Endosomal Proteolysis of the Ebola Virus Glycoprotein Is Necessary for Infection

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Ebola virus (EboV) causes rapidly fatal hemorrhagic fever in humans and there is currently no effective treatment. We found that the infection of African green monkey kidney (Vero) cells by vesicular stomatitis viruses bearing the EboV glycoprotein (GP) requires the activity of endosomal cysteine proteases. Using selective protease inhibitors and protease-deficient cell lines, we identified an essential role for cathepsin B (CatB) and an accessory role for cathepsin L (CatL) in EboV GP-dependent entry. Biochemical studies demonstrate that CatB and CatL mediate entry by carrying out proteolysis of the EboV GP subunit GP1 and support a multistep mechanism that explains the relative contributions of these enzymes to infection. CatB and CatB/CatL inhibitors diminish the multiplication of infectious EboV-Zaire in cultured cells and may merit investigation as anti-EboV drugs.

Ebola virus (EboV) is a member of the Filoviridae family of enveloped viruses with nonsegmented negative-sense RNA genomes (1). EboV infection is initiated by the fusion between viral and host cell membranes, which is mediated by the viral membrane glycoprotein (GP) (2, 3). Mature GP is a trimer of three disulfide-linked GP1-GP2 heterodimers that are generated by the proteolytic cleavage of the GP0 precursor polypeptide during virus assembly (4–6). The membrane-distal subunit, GP1, mediates viral adhesion to host cells and is proposed to regulate the transmembrane subunit GP2, which carries out membrane fusion (7–9). The processing and function of EboV GP are analogous to those of other type-I envelope glycoproteins, such as Env of the human immunodeficiency virus (HIV) and HA of the influenza virus (4, 7, 10–12). Current models of infection by these viruses (11) indicate that a specific signal within susceptible cells, such as receptor binding or exposure to acid pH, triggers the destabilization of intersubunit contacts, conformational rearrangement of the transmembrane subunits, and membrane fusion.

The triggering signal for the EboV GP1-GP2 trimer is unknown. Specifically, an essential EboV receptor analogous to CD4/CCR5 for HIV Env has not been identified (13). EboV infection is blocked by inhibitors of endosomal acidification (2, 3), indicating that this virus uses an acid-dependent pathway to enter cells. However, acid pH does not induce GP-dependent cell membrane fusion (8), as might be expected from studies of acid pH–triggered influenza virus and retroviruses (14, 15). These findings suggest the possibility that a critical host factor for EboV entry is dependent on acid pH. The nonenveloped mammalian reoviruses provide such a precedent: They require the activity of acid-dependent endosomal proteases to enter cells (16–18).

**Fig. 1.** Endosomal cysteine proteases CatB and CatL are host factors for VSV-GPΔMuc infection. (A and B) (Top) Effect of CatB-selective inhibitor CA074 (A) and CatL/CatB inhibitor FYdmk (B) on infectivities of VSV-G and VSV-GPΔMuc in Vero cells. (Bottom) CatB (A) and CatL (B) enzymatic activities in CA074- and FYdmk-treated Vero cells. Infectivities [infectious units (iu)/ml] are relative to the infectivity of the same virus in dimethyl sulfoxide (DMSO)–treated Vero cells (set to 100%) (25). (C) Wild-type (WT) and CatB-deficient (CatB–/–) CatB–/– (CatL–/–) MEFs were not transfected (none) or transfected with plasmid DNAs encoding β-galactosidase (β-gal), CatB (CatB), or CatL (CatL). After 24 hours, cells were exposed to VSV-GPΔMuc (~1 iu per cell), and the percentage of infected cells was determined 24 hours later by flow cytometry (25). (D) Capacity of VSV-GPΔMuc to infect CatB/CatL-deficient (CatB–/– CatL–/–) MEFs was determined as in (C). Infectivities from two replicates are shown in (A) and (B) and are representative of four independent experiments. Error bars, SD from at least three replicates.
To test the possibility that acid-dependent endosomal proteases are also host factors for EboV GP-dependent entry, we assessed the capacity of broad-spectrum protease inhibitors to block infection by vesicular stomatitis virus (VSV) particles pseudotyped with EboV GP (VSV-GP). The cysteine protease inhibitor E-64d specifically reduced VSV-GP infection in Vero African green monkey kidney epithelial cells by >99.9% (fig. S1). A similar profile of inhibition was observed with more highly infectious VSV particles containing a form of EboV GP that lacks the mucin-like/variable (Muc) domain in GP1 (VSV-GPA-Muc) (6, 19). These findings indicate that one or more cysteine proteases in Vero cells are required for EboV GP-dependent entry.

Cathepsin B (CatB) and cathepsin L (CatL) are E-64d-sensitive cysteine proteases that are present in endosomes and lysosomes and are active at acid pH in the broad range of mammalian cells susceptible to EboV infection (2, 20, 21). To examine the roles of these enzymes, we studied the effect of a selective CatB inhibitor [CA074 (22)] and a CatL/CatB inhibitor [FYdmk (23)] on VSV-GPA-Muc infection of Vero cells. Infection was inhibited in a manner that correlated closely with the inactivation of CatB but not CatL (Fig. 1, A and B). We next measured VSV-GPA-Muc infectivity in murine embryo fibroblasts (MEFs) derived from wild-type and CatB-deficient (CatB−/−CatL+/+) mice (24, 25) (Fig. 1C). We observed a >90% reduction in EboV GPA-Muc-dependent infection of CatB−/−CatL+/+ MEFs but no reduction in infection dependent on VSV’s own glycoprotein (VSV G) (26). VSV-GPA-Muc infection was enhanced by the expression of CatB but not CatL. Together, these results indicate that CatB is an essential host factor for EboV GP-dependent entry.

The inactivation of both CatB and CatL with high concentrations of FYdmk (Fig. 1B) or with a combination of CA074 and FYdmk (fig. S5) inhibited VSV-GPA-Muc infection more effectively than did the inactivation of CatB alone with CA074 (Fig. 1A and table S1), suggesting a role for CatL in entry. To investigate this possibility, we measured VSV-GPA-Muc infectivity in MEFs derived from CatB/CatL-deficient (CatB−/−CatL−/−) mice (Fig. 1D) (27). We observed a >99% reduction in EboV GPA-Muc-dependent infection of CatB−/−CatL−/− MEFs but no reduction in VSV G-dependent infection (26). VSV-GPA-Muc infection was enhanced by the expression of CatB but not CatL, providing additional evidence for the essential role of CatB. Although CatL is neither necessary nor sufficient for entry, we observed a synergistic increase in infection upon coexpression of CatL with CatB, suggesting that CatL enhances infection by contributing to the CatB-dependent entry mechanism.

To further investigate the roles of CatB and CatL in EboV GP-dependent entry, we examined the effect of the purified enzymes on VSV-GPA-Muc at pH 5.5 and 37°C (Fig. 2, A and B). CatB efficiently digests CatB-, cleaved GP118K by CatB and/or CatL is inhibited. Accordingly, we treated cells with inhibitor to reduce CatB activity to un- detectable levels, and we then challenged those cells with CatL-treated VSV particles containing increasing amounts of GP118K (Fig. 2D). Infection of these cells was enhanced in a GP118K-dependent manner, indicating that GP1 cleavage is an essential step in entry. In contrast, we observed little or no GP118K-dependent enhancement of infection in cells with ~100% CatL or ~100% CatB, indicating that the required intracellular cleavage of GP1 that is mimicked by in vitro
GP1→GP1* cleavage is mediated by CatL and/or CatB. VSV particles containing GP1* remain dependent on cellular CatB (Fig. 2, C and D), indicating the existence of a downstream CatB-dependent step. Purified CatB but not CatL, efficiently digested CatL-derived GP1* to fragments not detected by immunoblot (Fig. 2E) and inactivated infectivity by >90% (Fig. 2F). More work is needed to uncover the mechanistic details of this CatB-dependent step, but our results are consistent with a simple model in which CatB-mediated digestion of GP1* in vivo inactivates VSV particles by relieving GP1-dependent constraints on GP2 and inducing premature deployment of the fusion machinery. In this scheme, EboV GP1 digestion by cellular CatB and CatL, is functionally equivalent to fusion-triggering signals for other viruses, such as the binding of retroviruses to receptors (15) and the exposure of influenza virus to acidic pH (14, 25).

Taken together, our findings indicate that GP1 proteolysis by CatB and CatL during entry is a multistep process. We propose that this process is initiated by cleavages of GP1 by CatB and/or CatL to remove C-terminal sequences (figs. S3 and S4) (25) and to generate an N-terminal GP1-like species, which is then digested by CatB to trigger membrane fusion and entry. Our data suggest that CatL contributes to infection, particularly when CatB activity is low, by virtue of its ability to mediate initial GP1 cleavages, but is insufficient for entry because further digestion of GP1 requires CatB. The C-terminal region of GP1 contains highly variable and heavily glycosylated sequences, including the Muc domain (6), which promote viral adhesion (9) and may shield viral particles from immune recognition, but may have to be removed first to allow further GP1 digestion. An analogous multistep strategy is used by HIV: CD4-receptor binding is required for Env to be triggered by the CCR5 coreceptor (11). Even more striking parallels exist between the enveloped Ebola virus and the nonenveloped mammalian reovirus: reovirus entry also requires stepwise proteolysis of viral surface proteins by endosomal cysteine proteases (16–18).

Human fatalities from EboV infection range from 50 to 90% and treatment is currently restricted to supportive care (1). The development of an antiviral therapy for EboV is therefore a high priority. To examine whether endosomal cysteine proteases are potential anti-EboV targets, we measured the effects of E-64d and CA074 on growth of the Zaire strain of Ebola virus. Vero cells were then removed and viral growth was monitored. The yields of infectious EboV progeny (Fig. 3A) and expression of cell-associated GP1 (Fig. 3B) were markedly reduced in inhibitor-treated cells, suggesting that EboV multiplication in Vero cells is sensitive to inhibitors of endosomal cysteine proteases in general and of CatB in particular. Further investigation of the antiviral efficacy of such inhibitors may therefore be warranted. The wealth of existing knowledge regarding the design (21) and in vivo pharmacology (28) of these inhibitors may facilitate development of an anti-EboV therapy.

Supporting Online Material
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Materials and Methods
SOM Text
Figs. S1 to S5
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References
3 February 2005; accepted 1 April 2005
Published online 14 April 2005; 10.1126/science.110656
Include this information when citing this paper.
Endosomal Proteolysis of the Ebola Virus Glycoprotein Is Necessary for Infection
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Science 308 (5728), 1643-1645. [doi: 10.1126/science.1110656]
originally published online April 14, 2005

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