CoV-2 spike glycoprotein homo-
154 trimer bound to three Furin proteases at the adjoining conformation at the S1/S2 region.

155

156 **Figure 2: Surface and cartoon model showing the detailed amino acid interaction**
157 **between the Furin protease and SARS-CoV-2 spike glycoprotein** (A) Front and
158 orthogonal view of Furin (blue, surface) interacting with the SARS-CoV-2 spike glycoprotein
159 (green, sticks). For clear visualization one the Furin binding loop is shown. The canyon-like
160 crevice is distinguishable in Furin and the side chin residues of spike protein are labelled
161 accordingly. (B) Front and orthogonal view of Furin (blue, sticks and cartoon) interacting
162 with target S1/S2 cleavage site of SARS-CoV-2 spike glycoprotein (green, surface). The key
163 residues of Furin involved in the interaction with S1/S2 cleavage site are shown in sticks and
164 labelled accordingly.

165

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171 **References**

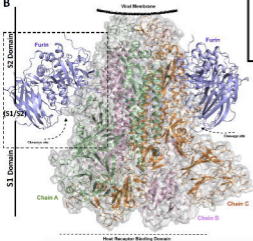
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Figure 1

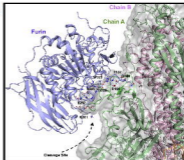
A

SARS-CoV-2 :	ASYQTQTN	SPRRAR	SVARSVASQS
SARS-CoV-1 :	ASYHTV	-----	SLLRSTSQKS
Bat-TG13 :	ASYQTQTN	-----	SRSRVASQES
MERS-CoV :	PSTLT	---FR---	SV-RSVPGEM
PangoL-CoV :	ASYQTQTN	-----	S-RSVSSKA

B



C



D

