Receptor Usage and Cell Entry of Porcine Epidemic Diarrhea Coronavirus

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Porcine epidemic diarrhea coronavirus (PEDV) has significantly damaged America's pork industry. Here we investigate the receptor usage and cell entry of PEDV. PEDV recognizes protein receptor aminopeptidase N from pig and human and sugar coreceptor N-acetylneuraminic acid. Moreover, PEDV infects cells from pig, human, monkey, and bat. These results support the idea of bats as an evolutionary origin for PEDV, implicate PEDV as a potential threat to other species, and suggest antiviral strategies to control its spread.

Porcine epidemic diarrhea coronavirus (PEDV) causes large-scale outbreaks of diarrhea in pigs and an 80 to 100% fatality rate in suckling piglets (1–3). Since 2013, PEDV has swept throughout the United States, wiped out more than 10% of America's pig population in less than a year, and significantly damaged the U.S. pork industry (4–6). No vaccine or antiviral drug is currently available to keep the spread of PEDV in check. PEDV belongs to the α genus of the coronavirus family (7, 8), which also includes porcine transmissible gastroenteritis coronavirus (TGEV), bat coronavirus 512/2005 (BtCoV/512/2005), and human NL63 coronavirus (HCoV-NL63). Although both PEDV and TGEV infect pigs, PEDV is genetically more closely related to BtCoV/512/2005 than to TGEV, leading to the hypothesis that PEDV originated from bats (9).

Receptor binding and cell entry are essential steps in viral infection cycles, critical determinants of viral host range and tropism, and important targets for antiviral interventions. An envelope-anchored spike protein mediates coronavirus entry into cells. The spike ectodomain consists of a receptor-binding subunit, S1, and a membrane fusion subunit, S2. S1 contains two domains, an N-terminal domain (S1-NTD) and a C-terminal domain (S1-CTD), both of which can potentially function as receptor-binding domains (RBDs) (Fig. 1A) (10, 11). The ability of coronavirus RBDs to recognize receptor orthologs from different species is one of the most important determinants of coronavirus host range and tropism (8, 12–14). HCoV-NL63 S1-CTD recognizes human angiotensin-converting enzyme 2 (ACE2), whereas TGEV S1-CTD recognizes porcine aminopeptidase N (APN), and its S1-NTD recognizes two sugar coreceptors, N-acetylneuraminic acid (Neu5Ac) and N-glycolylneuraminic acid (Neu5Gc) (15–18). Usage of sugar coreceptors is linked to the enteric tropism of coronaviruses (18, 19). It has been shown that PEDV uses porcine APN as its receptor (20). However, it is not known whether PEDV recognizes APN from other species or whether it uses sugar coreceptors. Addressing these questions will be critical for understanding the host range, tropism, and evolutionary origin of PEDV, for evaluating its potential risk to other species, particularly humans, and for developing effective vaccines and antiviral drugs to curb the spread of PEDV in pigs and to other species.

To characterize the receptor usage of PEDV, here we identified the two S1 domains of PEDV based on the sequence similarity between PEDV and TGEV S1 subunits (Fig. 1B). The S1-NTD and S1-CTD of PEDV cover residues 19 to 252 and residues 509 to 638, respectively. However, expression of the two domains individually gave low yields. Instead, we expressed and purified a longer fragment (residues 19 to 638) using a previously described procedure (21, 22). This fragment contains both of the S1 domains and is termed S1-NTD-CTD (Fig. 2A). For comparison studies, we prepared TGEV S1-NTD-CTD (residues 17 to 675) using the same procedure. We also expressed and purified human and porcine APN as previously described (23, 24). These purified recombinant proteins were subsequently used in biochemical studies.

We investigated the receptor binding capabilities of PEDV S1-NTD-CTD. First, using a dot blot hybridization assay as previously described (24), we showed that PEDV S1-NTD-CTD binds both porcine and human APN efficiently (Fig. 2B). Thus, both porcine and human APN serve as efficient receptors for PEDV. In contrast, TGEV S1-NTD-CTD binds porcine APN much more tightly than it binds human APN (Fig. 2B). Second, using the dot blot hybridization assay as previously described (25, 26), we demonstrated that PEDV S1-NTD-CTD binds bovine and porcine mucins, both of which contain a mixture of different types of

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sugar (Fig. 2C). Treatment of mucins with neuraminidase removed part of the coated sugars, reducing the binding by PEDV S1-NTD-CTD. Hence, sugar serves as a coreceptor for PEDV. As a comparison, TGEV S1-NTD-CTD also binds these mucins. Third, using a glycan screen array as previously described (26), we identified Neu5Ac as the type of sugar most favored by PEDV (Fig. 2D;

see also Table S1 in the supplemental material). Taken together, PEDV uses both porcine and human APNs as its protein receptors and Neu5Ac as a sugar coreceptor, whereas TGEV uses porcine APN and sugar, but not human APN, as its receptors.

To further understand the receptor usage and also to investigate the cell entry of PEDV, we performed a PEDV spike-mediated pseudovirus entry (27). Retroviruses pseudotyped with PEDV spike (i.e., PEDV pseudoviruses) efficiently entered MDCK (canine kidney) cells exogenously expressing human or porcine APN, and these entries could be blocked by anti-APN antibody (Fig. 3A). As a control, PEDV pseudoviruses could not enter MDCK cells not expressing human or porcine APN, consistent with a previous report that MDCK is nonpermissive to PEDV infection (20). In contrast, TGEV pseudoviruses efficiently entered MDCK cells exogenously expressing porcine APN but not those expressing human APN. Additionally, PEDV pseudoviruses efficiently entered both PK-15 (pig kidney) and Huh-7 (human lung) cells that endogenously express porcine and human APN, respectively (28, 29), and these entries could be blocked by anti-APN antibody and mucins (Fig. 3B and C). In contrast, TGEV pseudoviruses efficiently entered PK-15 cells but not Huh-7 cells. These data collectively confirmed that human and porcine APN and sugar serve as receptors for PEDV and play important roles in PEDV spike-mediated cell entry, whereas porcine APN and sugar, but not human APN, are receptors for TGEV.

To further examine PEDV entry into host cells, we carried out

FIG 3 PEDV spike-mediated pseudovirus entry into host cells. PEDV spike- and TGEV spike-pseudotyped retroviruses were produced and used to infect cells using a procedure as previously described (27). Trypsin was not included in the pseudovirus entry assay. The cells being infected were MDCK cells exogenously expressing human APN (hAPN), porcine APN (pAPN), or an empty vector (A), PK-15 cells (B), and Huh-7 cells (C). For antibody inhibition, cells were preincubated with 20 µg/ml anti-human APN antibody (Santa Cruz Biotechnology) for 1 h at 37°C before pseudovirus infection. For mucin inhibition, PEDV spike- or TGEV spike-pseudotyped retroviruses were preincubated with 500 µg/ml porcine or bovine mucin before they were used to infect cells. The pseudovirus entry efficiency was characterized as luciferase activity accompanying the entry. Error bars indicate standard errors of the means (SEM) ($n = 4$).

live-PEDV infection in the following cell lines: PK-15 (pig kidney), ST (pig testis), Huh-7 (human liver), MRC-5 (human lung), Vero CCL-81 (monkey kidney), and Tb1-Lu (bat lung) cells. To this end, PEDV strain Ohio VBS2 was isolated from a piglet in Ohio, USA, and propagated in Vero CCL-81 cells using a procedure as previously described (30). Vero CCL-81-adapted PEDV was used to infect each of the above-named cell lines at a multiplicity of infection (MOI) of 1.0. The results showed that PEDV efficiently infects cells from pig, human, monkey, and bat (Fig. 4).

It is worth noting that whereas pseudovirus entry is determined by receptor recognition and cell entry, the infection efficiency of live PEDV in cell culture is determined not only by receptor recognition and cell entry but also by postentry factors, such as viral replication and release (31).

PEDV is a highly pathogenic and lethal pig coronavirus. This study investigated how PEDV recognizes host receptors from different species and how it infects cells from different species. First, we verified that PEDV recognizes porcine APN and infects pig

FIG 4 PEDV infections in cell culture. PEDV strain Ohio VBS2 was used to infect different cell lines at an MOI of 1.0 using a procedure as previously described (30). Trypsin (5 µg/ml) was included in the cell culture medium to facilitate live-PEDV infections. Twenty-four hours postinoculation, cells were fixed with 4.0% (vol/vol) paraformaldehyde and 0.2% (vol/vol) glutaraldehyde. PEDV was detected with fluorescein isothiocyanate (FITC)-labeled mouse anti-PEDV N protein antibody and observed under a fluorescence microscope.

cells. Second, for the first time to our knowledge, we showed that PEDV recognizes a sugar coreceptor, Neu5Ac, which explains the enteric tropism of PEDV. Because TGEV also recognizes porcine APN and Neu5Ac, PEDV and TGEV are evolutionarily closely related despite the relatively low sequence similarity in their spikes (Fig. 1B). Third, we demonstrated that PEDV infects bat cells, providing evidence that PEDV originated from bats. Finally, unlike TGEV, which does not use human APN as its receptor, PEDV recognizes human APN and infects human cells. Thus, neither receptor recognition nor other host cellular factors (e.g., cellular restrictions of viral replication) pose a hurdle for PEDV to infect humans. It remains to be seen whether systemic factors (e.g., the host immune system) can prevent or clear in a timely manner PEDV infections in humans. Nevertheless, these results suggest that PEDV may be a potential threat to other species, including humans. Overall, our study provides insight into the host range, tropism, and evolution of PEDV.

Our study also has implications for the development of antiviral strategies against PEDV. The S1-NTD-CTD fragment as identified in this study may serve as a subunit vaccine candidate. Monoclonal antibodies against S1-NTD-CTD may serve as immunotherapeutic agents to block PEDV attachment to both the APN receptor and the sugar coreceptor. In addition, sugar or sugar analogues may serve as antiviral drugs to block PEDV attachment to its sugar coreceptor. The development of these antiviral strategies is urgent because of the damaging impact that PEDV exerts on the U.S. pork industry and the potential threat that PEDV poses to other species.

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