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A novel auto-cleavage assay for studying mutational effects on the active site of severe acute respiratory syndrome coronavirus 3C-like protease

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Abstract

The 3C-like protease (3CL\textsuperscript{pro}) of severe acute respiratory syndrome (SARS) has been proposed as an attractive target for drug design. His\textsuperscript{41} and Cys\textsuperscript{145} were essential for the active site as the principal catalytic residues. In this study, we mutated the two sites, expressed four resulting mutants in \textit{Escherichia coli} and characterized. All mutants showed undetectable activity in \textit{trans}-cleavage assay. In addition, we introduced a 31-mer peptide containing an auto-cleavage site to the N-terminal of the proteases and found the peptide could be cleaved efficiently by 3CL\textsubscript{sc} itself, but, among the four mutants, only the mutant Cys\textsuperscript{145} \rightarrow Ser showed residual activity as detected by the auto-cleavage assay. The data supported the proposition unequivocally that SARS-CoV 3CL\textsuperscript{pro} was a member of serine proteases involving His\textsuperscript{41} and Cys\textsuperscript{145} residues at the active site. The auto-cleavage assay also provided a sensitive and reliable compensation to the traditional \textit{trans}-cleavage assay.

Keywords: SARS; 3CL protease; Active site; Auto-cleavage assay; N\textsubscript{31}-tag

Severe acute respiratory syndrome (SARS) broke out in southern China in 2003 and spread rapidly. The pathogen of SARS was identified as a novel coronavirus (CoV), which belongs to \textit{Coronaviridae} family [1,2]. Coronavirus is a kind of positive-stranded RNA virus characterized with an exceptionally large genome size (up to 31 kb) known to date. SARS coronavirus (SARS-CoV) replicase gene encodes two overlapping large proteins, polyprotein 1a (pp1a, \textasciitilde450 kDa) and polyprotein 1ab (pp1ab, \textasciitilde750 kDa), which mediate the functions needed for transcription and replication of the virus. pp1a and pp1ab are cleaved extensively by the specific proteases to release functional proteins and peptides. One of the proteases encoded by the virus cleaves at least 11 conservative sites on pp1ab and plays a main role in proteolytic processing [3]. It is named main protease (M\textsuperscript{pro}) and also called 3C-like protease (3CL\textsuperscript{pro}). Ascribing to its pivotal role in virus life circle, SARS-CoV 3CL\textsuperscript{pro} has been suggested as a promising target for antiviral drug design [3].

The structure of the 33.8 kDa protease of SARS-CoV has three domains. And the active site is predicted to involve a catalytic dyad of His and Cys, which is similar to those of main proteases in other coronaviruses. There is a controversy about the coronavirus main proteases whether they all belong to the class of serine proteases because they have an “additional” domain at C-terminal. In previous studies, replacements of Cys with Ser in some of CoV main proteases produced inactive
enzymes as detected by trans-cleavage assay [4,5]. There were a few reports that Cys-to-Ser mutants showed residual activities either in a cis-cleavage assay [6] or in a trans-cleavage assay with an extremely high enzyme concentration [7]. Because no enzyme was detected simultaneously in both trans- and cis-cleavage assays, it is difficult to draw an unequivocal answer to the discrepancy about the role of Ser.

In the present study, we mutated the two residues at active site and detected the activities of mutants in both trans- and a newly developed cis-cleavage assays. The results showed that Cys[142]→Ser mutant had a residual activity only in the cis-cleavage assay. It suggested that our assay exploiting the auto-processing capability of 3CLpro has advantages over the traditional peptide-based activity detection system, and can be employed in the substrate specificity study or other relevant researches.

**Materials and methods**

**Construction of pET28a-3CLsm and pET28a-3CLsc.** The gene of SARS 3C-like protease was a gift from Dr. Li and was amplified by PCR using primers 3CLsm and 3CLr (see Table 1 for the sequences of primers). The PCR product was digested with NcoI and XhoI, and inserted into NcoI/XhoI cut plasmid pET-28a. The plasmid, pET28a-3CLsm, encodes a 34.7 kDa (3CLsm) protein flanked at a C-terminal His15-tag and with the first amino acid Ser replaced by Met. The PCR product was eluted with 20 ml buffer C (20 mM Tris–HCl, pH 8.0, 200 mM NaCl, and 2 mM of 2-mercaptoethanol) containing 200 mM imidazole. The recovered protein was concentrated and loaded on a gel filtration column (Sephacryl S-200HR), which was equilibrated with 250 ml buffer C. The eluted enzyme was concentrated and stored at −20°C in buffer C containing 50% glycerol. All mutants were performed in a similar way.

**Peptide synthesis and trans-cleavage assay.** A 16-mer peptide, P439 (TSAVLP...SGFRK), was performed in a similar way. The cleavage assay was carried out in 40 μl buffer D (20 mM Tris–HCl, pH 7.35, containing 400 μM P439, 200 mM NaCl, 1 mM DTT, and 1 mM EDTA) and the reaction was initiated by adding 2 μl enzyme. The reaction mixtures were incubated at 20°C for 0–16 h and then 40 μl of 2% trifluoroacetic acid was added to stop the reaction. The products were characterized by reverse-phase HPLC using a 5–65% linear gradient of acetonitrile/water containing 0.1% trifluoroacetic acid. Identity and homogeneity were confirmed by mass spectrometry (matrix-assisted laser desorption/ionization time-of-flight, MALDI-TOF). An 11-mer peptide, P440 (TSAVLPG...SGFRK), was performed in a similar way.

**Site-directed mutagenesis.** Site-directed mutagenesis was performed by a recombination PCR method. The nucleotide sequences of primers are given in Table 1. Mutants were also constructed into pET-28a plasmid and expressed in BL21 (DE3) cells. The homogenities of the purified mutant proteins were characterized by SDS–PAGE.

**Expression and purification.** pET28a-3CLsm and pET28a-3CLsc were transformed, respectively, into Escherichia coli BL21 (DE3) cells. The transformed cells were grown in 1 liter LB medium containing kanamycin (50 μg/ml) at 22°C until A600 reached to 0.6–0.8 and then induced with 10 μM isopropyl-1-thio-β-D-galactopyranoside for 6 h. The cells were harvested by centrifugation (5000g for 10 min) and suspended into 40 ml buffer A (20 mM Tris–HCl, pH 8.0, 200 mM NaCl, and 2 mM of 2-mercaptoethanol). Lysis of the cells was achieved by ultrasonic and the suspension was centrifuged at 25,000g for 20 min. Supernatant was applied to a buffer A equilibrated cobalt–nitrilotriacetic acid column (4 ml beads). The column was washed with 100 ml buffer A and then with buffer B (20 mM Tris–HCl, pH 8.0, 200 mM NaCl, and 10 mM imidazole) until A280 was less than 0.02. The target protein was eluted with 20 ml buffer C (20 mM Tris–HCl, pH 8.0, 200 mM NaCl, and 2 mM of 2-mercaptoethanol) containing 200 mM imidazole. The recovered protein was concentrated and loaded on a gel filtration column (Sephacryl S-200HR), which was equilibrated with 250 ml buffer C. The eluted enzyme was concentrated and stored at −20°C in buffer C containing 50% glycerol. All mutants were performed in a similar way.

**Table 1** Primers used for the amplification or mutagenesis of SARS-CoV 3CLpro

| Primer | Oligonucleotide sequence (5′ → 3′) | Polarity | Remark |
|--------|----------------------------------|----------|--------|
| 3CLsc  | ATGGCTAGCTCAATCATTCTCTGTTCTG     | Forward  | Introduce N11-tag |
| 3CLsm  | TATACCATGGGGTTTATTAGAAAATGGCATTC | Forward  | Amplification |
| 3CLR   | GGTGCTAGTTGGAAGTACACCCAGGATTGTC | Reverse  | Introduce His-tag |
| PH1    | TACTGTCATAGGGCTGTCATTTGCACAGC    | Forward  | His41 to Ala |
| PH2    | AATGCAGGGCTTGGCATTATCTGTCAGT    | Reverse  | His41 to Trp |
| PH3    | TACTGTCTAGGGCAGTACAGTAGGCAAG    | Reverse  | Cys415 to Ala |
| PH4    | AATGGACGCTAGGTATAGAAGG            | Reverse  | Cys415 to Ser |
| PC1    | AATGGATCAGCTGGTTAAGGA            | Forward  | Ala |
| PC2    | ACTACCGGCCAGCAATGGGAA            | Reverse  | Ala |
| PC3    | ACTACCGGCCAGCAATGGGAA            | Reverse  | Ser |

The oligonucleotide sequences indicating mutant codons are underlined.
Results and discussion

Expression, purification, and proteolytic activity of SARS-CoV 3CL\textsuperscript{pro}

3CL\textsubscript{sm} was successfully over-expressed in \textit{E. coli}. Most of the target protein was found in the soluble fraction of the cell lysate. About 20 mg of 3CL\textsubscript{sm} protein was recovered from 1 liter LB media. When 3CL\textsubscript{sc} was expressed in \textit{E. coli}, the product had a similar apparent molecular mass to that of 3CL\textsubscript{sm} (see Fig. 1). It indicated that an auto-cleavage had occurred during 3CL\textsubscript{sc} expression.

The activity of the recombinant 3CL\textsubscript{sm} was analyzed in peptide-based trans-cleavage assay in which 3CL\textsubscript{sm} (2 \(\mu\)g) was incubated with 400 \(\mu\)M peptide P439 in 40 \(\mu\)l buffer D. Analysis of the reaction products by reverse-phase HPLC and mass spectrum revealed that P439 could be hydrolyzed. As shown in Fig. 2A, more than half of the substrate was digested in 20 min.

Mutation analysis of the catalytic site of SARS-CoV 3CL\textsuperscript{pro}

It has been reported that His\textsuperscript{41} and Cys\textsuperscript{145} might play a key role in the catalytic process for coronavirus main proteases [3]. We mutated these two residues of the enzyme and obtained four mutants, H\textsuperscript{41}A, H\textsuperscript{41}W, C\textsuperscript{145}A, and C\textsuperscript{145}S. The mutants were characterized by SDS-PAGE and the proteolytic activities were measured in trans-cleavage assay. But, different from 3CL\textsubscript{sm}, the activities of H\textsuperscript{41}A, H\textsuperscript{41}W, C\textsuperscript{145}A, and C\textsuperscript{145}S were all under the detection limitation in trans-cleavage assay, even when the incubation time was prolonged to 16 h. As shown in Fig. 2B, the activity of 3CL\textsuperscript{pro} has a great dependence on enzyme concentration because the active form of enzyme was suggested to be a dimer. We had increased the concentration of the mutants up to 15 \(\mu\)M, but still no activity was detected. Even higher enzyme concentration could not be used because it will cause aggregation and precipitation at room temperature within a few hours. The great difference in trans-cleavage assay between 3CL\textsubscript{sm} and the mutant enzymes strongly supports a crucial catalytic function of His\textsuperscript{41} and Cys\textsuperscript{145}, and is consistent with the published data of other 3CL/3C proteases [8].

Tibbles et al. [6] reported that a mutant with the substitution of the active site Cys with Ser in avian infectious bronchitis virus 3CL\textsuperscript{pro} produced an enzyme with a residual activity in cis-cleavage assay. In contrast with their finding, although all 3CL proteases have conservative catalytic site characteristics, no activity could be detected for the corresponding Cys-to-Ser mutants of the mouse hepatitis virus and human coronavirus strain 229E 3CL\textsuperscript{pro} in trans-cleavage assay [4,5]. One
explanation for this discrepancy is that cis-cleavage assay has high sensitivity over the trans-cleavage one [8]. In our study, Cys-to-Ser substitution also produced an enzyme with undetectable activity in trans-cleavage assay. So we decided to test the cleavage activity of this mutant in the novel cis-cleavage assay.

Auto-cleavage assay of SARS-CoV 3CLpro mutants

As mentioned above, the 31-mer peptide (N31-tag) introduced to the N-terminal of 3CLsc could be cleaved efficiently, so it might be applied in cis-cleavage assay. Therefore, the N31-tag was introduced to four mutants. After expression, three of the mutants, H41A, H41W, and C145A, yielded a higher apparent molecular mass than that of 3CLsc (see Fig. 3). It suggested that the three mutants did not show enzyme activity. The results could serve as a negative control; it excluded the possibility that proteolytic process was caused by the expression system. The cleavage should be performed by SARS-CoV 3CLpro itself. Interestingly, for C145S mutant, there were two bands visualized in SDS–PAGE (see Fig. 3, lanes 4 and 6). The apparent molecular mass showed that the upper band retained the N31-tag and the lower one did not. It suggested that substitution Cys145 with Ser in SARS-CoV 3CLpro produced an enzyme with a very low activity, despite the fact that the mutant did not show activity in trans-cleavage assay.

To verify the fact, we purified C145S (with the N31-tag) and incubated 2 mg of the proteins in 1 ml buffer D at 20 °C for 0–36 h. The reaction mixture was analyzed by SDS–PAGE on 12% polyacrylamide gel. As shown in Fig. 4, the band with N31-tag disappeared gradually, but the reaction was not completed even after 36 h incubation. Under the same conditions, 6 μg purified C145S protein was incubated with 400 μM peptide P439 in 40 μl buffer D at 20 °C for trans-cleavage peptide assay, still no protease activity could be detected.

The cleavage sites of 3CLpro commonly contain a dipeptide (LQ) sequence, and the amino acid Gln is reported as an "absolutely" conservative residue [9]. Fan et al. [10] reported a peptide (TSAVLQ→SGFRK) could be cleaved by SARS-CoV 3CL protease. We synthesized the peptide P440 (TSAVLP→SGFRK) in which the Gln was replaced by Pro and performed trans-cleavage assay at 10 μM 3CLsm. No enzyme activity was detectable within 24 h. We also introduced LP dipeptide to the N31-tag at N-terminal and tested auto-cleavage assay. It had been found that, even though at a slow rate, the corresponding cleavage site could be processed (data not shown). It implied that the novel auto-cleavage assay is more sensitive.

In the study of Ziebuhr et al. [5], the final concentration of enzyme was 1 μM which is the same in the study of Seybert et al. [4]. Comparing with our data, those two 3CL proteases (C145S) probably also have residual activities in a cis-cleavage assay. Huang et al. [7] reported the very low cleavage activity of Cys-to-Ser mutant of 3CLpro in a peptide-based assay by using a synthetic p-nitroanilide compound (colorimetric substrate) and three synthetic peptides (S10, S06, and S09), in which the activity for substrate S09 was too low to be determined. It should be noted that the enzyme concentration used in their assay was extremely high (76.9 μM; about 2.6 mg/ml). Under such a high concentration of enzyme, unexpected non-specific side reactions could not be completely excluded. In addition, in case of the synthetic colorimetric substrate, it might not involve the specificities contributed by downstream subsites. And Shi et al. [11] reported the amino acids at C-terminal to the cleavage

![Fig. 3. Expression of SARS-CoV 3CLpro mutants containing N31-tag in E. coli BL21 (DE3). Total cell lysates of IPTG-induced E. coli samples were analyzed by SDS–PAGE on 12% polyacrylamide gel and stained with Coomassie brilliant blue; 1, lysate of mutant H41A; 2, lysate of mutant H41W; 3, lysate of mutant C145A; 4, lysate of mutant C145S; 5, purified 3CLpro (3CLsc) as a control; 6, purified 3CLpro (C145S); 7, total cell lysate of E. coli (3CLsc) without being induced; and M, protein molecular mass markers (kDa).](image)

![Fig. 4. Time course of SARS-CoV 3CLpro C145S in auto-cleavage assay. The purified 3CLpro C145S was incubated in buffer D for 0–36 h at 20 °C as described in Materials and methods, the reaction products were analyzed by SDS–PAGE on 12% polyacrylamide gel and stained with Coomassie brilliant blue. 1, reacted for 0 h; 2, reacted for 9 h; 3, reacted for 18 h; 4, reacted for 36 h; 5, 3CL-sc protease; and M, protein molecular mass markers (kDa).](image)
site also have extensive interactions with the 3CL protease. For these two reasons, the explicit conclusion could not be drawn unequivocally.

The novel assay is simple, sensitive, and reliable, and might be extended to other relevant protease studies. In addition, the results also support that the SARS-CoV 3CL\textsuperscript{pro} belongs to serine protease of the chymotrypsin family and clarified the discrepancy of previous researches.

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