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Highly Conserved Configuration of Catalytic Amino Acid Residues among Calicivirus-Encoded Proteases▽

Tomoichiro Oka,[1]* Mami Yamamoto,[1] Masaru Yokoyama,[2] Satoko Ogawa,[1] Grant S. Hansman,[1] Kazuhiko Katayama,[1] Kana Miyashita,[1] Hirotaka Takagi,[3] Yukinobu Tohya,[4] Hironori Sato,[2] and Naokazu Takeda[1]

Department of Virology II, National Institute of Infectious Diseases, Gakuen 4-7-1, Musashi-murayama, Tokyo 208-0011, Japan[1]; Center for Pathogen Genomics, National Institute of Infectious Diseases, Gakuen 4-7-1, Musashi-murayama, Tokyo 208-0011, Japan[2]; Division of Biosafety Control and Research, National Institute of Infectious Diseases, Toyama 1-23-1, Shinjuku-ku, Tokyo 162-8640, Japan[3]; and Department of Veterinary Microbiology, Graduate School of Agricultural and Life Sciences, The University of Tokyo, 1-1-1 Yayoi, Bunkyo-ku, Tokyo 113-8657, Japan[4]

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A common feature of caliciviruses is the proteolytic processing of the viral polyprotein catalyzed by the viral 3C-like protease encoded in open reading frame 1 (ORF1). Here we report the identification and structural characterization of the protease domains and amino acid residues in sapovirus (SaV) and feline calicivirus (FCV). The in vitro expression and processing of a panel of truncated ORF1 polyproteins and corresponding mutant forms showed that the functional protease domain is 146 amino acids (aa) in SaV and 154 aa in FCV. Site-directed mutagenesis of the protease domains identified four amino acid residues essential to protease activities: H^{31}, E^{52}, C^{116}, and H^{131} in SaV and H^{39}, E^{60}, C^{122}, and H^{137} in FCV. A computer-assisted structural analysis showed that despite high levels of diversity in the primary structures of the protease domains in the family *Caliciviridae*, the configurations of the H, E, C, and H residues are highly conserved, with these residues positioned closely along the inner surface of the potential binding cleft for the substrate. These results strongly suggest that the H, E, C, and H residues are involved in the formation of a conserved catalytic surface of the SaV and FCV 3C-like proteases.

The family *Caliciviridae* is composed of four genera, *Sapovirus*, *Lagovirus*, *Vesivirus*, and *Norovirus*, which include the species *Sapporo virus* (SaV), *Rabbit hemorrhagic disease virus* (RHDV), *Feline calicivirus* (FCV), and *Norwalk virus* (NoV), respectively (24). Caliciviruses infect a broad range of hosts, including humans and animals, and cause a variety of diseases and disorders, such as gastroenteritis, vesicular lesions, respiratory infections, reproductive failure, and hemorrhagic disease (10).

Calicivirus is a nonenveloped virus, and its genome is a linear, polyadenylated, positive-sense single-stranded RNA of about 7.3 to 8.3 kb with either two or three open reading frames (ORFs) (9). Calicivirus ORF1 encodes a polyprotein that contains amino acid motifs including 2C-like nucleoside triphosphatase (NTPase), VPg, 3C-like protease, and 3D-like RNA-dependent RNA polymerase (polymerase) (11, 25). In *Sapovirus* and *Lagovirus*, the structural protein VP1 is encoded in ORF1, whereas this protein is encoded in a separate ORF (ORF2) in *Vesivirus* and *Norovirus*. Cotranslational proteolytic processing of the ORF1 polyprotein is a common feature in the caliciviruses and is performed with the 3C-like protease encoded in ORF1 (11). The calicivirus 3C-like protease cleaves after the glutamic acid (E) or glutamine (Q) residue of the specific site in the polyprotein (2, 4, 14, 20, 21, 30, 32, 33, 35, 39). The protease itself is released by an autocatalytic cleavage in NoV (1, 2, 8, 15, 21, 32, 39) and RHDV (19, 25, 44), whereas cleavage between the protease and polymerase does not occur in FCV (7, 12, 40, 43) or SaV (7, 28–30).

The critical role of Cys in the calicivirus 3C-like protease motif GDCG in the cleavage activity in NoV and RHDV has been determined previously (4, 15, 20, 32, 34). In addition, the active-site residues of the 3C-like proteases of the NoV Chiba virus strain and the RHDV FRG strain have been identified by site-directed mutagenesis (5, 14, 36, 46). Recently, the X-ray crystal structures of the two 3C-like proteases of NoV (Chiba and Norwalk strains) were determined (27, 46). In contrast, although site-directed mutagenesis of the 3C-like proteases of the SaV Mc10 and FCV Urbana strains showed that C in the GDCG motif is crucial for the proteolytic processing activity (28–30), the remaining amino acids that are important for the activity have not been identified.

The aim of this study was to identify and structurally characterize the functional protease domains and the amino acid residues critical to the activities in SaV and FCV. For this purpose, an in vitro coupled transcription-translation analysis was performed with full-length or C-terminally truncated forms of the ORF1 polyprotein with or without amino acid mutations in the protease domain. In addition, three-dimensional (3-D) structural models of the 3C-like protease domains of the SaV Mc10, FCV F4, and RHDV FRG strains were constructed and compared with the X-ray crystal structure of the 3C-like protease of the NoV Chiba strain (27).

* Corresponding author. Mailing address: Department of Virology II, National Institute of Infectious Diseases, Gakuen 4-7-1, Musashi-murayama, Tokyo 208-0011, Japan. Phone: 81-42-561-0771. Fax: 81-42-561-4729. E-mail: oka-t@nih.go.jp.

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MATERIALS AND METHODS

Virus strains. The SaV Mc10 strain was isolated from a stool specimen from an infant hospitalized with acute gastroenteritis in Chiang Mai, Thailand (13).

The FCV F4 strain was isolated from a cat with respiratory symptoms in Japan (22).

Preparation of FCV F4. Crandell-Rees feline kidney cells (JCRB9035; Health Science Research Resources Bank, Japan) were grown in a 150-cm^2 flask containing Eagle's minimum essential medium (Sigma-Aldrich, St. Louis, MO) with 5% calf serum (JRH Bioscience Corp., Tokyo, Japan) and virus production serum-free medium with L-glutamine (Invitrogen, Carlsbad, CA). Approximately 10^4 PFU of the virus was added to a monolayer of Crandell-Rees feline kidney cells containing 10 ml of culture medium. The cells were incubated for 3 days at 37°C and were harvested when the cytopathic effect had reached 90%. After three cycles of freezing and thawing, the cell debris were removed by centrifugation and the supernatant was stored at −30°C until use.

Full-length cDNA clones. A plasmid designated pUC19/SaV Mc10 full-length containing a full-length SaV Mc10 genome with the T7 promoter, as well as a plasmid designated as pUC19/SaV Mc10 full-C1171A/ORF1 encoding a ^{1169}GDCG^{1172}-to-GDAG mutation in the protease, were expressed as previously described (29).

The FCV F4 genomic RNA was purified from the culture medium by the QIAamp viral RNA mini kit (QIAGEN, Hilden, Germany). FCV F4 cDNA was synthesized as previously described (16). The 5′ fragment corresponding to nucleotides (nt) 1 to 3785 was amplified with the sense primer 5′-GTAAAAG AAATTTGAGACAATGTCTC-3′ and the antisense primer 5′-GTTTACAAA CTAATCCCTTGTAGC-3′. The middle fragment corresponding to nt 2990 to 6971 was amplified with the sense primer 5′-AATGCCAACAGAAAGCTTG A-3′ and the antisense primer 5′-AGCACGCTAATGCGCACTAC-3′. The 3′ fragment corresponding to nt 6952 to 7681 was amplified with the sense primer 5′-GTAGTGCGCATTAGCGTGC-3′ and the antisense primer 5′-CCCTGGG GTTAGACGCAAATGC-3′. These three fragments were cloned into the pCR-BluntII-Topo vector (Invitrogen), and the resulting constructs were designated FCV F4 5′/Topo, FCV F4 middle/Topo, and FCV F4 3′/Topo, respectively. Several amplification and cloning steps were performed to yield a full-length construct with a T7 RNA polymerase promoter at the 5′ end and both a hepatitis D virus (HDV) ribozyme and a T7 terminator at the 3′ end, as described previously (15). To add the HDV ribozyme and the T7 terminator at the 3′ end of the FCV F4 genome, the region from nt 6952 to 7681 was reamplified from the clone 3′/Topo with a sense primer (5′-GTAGTGCGCATTAGCGTGC-3′) and an antisense primer (5′-GAGGTGGAGATGCCATGCCGACCCT$_{30}$CCCTGG GGTTAGACGCAAATGC-3′). HDV ribozyme and T7 terminator sequences were amplified from the pT7HCV09Luc plasmid (45) with a sense primer (5′-GGGTCGGCATGGCATCTCCACCTC-3′) and an antisense primer (5′-GAA CTAGTGGATCCGAGCTCAGATCTCCTTTCAGCAAAAAACCCCTCAA G-3′) that included a BglII site (underlined) and a SacI site (double underlined). These DNA fragments were joined by a primerless PCR as previously described (15), and the amplified fragment corresponding to nt 6952 to 7681 was purified from the gel by using the QIAGel extraction kit (QIAGEN). This DNA fragment was designated FCV F4 6952-7681 polyA-Rz-T7 term. Following these experiments, the FCV F4 region from nt 2990 to 6971 was reamplified with the sense primer 5′-AATGCCAACAGAAAGCTTGA-3′ and the antisense primer 5′-A GCACGCTAATGCGCACTAC-3′. The amplified DNA fragment was joined with 6952-7681 polyA-Rz-T7 term in a primerless PCR. The joined amplified fragment was purified and cloned into the pCR-BluntII-Topo vector, and the construct was designated FCV F4 2990-7681 polyA-Rz-T7 term/Topo. This plasmid was digested with KpnI and SacI (New England Biolabs, Beverly, MA), and the insert was cloned into a pUC19 vector (Toyobo, Osaka, Japan) which was previously digested with KpnI and SacI. The resultant plasmid was designated FCV F4 middle + 3′ polyA-Rz-T7 term/pUC19. Finally, the FCV F4 5′ region corresponding to nt 1 to 3780 was reamplified from FCV F4 5′/Topo with a sense primer (5′-CAGGGGCCCGTCGACCTGG**TAATACGACTCACTATA**GTAAA AGAAATTTGAGACAATGTC-3′) that included a SalI site (underlined) and a T7 RNA polymerase promoter sequence (bold) and an antisense primer (5′-T TGGGCCATGCAGGTGAGCG-3′). The amplified DNA was purified and digested with SalI and KpnI (New England Biolabs) and cloned into SalI- and KpnI-digested middle + 3′ polyA-Rz-T7 term/pUC19. The resultant plasmid was designated FCV F4 T7-GG full-length-Rz-T7 term/pUC19 ver2 (pUC19/FCV F4 full-length). Sequence analysis confirmed that the cloned genome corresponded to the consensus sequence of FCV F4 (GenBank accession number D31836), with the exception of a silent mutation (T to C) at the nucleotide position 4075.

Site-directed mutagenesis. Site-directed mutagenesis was performed using the GeneTailor site-directed mutagenesis system (Invitrogen), with pUC19/SaV Mc10 full-length (29) and pUC19/FCV F4 full-length as the templates. The site-directed mutagenesis primers are listed in Table 1. The resulting nine SaV Mc10 full-length mutant cDNA clones were designated as follows: pUC19/SaV Mc10 full-H1069A/ORF1 (where the H at amino acid [aa] residue 1069 in the ORF1 product is changed to A), pUC19/SaV Mc10 full-H1075A/ORF1, pUC19/SaV Mc10 full-H1086A/ORF1, pUC19/SaV Mc10 full-E1107A/ORF1, pUC19/SaV Mc10 full-H1120A/ORF1, pUC19/SaV Mc10 full-H1136A/ORF1, pUC19/SaV Mc10 full-E1143A/ORF1, pUC19/SaV Mc10 full-E1147A/ORF1, and pUC19/SaV Mc10 full-H1186A/ORF1. Similarly, 12 FCV F4 full-length mutant cDNA clones were constructed: pUC19/FCV F4 full-H1079A/ORF1, pUC19/FCV F4 full-H1093A/ORF1, pUC19/FCV F4 full-H1099A/ORF1, pUC19/FCV F4 full-H1102A/ORF1, pUC19/FCV F4 full-H1110A/ORF1, pUC19/FCV F4 full-E1121A/ORF1, pUC19/FCV F4 full-D1125A/ORF1, pUC19/FCV F4 full-E1131A/ORF1, pUC19/FCV F4 full-D1155A/ORF1, pUC19/FCV F4 full-E1164A/ORF1, pUC19/FCV F4 full-C1193A/ORF1, and pUC19/FCV F4 full-H1208A/ORF1. All of these full-length clones were verified by sequencing analysis to confirm that there were no additional mutations.

TABLE 1. Oligonucleotides used for the site-directed mutagenesis

Amino acid change[a]	Nucleotide sequence (5′–3′)[b]
SaV polyprotein	
H1069A	CACATCTGGGGGTGATgccATTGGGTATGGTTG
H1075A	CATTGGGTATGGTTGTgccATGGGTAATGGGGTG
H1086A	GTTGTCACAGTTACAgccGTGGCCTCTGCGTCTG
E1107A	CAGGAAGACCGAGGGTgcaACCACCTGGGTGAAC
H1120A	CTTGGTCACTTGCCCgccTACCAGATCGGTGATG
H1136A	CTACTACTCGGCGCGCCTAgccCCTGTCACCACGC
E1143A	GTCACCACGCTTGCGgcgGGGACGTATGAG
E1147A	GCGGAGGGGACGTATgcgACACCCAATATCACG
H1186A	CGTTTGGTCGGACTGgccGCAGCCACATCAAC
FCV polyprotein	
C1193A	ACTCACCCTGGAGATgccGGGTTGCCGTATATTGATGAT
H1079A	GGGCCTGGCACTAAATTTgccAAAAATGCCATTGGATCAG
H1093A	GATGTGTGTGGGGAGgccAAGGGTTACTGCGTCCAC
H1099A	CACAAGGGTTACTGCGTCgccATGGGTCATGGGGTCTATG
H1102A	GGTTACTGCGTCCACATGGGTgctGGGGTCTATGCCTCTG
H1110A	TATGCCTCTGTGGCAgccGTGGTGAAAGGTGATTCCTAT
E1121A	GATTCCTATTTCTTGGGTgccAGGATCTTTGATGTAAAAACC
D1125A	GGTGAAAGGATCTTTgccGTAAAAACCAATGGTGAATTCTG
E1131A	GTAAAAACCAATGGTgccTTCTGTTGTTTCCGAAGCACT
D1155A	GGGAAACCAACCCGCgccCCATGGGGGTCGCCAGTTG
E1164A	TGGGGGTCGCCAGTTGCAACAgcgTGGAAACCAAAGGCCTATAC
H1208A	AGGGTTACCGGCTTAgccACTGGATCTGGTGGACCCAAA

[a] Amino acids are shown in the one-letter code. Letters before the numbers indicate the original amino acid residues, and letters after the numbers indicate the mutant amino acid residues.

[b] Only the positive-sense oligonucleotide sequences are shown. The codons corresponding to the changed amino acids are indicated as lowercase letters.

In vitro coupled transcription-translation assay. For an in vitro coupled transcription-translation, linear DNA fragments containing the T7 promoter were generated by PCR with 100 ng of pUC19/SaV Mc10 full-length (29) and nine full-length mutant cDNA clones. DNA fragments corresponding to the entire SaV Mc10 ORF1-encoded region, aa 1 to 2278, were generated with the forward primer SaV Mc10-1F and the antisense primer SaV Mc10-2278R (Table 2). The C-terminally truncated SaV Mc10 ORF1-encoded mutant forms corresponding to the regions from aa 1 to 1246, 1 to 1240, 1 to 1234, 1 to 1229, 1 to 1223, 1 to 1218, 1 to 1212, 1 to 1206, 1 to 1205, 1 to 1204, 1 to 1203, 1 to 1202, 1 to 1201, 1 to 1200, and 1 to 1194 were generated with the forward primer SaV Mc10-1F and the antisense primers SaV Mc10-1246R, SaV Mc10-1240R, SaV Mc10-1234R, SaV Mc10-1229R, SaV Mc10-1223R, SaV Mc10-1218R, SaV Mc10-1212R, SaV Mc10-1206R, SaV Mc10-1205R, SaV Mc10-1204R, SaV Mc10-1203R, SaV Mc10-1202R, SaV Mc10-1201R, SaV Mc10-1200R, and SaV Mc10-1194R (Table 2). Similarly, linear DNA fragments corresponding to the entire and the C-terminally truncated FCV F4 ORF1-encoded regions and containing the T7 promoter were generated by PCR with 100 ng of the pUC19/FCV F4 full-length clone or with 12 full-length mutant cDNA clones. DNA fragments corresponding to the entire FCV ORF1-encoded region, aa 1 to 1763, were generated with the forward primer FCV F4-1F and the antisense primer FCV F4-1763R (Table 2). The truncated FCV F4 ORF1 mutant forms corresponding to the regions from aa 1 to 1419, 1 to 1345, 1 to 1267, 1 to 1245, 1 to 1240, 1 to 1235, 1 to 1230, 1 to 1225, 1 to 1224, and 1 to 1223 were generated with the forward primer FCV F4-1F and the antisense primers FCV F4-1419R, FCV F4-1345R, FCV F4-1267R, FCV F4-1245R, FCV F4-1240R, FCV F4-1235R, FCV F4-1230R, FCV F4-1225R, FCV F4-1224R, and FCV F4-1223R (Table 2).

In vitro T7 polymerase coupled transcription-translation was performed by using the TNT T7 Quick for PCR DNA kit (Promega, Madison, WI) as previ-

TABLE 2. PCR primers to prepare templates for in vitro transcription-translation

Primer name[a]	Sequence (5′–3′)
SaV primers	
SaV Mc10-1F	GCTTCCAAGCCATTCTACCCAATAGAG
SaV Mc10-2278R	TTCTAAGAACCTAACGGCCCGG
SaV Mc10-1246R	TTCTCCTTCCACAGGGTTGGGC
SaV Mc10-1240R	GGGCCATGCAGGTGAGCGGTG
SaV Mc10-1234R	GTGGTAACGAGTCCCCGTGG
SaV Mc10-1229R	CGTGGGCATGCCGCCACAGTC
SaV Mc10-1223R	GTCGGGGCCTCGAACCACTGGTAG
SaV Mc10-1218R	CACTGGTAGACCCTTCCAAGC
SaV Mc10-1212R	AGCAAAAGCATTCTCCAC
SaV Mc10-1206R	CTTGGATGTTTTAGTCAC
SaV Mc10-1205R	GGATGTTTTAGTCACTCGCTGAGCAAGCTTGG
SaV Mc10-1204R	TGTTTTAGTCACTCGCTGAGCAAGCTTGG
SaV Mc10-1203R	TTTAGTCACTCGCTGAGCAAGCTTGG
SaV Mc10-1202R	AGTCACTCGCTGAGCAAGCTTGG
SaV Mc10-1201R	CACTCGCTGAGCAAGCTTGG
SaV Mc10-1200R	TCGCTGAGCAAGCTTGG
SaV Mc10-1194R	CTCACTGAATGACAATTTGGTG
FCV primers	
FCV F4-1F	TCTCAAACTCTGAGCTTCGTG
FCV F4-1763R	TCAAACTTCGAACACATCACAGTG
FCV F4-1419R	CTCTTGCACCTTCTCAATGGG
FCV F4-1345R	TTCAGAGGAGATGTTCATGGG
FCV F4-1267R	AGTGCCTTTTGGTATGATCC
FCV F4-1245R	AGGTTTTGTTTCATCATACTT
FCV F4-1240R	ATACTTTTGAGGGGTTACAGATTTG
FCV F4-1235R	TACAGATTTGTTTTTCATATCAATG
FCV F4-1230R	CATATCAATGTGGATGTAGGGTAC
FCV F4-1225R	GTAGGGTACCACCAATTTTGCGCTTGG
FCV F4-1224R	GGGTACCACCAATTTTGCGCTTGG
FCV F4-1223R	TACCACCAATTTTGCGCTTGG

[a] Primer names ending in F are those of forward primers that include the sequence 5′-GGATCCTAATACGACTCACTATAGGGAACAGCCACCA**TG**-3′ with the T7 promoter (underlined) and an additional start codon (bold) at the 5′ ends. Primer names ending in R are those of reverse primers (5′-T_{30}**TTA**-3′) that include poly(A) with a stop codon (bold) at the 5′ ends.

ously described, except that a 25-μl reaction volume and 3 h of incubation were used. The translation products were separated by sodium dodecyl sulfate-polyacrylamide gel electrophoresis (SDS-PAGE), and the radiolabeled proteins were detected as previously described (29, 30).

Nucleotide and amino acid sequence analyses. Nucleotide sequence analysis was performed with the BigDye Terminator (version 3.1) cycle sequencing ready reaction kit (Applied Biosystems, Tokyo, Japan) and an automated sequencer (genetic analyzer 3130; Applied Biosystems). Nucleotide sequences were assembled with the program Sequencher, version 4.2.2 (Gene Codes Corp., Ann Arbor, MI). Nucleotide and amino acid sequences were analyzed with GENETYX Mac software, version 12.2.6 (Genetyx Corp., Tokyo, Japan).

Molecular modeling of SaV, FCV, and RHDV 3C-like proteases. The crystal structure of the NoV 3C-like protease (Protein Data Bank [PDB] code, 1WQS) (27) at a resolution of 2.80 Å was used as the template for the molecular modeling of the SaV, FCV, and RHDV 3C-like proteases. To minimize misalignments of the target and template sequences, multiple-sequence alignments of 3C cysteine proteases, including rhinovirus 3C protease (PDB code, 1CQQ) (23), poliovirus 3C protease (PDB code, 1L1N) (26), and hepatitis A virus 3C protease (PDB code, 1QA7) (3), were used. The alignments were generated using MOE-Align in the Molecular Operating Environment (MOE) package (Chemical Computing Group, Inc., Montreal, Quebec, Canada). 3-D models of SaV Mc10, FCV F4, and RHDV FRG 3C-like proteases were constructed by the homology modeling technique using MOE-Homology in the MOE package as described previously (17, 18). The 3-D structures were thermodynamically optimized by energy minimization with the MOE package and an AMBER99 force field (31). A physically unacceptable local structure of the optimized 3-D model was further refined on the basis of Ramachandran plot evaluation using the MOE package. The quality of the models was assessed using the 3-D-structure evaluation program Verify3D (6, 47).

Strains for amino acid sequence alignments. The 16 SaV strains used for amino acid sequence alignments are as follows, with the nucleotide sequence accession numbers for the corresponding nucleotide regions given in parentheses: Mc114 (AY237422), Manchester (X86560), Dresden (AY694184), N21 (AY237423), Nongkhai50 (AY646853), Chantaburi74 (AY646854), Mc10 (AY237420), Bristol (AJ249939), C12 (AY603425), Mc2 (AY237419), SK15 (AY646855), PEC Cowden (AF182760), PEC LL14 (NC 000940), Ehime1107 (DQ058829), Sw278 (DQ125333), and NK24 (AY646856). The 13 FCV strains used for amino acid sequence alignments are as follows, with the nucleotide sequence accession numbers for the corresponding nucleotide regions given in parentheses: F4 (D31836), F65 (AF109465), 2024 (AF479590), Urbana (L40021), F9 (M86379), CFI/68 (U13992), DD/2006/GE (DQ424892), UTCV-NH1 (AY560113), UTCV-NH2 (AY560114), UTCV-NH3 (AY560115), UTCV-H1 (AY560116), UTCV-H2 (AY560117), and USDA (AY560118).

RESULTS AND DISCUSSION

Identification of the C terminus of the SaV Mc10 3C-like protease. The SaV protease-polymerase (Pro-Pol) is a stable product in both an in vitro translation system and an *Escherichia coli* expression system (28–30). Chang et al. also identified Pro-Pol as a stable product in porcine SaV-infected cells (7). Recently, we identified A^{1056} and E^{1722} as the N and C termini, respectively, of the SaV Mc10 Pro-Pol (Fig. 1A) (28, 30). To define the amino acid residues essential for protease activity, full-length forms and a series of 15 C-terminally truncated forms of the ORF1 polyprotein were expressed in an in vitro transcription-translation system (Fig. 1B; Table 1). The expression was carried out with both wild-type (Pro^{w}) and C1171A mutant (Pro^{mut}) forms of the protease, and the latter were used as a negative control for the proteolytic processing as previously described (29, 30).

At least seven proteins, p28, p32, p35 (NTPase), p46 (p32-VPg), p60 (VP1), p66 (p28-NTPase), and p120 (p32-VPg-Pro-Pol), were detected by direct SDS-PAGE analysis when the ORF1 Pro^{w} form corresponding to aa 1 to 2278 was expressed, and a major 250-kDa product (p250) corresponding to the ORF1 polyprotein appeared when the full-length ORF1 Pro^{mut} form was expressed (29). If the functional protease domain is eliminated, the cleavage patterns of the Pro^{w} forms should be significantly changed. We first analyzed two C-terminally truncated forms corresponding to aa 1 to 1246 and aa 1 to 1194. The proteolytic cleavage occurred in aa 1 to 1246 but not in aa 1 to 1194 (Fig. 1B). The translated product size of the Pro^{w} form of aa 1 to 1194 was identical to that of the Pro^{mut} form of aa 1 to 1194 (Fig. 1B), demonstrating that the C terminus of the functional protease domain is positioned downstream of aa 1194. Next, eight C-terminally truncated forms of the ORF1 polyprotein, aa 1 to 1240, 1 to 1234, 1 to 1229, 1 to 1223, 1 to 1218, 1 to 1212, 1 to 1206, and 1 to 1200, were expressed and analyzed. The proteolytic cleavage occurred efficiently in the Pro^{w} forms of the C-terminally truncated ORF1 polyproteins with aa 1 to 1240, 1 to 1234, 1 to 1229, 1 to 1223, 1 to 1218, 1 to 1212, and 1 to 1206 but not in the form with aa 1 to 1200 (Fig. 1B), demonstrating that the C terminus of the functional protease domain is positioned between aa 1200 and 1206. Finally, we expressed and analyzed five C-terminally truncated forms of the ORF1 polyprotein, aa 1 to 1205, 1 to 1204, 1 to 1203, 1 to 1202, and 1 to 1201. The cleavage occurred efficiently in the Pro^{w} forms of these C-terminally truncated ORF1 polyproteins (Fig. 1B). These results indicated that the C terminus of the functional protease

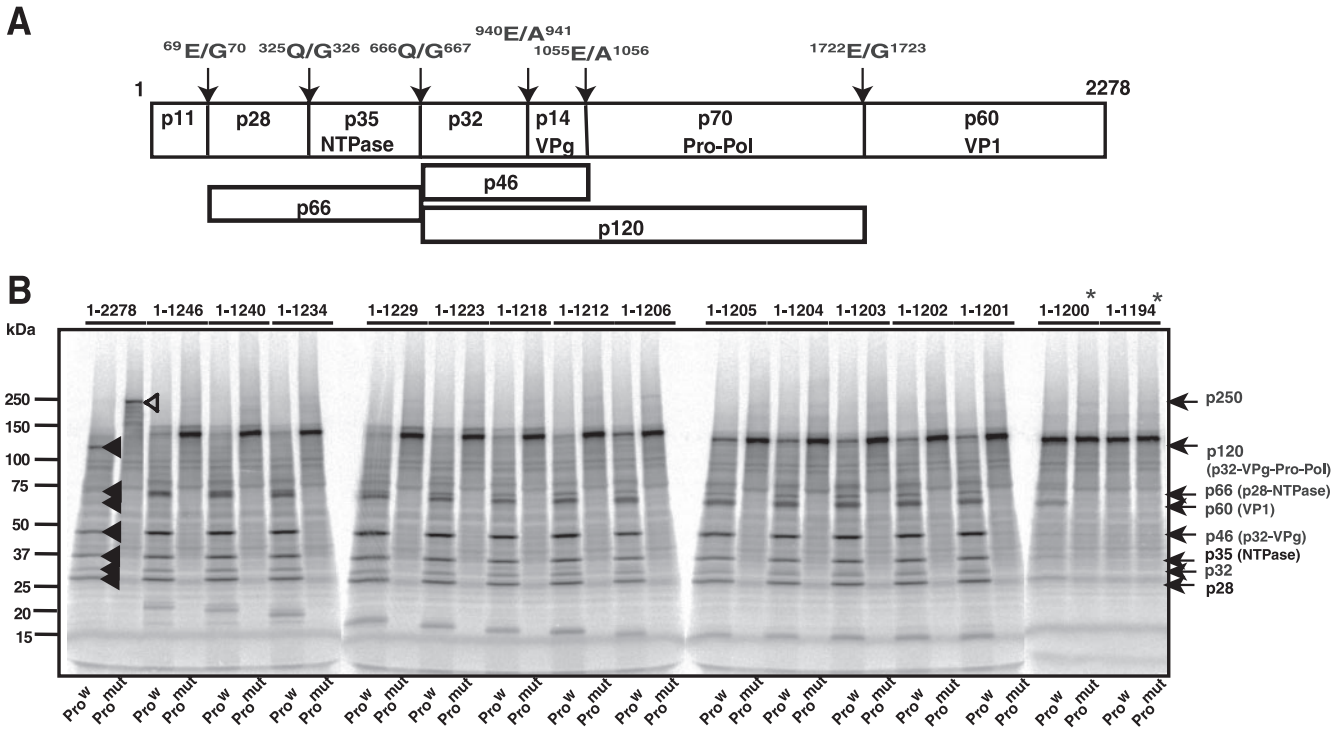

FIG. 1. Identification of the C terminus of the SaV Mc10 protease. (A) Proteolytic cleavage map of the SaV Mc10 ORF1 polyprotein and the processing intermediates (30). (B) SDS-PAGE of in vitro ^{35}S-labeled wild-type (Pro^{w}) and C1171A mutant (Pro^{mut}) forms of the entire ORF1 polyprotein (aa 1 to 2278) and 15 C-terminally truncated polyproteins corresponding to aa 1 to 1246, 1 to 1240, 1 to 1234, 1 to 1229, 1 to 1223, 1 to 1218, 1 to 1212, 1 to 1206, 1 to 1205, 1 to 1204, 1 to 1203, 1 to 1202, 1 to 1201, 1 to 1200, and 1 to 1194. The protein bands corresponding to either the Pro^{w} or Pro^{mut} form of the entire ORF1 polyprotein are indicated by filled and open arrowheads, respectively. The molecular sizes of viral proteins are shown on the right, and size markers are shown on the left. Asterisks indicate two C-terminally truncated forms, corresponding to aa 1 to 1200 and 1 to 1194, which show affected protease activity. Products of approximately 15 to 20 kDa would be the truncated Pro-Pol, released from the truncated ORF1 polyprotein. A 60-kDa product of the C-terminally truncated form corresponding to aa 1 to 1200 was identified as p32-VPg-truncated Pro-Pol.

of SaV Mc10 is V^{1201}, and it seems that the polymerase domain is not important for the protease activity. This amino acid residue was conserved in the 14 human and 2 porcine SaV strains listed in Materials and Methods (data not shown). The Mc10 3C-like protease domain comprises 146 aa (A^{1056} to V^{1201}), similar to the proteases of RHDV (143 aa) and NoV (181 aa) (5, 36).

Identification of the active-site residues of the SaV Mc10 3C-like protease. SaV Mc10 3C-like protease cleaves after the E or Q residue of the specific site in the ORF1 polyprotein (Fig. 1), and the C^{1171} in the GDCG motif was shown to be critical to the protease activity (28–30). Furthermore, the functional SaV Mc10 protease was found to be similar in size to those of RHDV and NoV. These results suggested that the catalytic amino acid residues of the SaV Mc10 protease would also be similar to those of other caliciviruses. In RHDV and NoV, the amino acid residues critical to protease activity have been identified as H^{27}, D^{44}, C^{104}, and H^{119} and H^{30}, E^{54}, C^{139}, and H^{157}, respectively, although it remains controversial whether or not E^{54} has a critical role in NoV protease activity (5, 14, 36, 46). The amino acid essential for the protease activity will definitely be conserved among all SaV strains (at least among human SaV strains) as it is in NoV and RHDV (36) (data not shown). Nine amino acid residues (H^{1069}, H^{1075}, H^{1086}, E^{1107}, H^{1120}, H^{1136}, E^{1143}, E^{1147}, and H^{1186}) within the

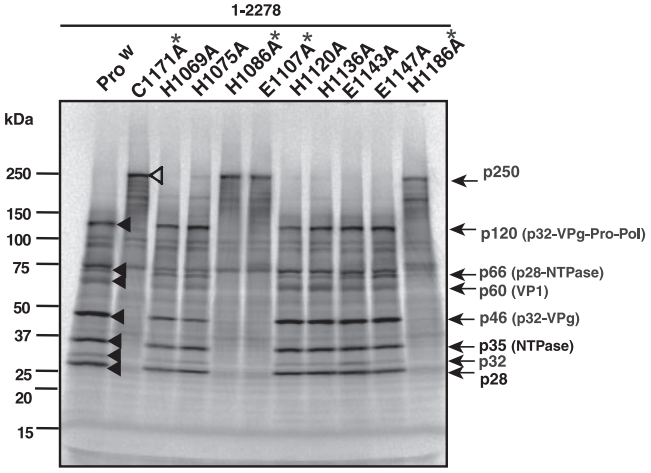

FIG. 2. Identification of the amino acid residues critical to SaV Mc10 protease activity. Shown are the results of SDS-PAGE of in vitro ^{35}S-labeled wild-type (Pro^{w}) and C1171A mutant forms of the entire ORF1 polyprotein (aa 1 to 2278) and nine other mutant forms, the H1069A, H1075A, H1086A, E1107A, H1120A, H1136A, E1143A, E1147A, and H1186A polyproteins. The protein bands corresponding to either the Pro^{w} or C1171A form of the entire ORF1 polyprotein are indicated by filled and open arrowheads, respectively. The molecular sizes of viral proteins are shown on the right, and size markers are shown on the left. Asterisks indicate four mutant forms, the C1171A, H1086A, E1107A, and H1186A polyproteins, which display affected protease activity.

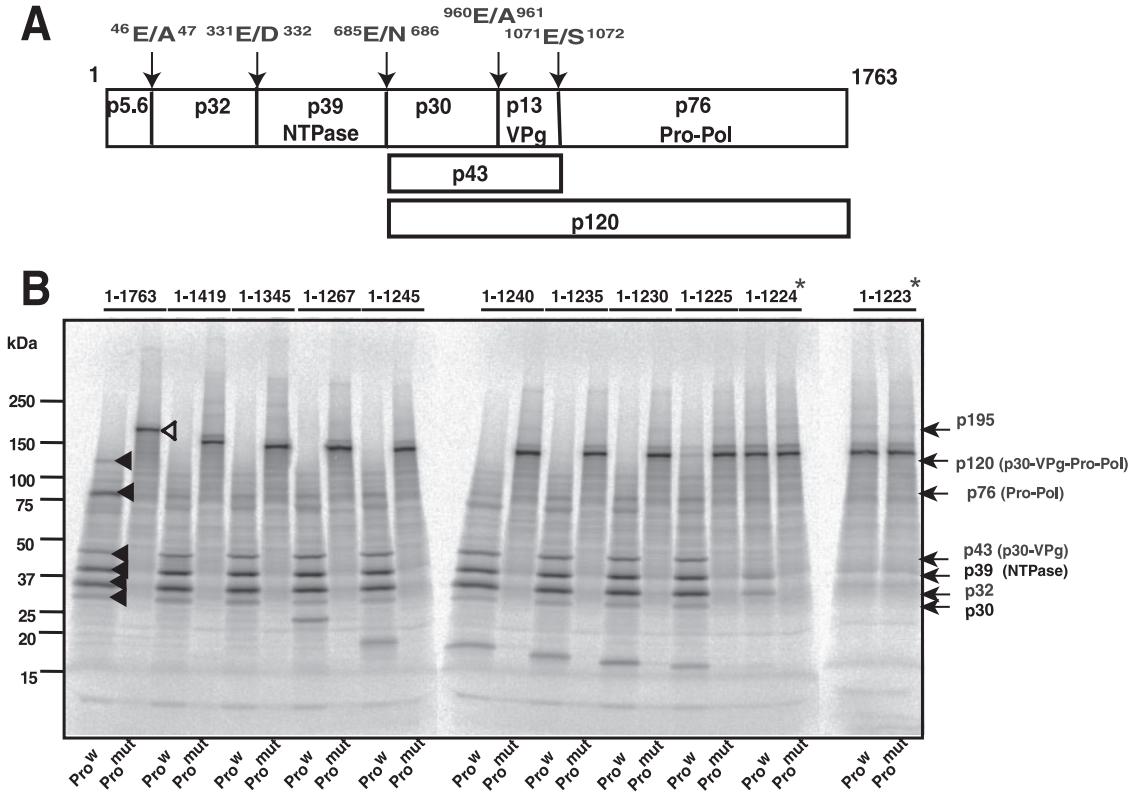

FIG. 3. Identification of the C terminus of the FCV F4 protease. (A) Proteolytic cleavage map of the FCV F4 ORF1 polyprotein and processing intermediates. The locations and designations of the proteins are adopted from the studies by Sosnovtsev et al. (40). (B) SDS-PAGE of in vitro ^{35}S-labeled wild-type (Pro^{w}) and C1193A mutant (Pro^{mut}) forms of the entire ORF1 polyprotein (aa 1 to 1763) and 10 C-terminally truncated polyproteins corresponding to aa 1 to 1419, 1 to 1345, 1 to 1267, 1 to 1245, 1 to 1240, 1 to 1235, 1 to 1230, 1 to 1225, 1 to 1224, and 1 to 1223. The protein bands corresponding to either the Pro^{w} or Pro^{mut} form of the entire ORF1 polyprotein are indicated by filled and open arrowheads, respectively. The molecular sizes of viral proteins are shown on the right, and size markers are shown on the left. Asterisks indicate two C-terminally truncated forms, corresponding to aa 1 to 1224 and 1 to 1223, which display affected protease activity. Products of approximately 15 to 25 kDa would be the truncated Pro-Pol released from the truncated ORF1 polyprotein.

protease domain were selected based on the amino acid alignment of 14 human SaV strains, with one exception: D instead of E^{1147} in a human SaV NK24 strain (data not shown). These nine amino acid residues were changed to A by site-directed mutagenesis (Table 1), and nine mutant forms of the ORF1 polyprotein, the H1069A, H1075A, H1086A, E1107A, H1120A, H1136A, E1143A, E1147A, and H1186A forms, were expressed in an in vitro translation system. Two forms of the ORF1 polyprotein, the full-length Pro^{w} and Pro^{mut} (C1171A) forms, were used as positive and negative controls, respectively (Fig. 2) (29, 30). Three mutant forms of the ORF1 polyprotein, the H1086A, E1107A, and H1186A forms, each produced a major 250-kDa product (Fig. 2), demonstrating that the proteolytic processing of the ORF1 polyprotein was completely blocked with these mutant forms. In contrast, the cleavage products of six mutant forms, the H1069A, H1075A, H1120A, H1136A, E1143A, and E1147A forms, were identical to those of Pro^{w}, although their cleavages were slightly affected (Fig. 2). From these results, we concluded that the amino acid residues critical to SaV Mc10 3C-like protease activity are H$^{1086(31)}$, E$^{1107(52)}$, C$^{1171(116)}$, and H$^{1186(131)}$. The first three of these would form the catalytic triad (general base, anion, and nucleophile, respectively), and the last one would correspond to part of the binding pocket as previously described for other calicivirus proteases (5, 27, 36, 46). Two amino acids, E^{1107} and H^{1186}, essential to the SaV Mc10 protease activity are not conserved in porcine SaV; (i) E^{1107} in Mc10 is D in the PEC LL14 and Cowden strains, and (ii) H^{1186} in Mc10 is Y in the PEC LL14 strain, whereas H^{1186} is conserved in the PEC Cowden strain (data not shown).

Identification of the C terminus of the FCV F4 3C-like protease. The FCV protease-polymerase (Pro-Pol) has been identified as a stable product in both infected cells and an in vitro translation system (12, 40). Sosnovtseva et al. reported that the entire Pro-Pol region is not essential for the autocatalytic polyprotein processing in the Urbana strain in vitro translation system (42). However, the exact C terminus of the functional protease domain has not been determined.

We generated two full-length cDNA clones, pUC19/FCV F4 full-length and pUC19/FCV F4 full-C1193A/ORF1, the latter of which encodes a ^{1191}GDCG^{1194}-to-GDAG mutation in the protease. The expression was carried out with both Pro^{w} and Pro^{mut} (C1193A) forms of the protease, and the latter were used as a negative control for the proteolytic processing. Six major cleavage products, p30, p32, p39 (NTPase), p43 (p30-VPg), p76 (Pro-Pol), and p120 (p30-VPg-Pro-Pol), were detected when the Pro^{w} form corresponding to aa 1 to 1763 was expressed in an in vitro translation system (Fig. 3). These

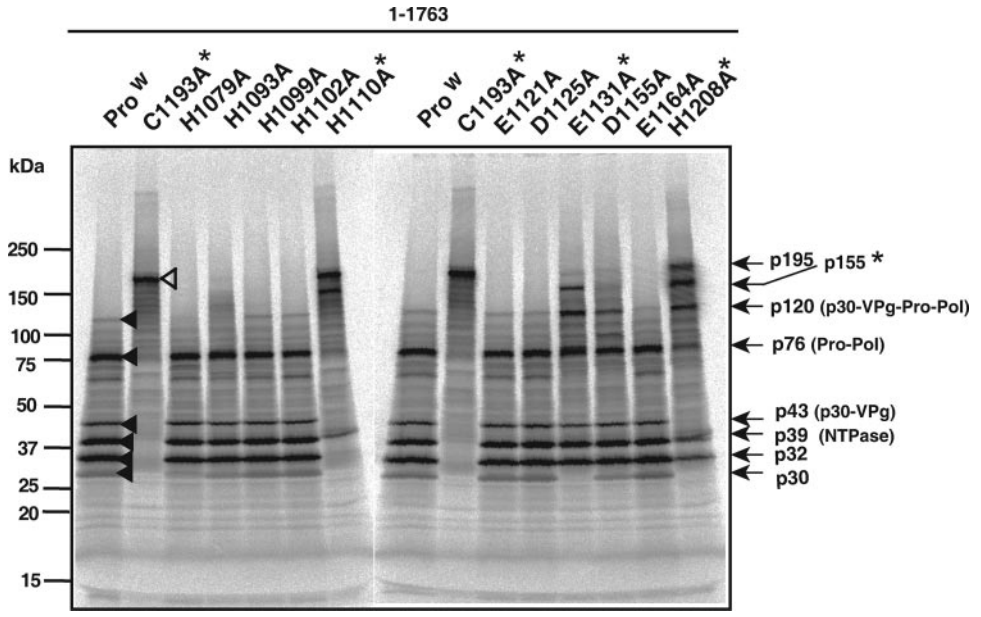

FIG. 4. Identification of the amino acid residues critical to FCV F4 protease activity. Shown are the results of SDS-PAGE of in vitro ^{35}S-labeled wild-type (Pro^{w}) and C1193A mutant forms of the entire ORF1 polyprotein (aa 1 to 1763) and 11 other mutant forms, the H1079A, H1093A, H1099A, H1102A, H1110A, E1121A, D1125A, E1131A, D1155A, E1164A, and H1208A polyproteins. The protein bands corresponding to either the Pro^{w} or C1193A form of the entire ORF1 polyprotein are indicated by filled and open arrowheads, respectively. The molecular sizes of viral proteins are shown on the right, and size markers are shown on the left. Asterisks indicate four mutant forms, the C1193A, H1110A, E1131A, and H1208A polyproteins, which show affected protease activity. The newly appearing product, p155, also marked with an asterisk, probably corresponds to NTPase-p30-VPg-Pro-Pol.

cleavage products were identical to those of the Urbana strain (40). A major 195-kDa product (p195) corresponding to the ORF1 polyprotein appeared when the Pro^{mut} form was expressed (Fig. 3B), demonstrating that the C^{1193} is critical to the FCV F4 3C-like protease activity, consistent with a previous report (42).

To define the C terminus of the functional protease domain of FCV F4, a series of 10 C-terminally truncated ORF1 polyproteins were expressed in an in vitro translation system (Fig. 3B; Table 1). Both Pro^{w} and Pro^{mut} forms of each of these regions were expressed, and the latter were used as a negative control for the proteolytic processing. Eight C-terminally truncated templates corresponding to aa 1 to 1419, 1 to 1345, 1 to 1267, 1 to 1245, 1 to 1240, 1 to 1235, 1 to 1230, and 1 to 1223 were first expressed and analyzed. The proteolytic cleavage occurred in the Pro^{w} forms of the C-terminally truncated ORF1 polyproteins corresponding to aa 1 to 1419, 1 to 1345, 1 to 1267, 1 to 1245, 1 to 1240, 1 to 1235, and 1 to 1230 but not in that corresponding to aa 1 to 1223. The translated product size of the Pro^{w} form of aa 1 to 1223 was identical to that of the Pro^{mut} form of aa 1 to 1223 (Fig. 3B), demonstrating that the C terminus of the functional protease domain is positioned upstream of aa 1223. Next, we expressed and analyzed two additional C-terminally truncated forms, aa 1 to 1225 and 1 to 1224. The proteolytic cleavage occurred efficiently when the Pro^{w} form of aa 1 to 1225 was expressed, whereas it occurred partially when the Pro^{w} form of aa 1 to 1224 was expressed (Fig. 3B). The C terminus of the functional protease domain for FCV F4 was determined to be Y^{1225}. This amino acid is conserved in 13 FCV strains (data not shown). Although we did not identify the cleavage sites of the FCV F4 ORF1 polyprotein, the cleavage pattern and the sizes of the products were consistent with the results of Sosnovtsev et al. (40). Therefore, the size of the functional protease of FCV F4 would be 154 aa (S^{1072} to Y^{1225}) when the cleavage site of the N terminus of the Urbana strain Pro-Pol is considered (40). The FCV F4 functional protease domain is similar in size to those of other caliciviruses, including SaV.

Identification of the active sites of the FCV F4 3C-like protease. The FCV 3C-like protease cleaves after the E residues of the specific site in the ORF1 polyprotein (Fig. 3A), and the C in the GDCG motif is critical to the protease activity (40–42). The functional FCV F4 protease is similar in size to those of SaV, RHDV, and NoV. Thus, the catalytic amino acid residues of the FCV protease would also be similar to those of SaV, RHDV, and NoV. Therefore, 11 amino acid residues (H^{1079}, H^{1093}, H^{1099}, H^{1102}, H^{1110}, E^{1121}, D^{1125}, E^{1131}, D^{1155}, E^{1164}, and H^{1208}) within the protease domain were selected and were changed to A by site-directed mutagenesis (Table 1).

Eleven mutant forms of the ORF1 polyprotein, the H1079A, H1093A, H1099A, H1102A, H1110A, E1121A, D1125A, E1131A, D1155A, E1164A, and H1208A forms, were expressed in an in vitro translation system. Two forms of ORF1 polyprotein, the full-length Pro^{w} and Pro^{mut} (C1193A) forms, were used as positive and negative controls for the proteolytic processing (Fig. 4). H1110A did significantly affect the ORF1 polyprotein processing, whereas E1131A and H1208A affected the processing partially (Fig. 4). That is, (i) p195, the entire ORF1 polyprotein, was detected when the H1110A form was expressed, (ii) p30 disappeared and p155 (likely the stable intermediate of NTPase-p30-VPg-Pro-Pol) appeared when the E1131A form was expressed, and (iii) p195 and p155 (NTPase-

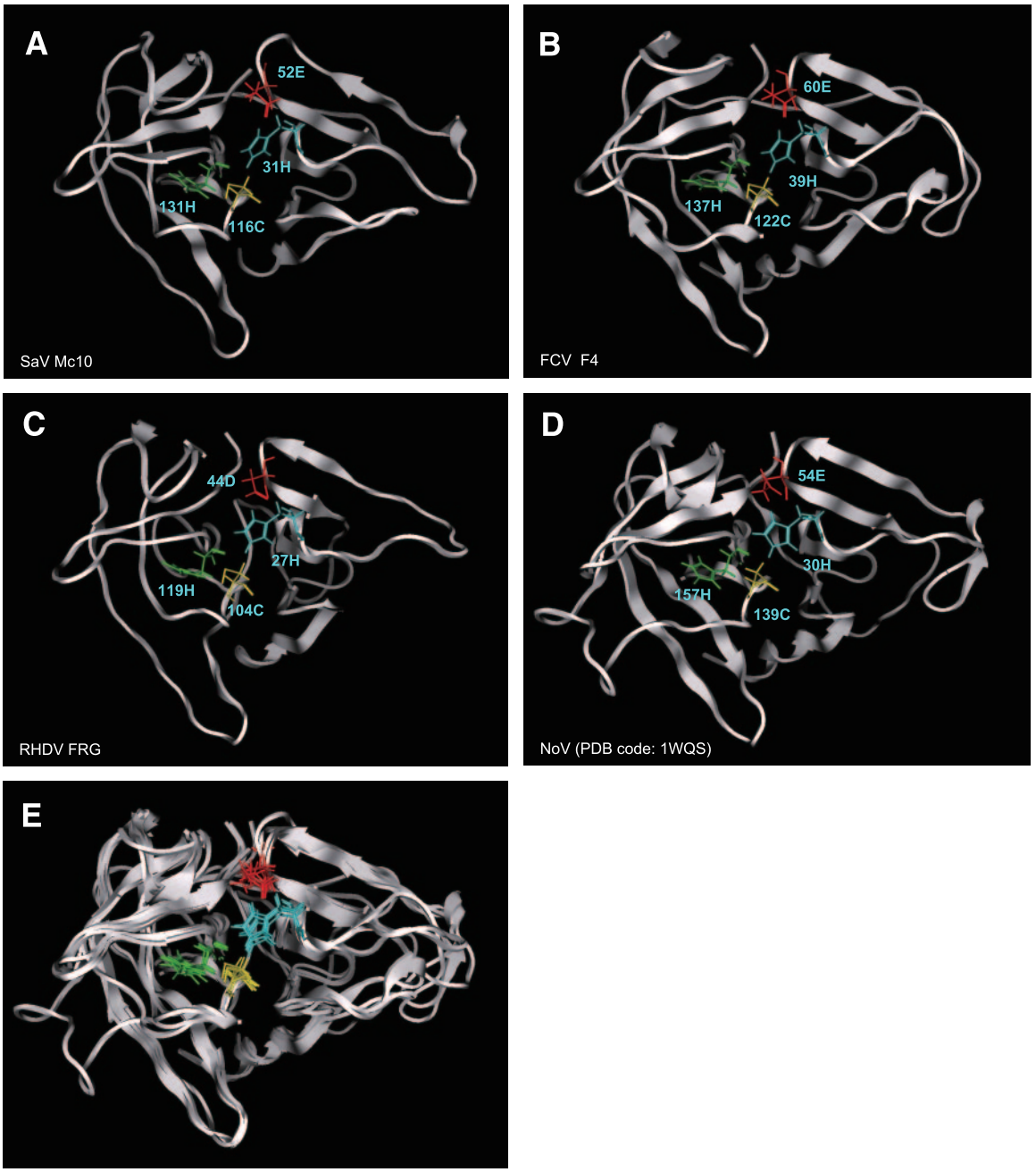

FIG. 5. 3-D models of the calicivirus 3C-like proteases. (A to D) Structural models of calicivirus 3C-like protease domains of the SaV Mc10 (A), FCV F4 (B), and RHDV FRG (C) strains and crystal structure of the NoV Chiba strain protease (27) (D). (E) Superimposition of 3C-like protease structures of the SaV Mc10, FCV F4, RHDV FRG, and NoV Chiba strains. The models were constructed with a homology modeling technique by using programs in the MOE package. Ribbons represent the backbone of the 3C-like protease domain. Side chains of the catalytically important amino acids identified in this study are shown as cyan sticks (H), red sticks (D and E), yellow sticks (C), and green sticks (H).

p30-VPg-Pro-Pol) appeared whereas p43 (p30-VPg) and p30 disappeared when the H1208A form was expressed. Prolonged incubation for up to 16 h did not change the processing patterns of these templates (data not shown). In contrast, the proteolytic processing of the ORF1 polyprotein was barely affected when five mutant forms, the H1099A, H1102A, E1121A, D1125A, and D1155A forms, were expressed (Fig. 4). The p120 (p30-VPg-Pro-Pol) band disappeared when two mutant forms, the H1079A and H1093A forms, were expressed. However, the mutated amino acid residues in these forms are not critical to protease activity, because other cleavage products were produced normally. Therefore, this product would be a precursor intermediate. Combining these results, we concluded that the amino acid residues important to FCV F4 3C-like protease activity are $H^{1110(39)}$, $E^{1131(60)}$, $C^{1193(122)}$, and $H^{1208(137)}$. The former three amino acid residues would form

the catalytic triad, and the last amino acid residue would correspond to a part of the binding pocket as discussed for other calicivirus proteases. A reverse genetics system has been reported for FCV (37, 38, 40), and it would be interesting to evaluate whether the E1131A and H1208A mutant forms are also important in vivo.

Structural modeling of SaV and FCV 3C-like proteases. Processing activities and specificities of the SaV and FCV 3C-like protease were similar when 3D-like RNA-dependent RNA polymerase domains were sequentially deleted (Fig. 1 and 3), strongly suggesting that the structure of the protease active site is self-determined and preserved in the part of the Pro-Pol polypeptide independent of the Pol domain. To obtain structural insights into the roles of the amino acid residues critical to protease activity, 3-D models of the 3C-like protease domains of the SaV Mc10, FCV F4, and RHDV FRG strains were constructed and compared with the X-ray crystal structure of the 3C-like protease of the NoV Chiba strain (27). Despite the low levels of amino acid sequence similarity of proteases among these strains (about 20%), the overall structures were predicted to be similar and to retain structural characteristics seen in the functional protease in general (Fig. 5A to D). The calicivirus proteases consist of N- and C-terminal subdomains, which are separated by a large cleft, probably for substrate binding. H and E in SaV, FCV, and NoV and H and D in RHDV are located along the inner surface of the N-terminal subdomain, whereas C and H in all viruses are located along the inner surface of the C-terminal subdomain. In contrast to the overall similarity, the conformations and configurations of the local structures around the active site are often different among the viruses, suggesting their potential roles in determining protein substrate specificity.

Notably, the superimposition of the calicivirus protease domain structures showed that the thermodynamically favored configurations of the amino acids H, E/D, C, and H are highly conserved (Fig. 5E); the side chains of these amino acids protrude from the main chains at almost identical positions, with very similar configurations along the inner surface of the potential binding cleft for the substrate. The C is a part of the GDCG motif, a conserved and functionally important 3C-like protease motif, and is surrounded closely by other amino acid residues, H, E, and H. The side chain orientations are almost identical to those of the protease. Higher-resolution X-ray crystal structures from distinct NoV strains (46) supported the conservation of the configuration of these catalytic amino acid residues among calicivirus proteases. These findings are consistent with the critical roles of these amino acids in the proteolytic activity and suggest strongly that the H, E, C, and H residues are involved in the formation of a conserved catalytic surface of the SaV and FCV 3C-like proteases.

Conclusions. The functional domains, amino acid residues critical to the proteolytic processing activity, and structural characteristics of SaV and FCV 3C-like proteases were identified. The molecular genetics study showed that the sizes and catalytically important amino acids of the SaV and FCV proteases are similar to those of RHDV and NoV proteases. The computer-assisted structural study strongly suggested that these amino acids are involved in the formation of a conserved catalytic surface of the calicivirus 3C-like protease. In this study, we studied both primary and 3-D structures of SaV and FCV proteases, which are mutually closely related subjects and should be understood in concert. In collaboration with other resources, the data obtained in this study will provide important bases to study the molecular function and inhibitors of calicivirus proteases.

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REFERENCES

1. **Asanaka, M., R. L. Atmar, V. Ruvolo, S. E. Crawford, F. H. Neill, and M. K. Estes.** 2005. Replication and packaging of Norwalk virus RNA in cultured mammalian cells. Proc. Natl. Acad. Sci. USA **102:**10327–10332.
2. **Belliot, G., S. V. Sosnovtsev, T. Mitra, C. Hammer, M. Garfield, and K. Y. Green.** 2003. In vitro proteolytic processing of the MD145 norovirus ORF1 nonstructural polyprotein yields stable precursors and products similar to those detected in calicivirus-infected cells. J. Virol. **77:**10957–10974.
3. **Bergmann, E. M., M. M. Cherney, J. McKendrick, S. Frormann, C. Luo, B. A. Malcolm, J. C. Vederas, and M. N. James.** 1999. Crystal structure of an inhibitor complex of the 3C proteinase from hepatitis A virus (HAV) and implications for the polyprotein processing in HAV. Virology **265:**153–163.
4. **Blakeney, S. J., A. Cahill, and P. A. Reilly.** 2003. Processing of Norwalk virus nonstructural proteins by a 3C-like cysteine proteinase. Virology **308:**216–224.
5. **Boniotti, B., C. Wirblich, M. Sibilia, G. Meyers, H. J. Thiel, and C. Rossi.** 1994. Identification and characterization of a 3C-like protease from rabbit hemorrhagic disease virus, a calicivirus. J. Virol. **68:**6487–6495.
6. **Bowie, J. U., R. Luthy, and D. Eisenberg.** 1991. A method to identify protein sequences that fold into a known three-dimensional structure. Science **253:**164–170.
7. **Chang, K. O., S. S. Sosnovtsev, G. Belliot, Q. Wang, L. J. Saif, and K. Y. Green.** 2005. Reverse genetics system for porcine enteric calicivirus, a prototype sapovirus in the *Caliciviridae*. J. Virol. **79:**1409–1416.
8. **Chang, K. O., S. V. Sosnovtsev, G. Belliot, A. D. King, and K. Y. Green.** 2006. Stable expression of a Norwalk virus RNA replicon in a human hepatoma cell line. Virology **353:**463–473.
9. **Clarke, I. N., and P. R. Lambden.** 2000. Organization and expression of calicivirus genes. J. Infect. Dis. **181**(Suppl. 2)**:**S309–S316.
10. **Clarke, I. N., and P. R. Lambden.** 1997. The molecular biology of caliciviruses. J. Gen. Virol. **78:**291–301.
11. **Green, K. Y., T. Ando, M. S. Balayan, T. Berke, I. N. Clarke, M. K. Estes, D. O. Matson, S. Nakata, J. D. Neill, M. J. Studdert, and H. J. Thiel.** 2000. Taxonomy of the caliciviruses. J. Infect. Dis. **181**(Suppl. 2)**:**S322–S330.
12. **Green, K. Y., A. Mory, M. H. Fogg, A. Weisberg, G. Belliot, M. Wagner, T. Mitra, E. Ehrenfeld, C. E. Cameron, and S. V. Sosnovtsev.** 2002. Isolation of enzymatically active replication complexes from feline calicivirus-infected cells. J. Virol. **76:**8582–8595.
13. **Hansman, G. S., K. Katayama, N. Maneekarn, S. Peerakome, P. Khamrin, S. Tonusin, S. Okitsu, O. Nishio, N. Takeda, and H. Ushijima.** 2004. Genetic diversity of norovirus and sapovirus in hospitalized infants with sporadic cases of acute gastroenteritis in Chiang Mai, Thailand. J. Clin. Microbiol. **42:**1305–1307.
14. **Hardy, M. E., T. J. Crone, J. E. Brower, and K. Ettayebi.** 2002. Substrate specificity of the Norwalk virus 3C-like proteinase. Virus Res. **89:**29–39.
15. **Katayama, K., G. S. Hansman, T. Oka, S. Ogawa, and N. Takeda.** 2006. Investigation of norovirus replication in a human cell line. Arch. Virol. **151:**1291–1308.
16. **Katayama, K., H. Shirato-Horikoshi, S. Kojima, T. Kageyama, T. Oka, F. Hoshino, S. Fukushi, M. Shinohara, K. Uchida, Y. Suzuki, T. Gojobori, and N. Takeda.** 2002. Phylogenetic analysis of the complete genome of 18 Norwalk-like viruses. Virology **299:**225–239.
17. **Kinomoto, M., R. Appiah-Opong, J. A. Brandful, M. Yokoyama, N. Nii-Trebi, E. Ugly-Kwame, H. Sato, D. Ofori-Adjei, T. Kurata, F. Barre-Sinoussi, T. Sata, and K. Tokunaga.** 2005. HIV-1 proteases from drug-naive West African patients are differentially less susceptible to protease inhibitors. Clin. Infect. Dis. **41:**243–251.
18. **Kinomoto, M., M. Yokoyama, H. Sato, A. Kojima, T. Kurata, K. Ikuta, T. Sata, and K. Tokunaga.** 2005. Amino acid 36 in the human immunodeficiency virus type 1 gp41 ectodomain controls fusogenic activity: implications for the molecular mechanism of viral escape from a fusion inhibitor. J. Virol. **79:**5996–6004.
19. **Konig, M., H. J. Thiel, and G. Meyers.** 1998. Detection of viral proteins after infection of cultured hepatocytes with rabbit hemorrhagic disease virus. J. Virol. **72:**4492–4497.

20. **Liu, B., I. N. Clarke, and P. R. Lambden.** 1996. Polyprotein processing in Southampton virus: identification of 3C-like protease cleavage sites by in vitro mutagenesis. J. Virol. **70:**2605–2610.
21. **Liu, B. L., G. J. Viljoen, I. N. Clarke, and P. R. Lambden.** 1999. Identification of further proteolytic cleavage sites in the Southampton calicivirus polyprotein by expression of the viral protease in E. coli. J. Gen. Virol. **80:**291–296.
22. **Makino, A., M. Shimojima, T. Miyazawa, K. Kato, Y. Tohya, and H. Akashi.** 2006. Junctional adhesion molecule 1 is a functional receptor for feline calicivirus. J. Virol. **80:**4482–4490.
23. **Matthews, D. A., P. S. Dragovich, S. E. Webber, S. A. Fuhrman, A. K. Patick, L. S. Zalman, T. F. Hendrickson, R. A. Love, T. J. Prins, J. T. Marakovits, R. Zhou, J. Tikhe, C. E. Ford, J. W. Meador, R. A. Ferre, E. L. Brown, S. L. Binford, M. A. Brothers, D. M. DeLisle, and S. T. Worland.** 1999. Structure-assisted design of mechanism-based irreversible inhibitors of human rhinovirus 3C protease with potent antiviral activity against multiple rhinovirus serotypes. Proc. Natl. Acad. Sci. USA **96:**11000–11007.
24. **Mayo, M. A.** 2002. A summary of taxonomic changes recently approved by ICTV. Arch. Virol. **147:**1655–1663.
25. **Meyers, G., C. Wirblich, H. J. Thiel, and J. O. Thumfart.** 2000. Rabbit hemorrhagic disease virus: genome organization and polyprotein processing of a calicivirus studied after transient expression of cDNA constructs. Virology **276:**349–363.
26. **Mosimann, S. C., M. M. Cherney, S. Sia, S. Plotch, and M. N. James.** 1997. Refined X-ray crystallographic structure of the poliovirus 3C gene product. J. Mol. Biol. **273:**1032–1047.
27. **Nakamura, K., Y. Someya, T. Kumasaka, G. Ueno, M. Yamamoto, T. Sato, N. Takeda, T. Miyamura, and N. Tanaka.** 2005. A norovirus protease structure provides insights into active and substrate binding site integrity. J. Virol. **79:**13685–13693.
28. **Oka, T., K. Katayama, S. Ogawa, G. S. Hansman, T. Kageyama, T. Miyamura, and N. Takeda.** 2005. Cleavage activity of the sapovirus 3C-like protease in Escherichia coli. Arch. Virol. **150:**2539–2548.
29. **Oka, T., K. Katayama, S. Ogawa, G. S. Hansman, T. Kageyama, H. Ushijima, T. Miyamura, and N. Takeda.** 2005. Proteolytic processing of sapovirus ORF1 polyprotein. J. Virol. **79:**7283–7290.
30. **Oka, T., M. Yamamoto, K. Katayama, G. S. Hansman, S. Ogawa, T. Miyamura, and N. Takeda.** 2006. Identification of the cleavage sites of sapovirus open reading frame 1 polyprotein. J. Gen. Virol. **87:**3329–3338.
31. **Ponder, J. W., and D. A. Case.** 2003. Force fields for protein simulations. Adv. Protein Chem. **66:**27–85.
32. **Seah, E. L., J. A. Marshall, and P. J. Wright.** 1999. Open reading frame 1 of the Norwalk-like virus Camberwell: completion of sequence and expression in mammalian cells. J. Virol. **73:**10531–10535.
33. **Seah, E. L., J. A. Marshall, and P. J. Wright.** 2003. *trans* activity of the norovirus Camberwell proteinase and cleavage of the N-terminal protein encoded by ORF1. J. Virol. **77:**7150–7155.
34. **Someya, Y., N. Takeda, and T. Miyamura.** 2005. Characterization of the norovirus 3C-like protease. Virus Res. **110:**91–97.
35. **Someya, Y., N. Takeda, and T. Miyamura.** 2000. Complete nucleotide sequence of the chiba virus genome and functional expression of the 3C-like protease in Escherichia coli. Virology **278:**490–500.
36. **Someya, Y., N. Takeda, and T. Miyamura.** 2002. Identification of active-site amino acid residues in the Chiba virus 3C-like protease. J. Virol. **76:**5949–5958.
37. **Sosnovtsev, S., and K. Y. Green.** 1995. RNA transcripts derived from a cloned full-length copy of the feline calicivirus genome do not require VpG for infectivity. Virology **210:**383–390.
38. **Sosnovtsev, S. V., G. Belliot, K. O. Chang, O. Onwudiwe, and K. Y. Green.** 2005. Feline calicivirus VP2 is essential for the production of infectious virions. J. Virol. **79:**4012–4024.
39. **Sosnovtsev, S. V., G. Belliot, K. O. Chang, V. G. Prikhodko, L. B. Thackray, C. E. Wobus, S. M. Karst, H. W. Virgin, and K. Y. Green.** 2006. Cleavage map and proteolytic processing of the murine norovirus nonstructural polyprotein in infected cells. J. Virol. **80:**7816–7831.
40. **Sosnovtsev, S. V., M. Garfield, and K. Y. Green.** 2002. Processing map and essential cleavage sites of the nonstructural polyprotein encoded by ORF1 of the feline calicivirus genome. J. Virol. **76:**7060–7072.
41. **Sosnovtsev, S. V., S. A. Sosnovtseva, and K. Y. Green.** 1998. Cleavage of the feline calicivirus capsid precursor is mediated by a virus-encoded proteinase. J. Virol. **72:**3051–3059.
42. **Sosnovtseva, S. A., S. V. Sosnovtsev, and K. Y. Green.** 1999. Mapping of the feline calicivirus proteinase responsible for autocatalytic processing of the nonstructural polyprotein and identification of a stable proteinase-polymerase precursor protein. J. Virol. **73:**6626–6633.
43. **Wei, L., J. S. Huhn, A. Mory, H. B. Pathak, S. V. Sosnovtsev, K. Y. Green, and C. E. Cameron.** 2001. Proteinase-polymerase precursor as the active form of feline calicivirus RNA-dependent RNA polymerase. J. Virol. **75:**1211–1219.
44. **Wirblich, C., H. J. Thiel, and G. Meyers.** 1996. Genetic map of the calicivirus rabbit hemorrhagic disease virus as deduced from in vitro translation studies. J. Virol. **70:**7974–7983.
45. **Yap, C. C., K. Ishii, H. Aizaki, H. Tani, Y. Aoki, Y. Ueda, Y. Matsuura, and T. Miyamura.** 1998. Expression of target genes by coinfection with replication-deficient viral vectors. J. Gen. Virol. **79:**1879–1888.
46. **Zeitler, C. E., M. K. Estes, and B. V. Venkataram Prasad.** 2006. X-ray crystallographic structure of the Norwalk virus protease at 1.5-A resolution. J. Virol. **80:**5050–5058.
47. **Zhang, K. Y., and D. Eisenberg.** 1994. The three-dimensional profile method using residue preference as a continuous function of residue environment. Protein Sci. **3:**687–695.