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Ebolavirus Is Internalized into Host Cells via Macropinocytosis in a Viral Glycoprotein-Dependent Manner

Asuka Nanbo1‡, Masaki Imai1, Shinji Watanabe2, Takeshi Noda3, Kei Takahashi3, Gabriele Neumann1, Peter Halfmann1, Yoshihiro Kawaoka1,2,3,4,*

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Abstract
Ebolavirus (EBOV) is an enveloped, single-stranded, negative-sense RNA virus that causes severe hemorrhagic fever with mortality rates of up to 90% in humans and nonhuman primates. Previous studies suggest roles for clathrin- or caveolae-mediated endocytosis in EBOV entry; however, ebolavirus virions are long, filamentous particles that are larger than the plasma membrane invaginations that characterize clathrin- or caveolae-mediated endocytosis. The mechanism of EBOV entry remains, therefore, poorly understood. To better understand Ebolavirus entry, we carried out internalization studies with fluorescently labeled, biologically contained Ebolavirus and Ebolavirus-like particles (Ebola VLPs), both of which resemble authentic Ebolavirus in their morphology. We examined the mechanism of Ebolavirus internalization by real-time analysis of these fluorescently labeled Ebolavirus particles and found that their internalization was independent of clathrin- or caveolae-mediated endocytosis, but that they co-localized with sorting nexin (SNX) 5, a marker of macropinocytosis-specific endosomes (macropinosomes). Moreover, the internalization of Ebolavirus virions accelerated the uptake of a macropinocytosis-specific cargo, was associated with plasma membrane ruffling, and was dependent on cellular GTPases and kinases involved in macropinocytosis. A pseudotyped vesicular stomatitis virus possessing the Ebolavirus glycoprotein (GP) also co-localized with SNX5 and its internalization and infectivity were affected by macropinocytosis inhibitors. Taken together, our data suggest that Ebolavirus is internalized into cells by stimulating macropinocytosis in a GP-dependent manner. These findings provide new insights into the lifecycle of Ebolavirus and may aid in the development of therapeutics for Ebolavirus infection.

Introduction
Viruses have evolved a variety of mechanisms to enter host cells [1,2,3], including clathrin- and caveolae-mediated endocytosis, phagocytosis, and macropinocytosis. The main route of endocytosis, mediated by clathrin, is characterized by the formation of clathrin-coated pits (CCP) of 85–110 nm in diameter that bud into the cytoplasm to form clathrin-coated vesicles. Influenza virus, vesicular stomatitis virus (VSV) and Semliki forest virus all enter their host cells via this pathway [4,5,6]. Although Listeria monocytogenes is larger than a CCP in diameter, it exploits non-classical clathrin-mediated endocytosis along with actin rearrangement to facilitate its infection [7,8]. Caveolae are small vesicles of 50–80 nm in diameter enriched in caveolin, cholesterol, and sphingolipid, and have been implicated in simian virus 40 (SV40) entry [9]. Clathrin- and caveolae-mediated endocytosis requires large guanosine trypophosphatases (GTPase) dynamin 2 for vesicle scission [3].

Phagocytosis plays a role in the uptake of microorganisms, cell debris, and apoptotic cells [10]. It is initiated by the interaction of cell surface receptors, such as mannose receptors, Fc receptors and lectin receptors, with their ligands at the surface of the internalized particles. Particles are internalized through a dynamin 2- and actin-dependent mechanism [11] that results in the formation of phagosomes, large particles of >500 nm in diameter. Human herpes simplex virus and acanthamoeba polyphaga mimivirus are internalized through this mechanism [12,13].

Macropinocytosis is characterized by actin-dependent membrane ruffling and, unlike phagocytosis, was thought to be independent of receptors or dynamin 2 [14,15,16,17]. Macropinocytosis is constitutively activated in some immune cells, such as dendritic cells and macrophages [18,19,20]. In the other cell types, including epithelial cells and fibroblasts, macropinocytosis is initiated by growth factor stimulation [21,22] or expression of ruffling kinases [23,24,25]. Macropinocytosis is also associated

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Ebolavirus (EBOV) is internalized via macropinocytosis.

**Author Summary**

Ebolavirus (EBOV) is an enveloped, single-stranded, negative-sense RNA virus that causes severe hemorrhagic fever with high mortality rates in humans and nonhuman primates. Previous studies suggest roles for clathrin- or caveolea-mediated endocytosis in EBOV entry; however, questions remain regarding the mechanism of EBOV entry. Here, we demonstrate that internalization of EBOV particles is independent of clathrin- or caveolea-mediated endocytosis. Specifically, we show that internalized EBOV particles co-localize with macropinocytosis-specific endosomes (macropinosomes) and that their entry is negatively affected by treatment with macropinocytosis inhibitors. Moreover, the internalization of Ebola virions accelerated the uptake of a macropinocytosis-specific cargo, was associated with plasma membrane ruffling, and was dependent on cellular GTPases and kinases involved in macropinocytosis. We further demonstrate that a pseudo-typed vesicular stomatitis virus possessing the EBOV glycoprotein (GP) also co-localizes with macropinosomes and its internalization is similarly affected by macropinocytosis inhibitors. Our results indicate that EBOV uptake into cells involves the macropinocytic pathway and is GP-dependent. These findings provide new insights into the lifecycle of EBOV and may aid in the development of therapeutics for EBOV infection.

With the activation of Rho GTPases, such as Rac1 and Cdc42, which are responsible for triggering membrane ruffles by actin polymerization [26,27,28,29], Macropinocytosis is dependent on a series of kinases; a serine/threonine p21-activated kinase 1 (Pak1) is activated by Rac1 or Cdc42 and is essential for the regulation of cytoskeleton dynamics [24,30]. In addition, Pak1 plays a role in macropinocysosme closure by activating carboxy-terminal-binding protein-1/brefeldin A-ADP ribosylated substrate (CtBP-1/BARS) [30]. Phosphatidylinositol-3-kinase (PI3K) and its effectors are responsible for ruffling and macropinocytosis [23,31]. Protein kinase C (PKC) is activated by a receptor tyrosine kinase or PI3K and also promotes plasma membrane ruffling and macropinocytosis [23]. Membrane ruffling is associated with the formation of macropinocytosis-specific endosomes, macropinosomes, of approximatly 0.5–10 μm in diameter [32]. Human adenovirus type 3 (Ad3) [33], vaccinia virus [26], Kaposi’s Sarcoma Associated Herpesvirus [34], and Nipah virus [35] enter cells via macropinocytosis. Human immunodeficiency virus (HIV) [36,37] and Ad42/5 [38] may also trigger this pathway.

Ebolavirus (EBOV) is an enveloped, single-stranded, negative-sense RNA virus that belongs to the family Filoviridae. In humans and nonhuman primates, it causes severe hemorrhagic fever with mortality rates of up to 90%. Ebolavirus virions are long, filamentous particles of varied length (typically, 1–2 μm) and a diameter of 80–100 nm. EBOV infects a wide range of host cells associated with plasma membrane ruffling, and was dependent on cellular GTPases and kinases involved in macropinocytosis. We further demonstrate that a pseudo-typed vesicular stomatitis virus possessing the EBOV glycoprotein (GP) also co-localizes with macropinosomes and its internalization is similarly affected by macropinocytosis inhibitors. Our results indicate that EBOV uptake into cells involves the macropinocytic pathway and is GP-dependent. These findings provide new insights into the lifecycle of EBOV and may aid in the development of therapeutics for EBOV infection.

Studies suggest that EBOV internalization depends on cholesterol, a major component of caveolae and lipid rafts [50,57,58]. Another study suggests a role for clathrin-mediated endocytosis in wild-type EBOV and retrovirus pseudotyped with EBOV GP entry [59,60]. These discrepancies may reflect differences in the experimental systems and/or conditions used. Most studies have been carried out with retroviruses or vesicular stomatitis virus (VSV) pseudotyped with EBOV GP [52,53,54,56,58,61]. These pseudotyped systems have limitations because the morphology of the virions differs significantly from that of authentic Ebola virions (spherical for retrovirus or VSV-pseudotyped virions versus filamentous for authentic Ebola virions).

To better understand EBOV entry, we conducted internalization studies with fluorescently labeled, biologically contained EBOV [62], and Ebolavirus-like particles (Ebola VLPs), both of which resemble authentic EBOV in their morphology [62,63,64,65]. Our results suggest that EBOV uptake into cells involves the macropinocytic pathway and is GP-dependent.

**Results**

Internalization of fluorescently labeled Ebola virions and Ebolavirus-like particles (Ebola VLPs)

To assess the mechanism of EBOV entry, we established a real-time monitoring system for fluorescently labeled, biologically contained Ebola virions [62], and fluorescently labeled Ebola VLPs [63,64,65]. The biologically contained EBOV (EbolaΔVP30) lacks the gene for the viral transcriptional co-activator VP30 and can only replicate in VP30-expressing cells [62]. EbolaΔVP30 resembles authentic EBOV [62] and thus provides an ideal system to study EBOV entry. Likewise, co-expression of the EBOV GP glycoprotein and the VP40 matrix protein yields virus-like particles (VLPs) with filamentous architecture [63,64,65]. Since co-expression of the EBOV nucleoprotein (NP) increases the efficiency of VLP generation [66], we generated VLPs by co-expressing GP, VP40, and NP. To establish a real-time monitoring system for EBOV cell entry, EbolaΔVP30 virions and Ebola VLPs were generated and purified as described in the Material and Methods, and labeled with a lipophilic tracer, 1,1'-dioctadecyl-3,3,3',3'-tetramethylindocarbocyanine perchlorate (DiI), which is incorporated into the envelope of the virions [67,68,69]. The infectivity of DiI-labeled EbolaΔVP30 was equivalent to that of unlabeled virions as measured by plaque assays (data not shown), demonstrating that DiI labeling did not interfere with virion binding and infectivity.

We synchronized the adsorption of DiI-labeled EbolaΔVP30 and Ebola VLPs to African green monkey kidney epithelial (Vero) cells, which support EBOV replication, for 30 min on ice. We assessed the effect of low temperature incubation on the internalization of the DiI-virions by incubation on ice, room temperature, or 37°C in parallel, followed by a temperature shift to 37°C and found that there were no appreciable differences in the total numbers of internalized virions across these conditions, suggesting that incubation of cells and virions on ice had a limited effect on the subsequent viral internalization (Figure S1).

After adsorption, we shifted the temperature to 37°C and visualized the labeled particles by using confocal laser scanning microscope at various times. DiI-labeled EbolaΔVP30 and Ebola VLPs were visualized as red particles of various sizes (red, Figure S2A), indicating that viral particles of various lengths had been produced, an observation that we confirmed by electron microscopy (Figure S3). Both DiI-labeled EbolaΔVP30 and Ebola VLPs were internalized efficiently, migrated immediately after the temperature shift, and eventually trafficked to intracellular compartments (Figure S2A and B, left panels, Video S1). As a...
Figure 1. Internalization of Dil-labeled Ebola virions is independent of the clathrin-mediated endocytic pathway. (A) Dil-labeled Ebola virions (red) do not co-localize with eGFP-labeled CCPs. Dil-EbolaΔVP30 virions (left panel) or Dil-Ebola VLPs (right panel) were adsorbed to Vero cells expressing CLCa-eGFP for 30 min on ice. Cells were then incubated for 15 min at 37°C and the co-localization of Dil-labeled viral particles with eGFP-labeled CCPs was analyzed by using confocal microscope. Insets show enlargements of the boxed areas. Scale bars, 10 μm. (B) Effect of clathrin-heavy chain down-regulation on the internalization of Dil-labeled Ebola virions. Vero cells were transfected with control siRNA (left panels) or CHC siRNA (right panels) to down-regulate CHC expression. The efficiency of CHC down-regulation was analyzed by immunofluorescent staining 48 h post-transfection (red; lower panels); the effect of siRNA on Alexa Fluor 633-Tf is apparent (green; lower panels). Labeled Ebola VLPs were adsorbed to the...
control, we tested VLPs that lacked GP [Ebola VLPs (-GP)]. These particles bound to the cells with low efficiency and remained stationary even after long-term incubation at 37°C (Figure S2A and B, right panels, Video S2), confirming the requirement of GP for binding and internalization of EBOV.

Role of clathrin-mediated endocytosis in EBOV entry

Previous studies suggested that EBOV enters cells via clathrin-mediated endocytosis [50,59]. The typical architecture of Ebola virions (length 1–2 µm and diameter 80–100 nm) is larger than the diameter of clathrin-coated pits (85–110 nm). However, *Listeria monocytogenes* is internalized into cells via non-classical clathrin-mediated endocytosis [7,8]. Therefore, we visualized clathrin-coated pits (CCPs) via the expression of clathrin light chain a (CLCa) fused to enhanced green fluorescent protein (eGFP) to assess the significance of this pathway for EBOV internalization. The functional integrity of clathrin is not compromised by fusion to eGFP and the expressed fusion protein forms CCPs with endogenous CLCa [70,71]. We did not detect co-localization of eGFP-labeled CLCa (CLCa-eGFP) with Dil-labeled EbolaVAP30 virions (Figure 1A, left panel and Video S3) or Ebola VLPs (Figure 1A, right panel) at 15 min or 60 min after the temperature shift, whereas fluorescence-labeled Transferrin (TF), a specific ligand of the clathrin-mediated pathway, was co-localized with eGFP-CLCa (Figure S4, left panel). These results suggest that clathrin-mediated endocytosis may not be critical for EBOV entry.

To further assess the role of clathrin-dependent endocytosis in EBOV entry, we down-regulated endogenous clathrin heavy chain (CHC) with small interfering RNAs (siRNA) and assessed the significance of this pathway for EBOV internalization. Our data argue against a role for clathrin-mediated endocytosis in EBOV internalization, we first generated Vero cells expressing an eGFP-SNX5 fusion protein and confirmed that a specific ligand of macropinocytosis, dextran Mw 10,000 (Dex Mw 10K) co-localized with expressed eGFP-SNX5 in Vero cells (Figure S6A) but not with CLCa-eGFP or Cav1-eGFP in Vero cells (Figure S6B). We then asked whether Dil-labeled EbolaVAP30 and Ebola VLPs co-localize with eGFP-SNX5-positive vesicles. Approximately 70% of Dil-labeled EbolaVAP30 (blue bars in Figure 3B) and 45% of Dil-labeled Ebola VLPs (yellow bars in Figure 3B) associated with eGFP-SNX5-positive vesicles within 10 min of the temperature shift to 37°C (Figure 3A, upper panels, Figure 3B, and Video S5). Co-localization of viral particles with eGFP-SNX5-positive vesicles occurred within 30 min after the temperature shift and then decreased (Figure 3B). On the other hand, Dil-labeled influenza viruses, which are mainly internalized by clathrin-mediated endocytosis [5], did not appreciably co-localize with eGFP-SNX5-positive vesicles (Figure 3A, red bars in lower panels, Figure 3B, and Video S6).

Ebola virions co-localize with sorting nexin (SNX) 5, a component of macropinosomes

Our data argue against a role for clathrin-, caveolae-, or phagocytosis-mediated endocytosis in the internalization of EBOV. We therefore considered macropinocytosis as a potential mode of EBOV entry. Induction of macropinocytosis leads to the formation of macropinocytosis-specific endosomes (macropinosomes), which are large enough (0.5–10 µm of diameter) [32] to accommodate Ebola virions.

Sorting nexin (SNX) 5 comprises a large family of peripheral membrane proteins that associate with newly formed macropinosomes and are involved in their maturation [77,78]. To assess the role of macropinocytosis in EBOV internalization, we first generated Vero cells expressing an eGFP-SNX5 fusion protein and confirmed that a specific ligand of macropinocytosis, dextran Mw 10,000 (Dex Mw 10K) co-localized with expressed eGFP-SNX5 in Vero cells (Figure S6A) but not with CLCa-eGFP or Cav1-eGFP in Vero cells (Figure S6B). We then asked whether Dil-labeled EbolaVAP30 and Ebola VLPs co-localize with eGFP-SNX5-positive vesicles. Approximately 70% of Dil-labeled EbolaVAP30 (blue bars in Figure 3B) and 45% of Dil-labeled Ebola VLPs (yellow bars in Figure 3B) associated with eGFP-SNX5-positive vesicles within 10 min of the temperature shift to 37°C (Figure 3A, upper panels, Figure 3B, and Video S5). Co-localization of viral particles with eGFP-SNX5-positive vesicles occurred within 30 min after the temperature shift and then decreased (Figure 3B). On the other hand, Dil-labeled influenza viruses, which are mainly internalized by clathrin-mediated endocytosis [5], did not appreciably co-localize with eGFP-SNX5-positive vesicles (Figure 3A, red bars in lower panels, Figure 3B, and Video S6).

We further confirmed co-localization of Ebola VLPs with endogenous SNX5 (Figure S7A). These observations suggest an association of internalized Ebola virions with macropinosomes.

*In situ* localization of Ebola virions

The movement of RNA viruses and their enveloped proteins from initial contact on the cell surface to the endosomal compartment was visualized using a combination of FRET microscopy (Figure S7B) and confocal laser scanning microscopy (Figure S7C). Our findings suggest that the internalization of Ebola virions is mediated by macropinocytosis and not by clathrin- or caveolae-dependent endocytosis.

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**Internalized Dil-labeled Ebola virions traffic to endosomal compartments**

Once internalized, macropinosomes mature into endocytic vesicles [77,79]. However, the endocytic pathway is also part of

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Figure 2. Internalization of Dil-labeled EBOV particles is independent of the caveolae-mediated endocytic pathway. (A) Dil-labeled EBOV particles do not co-localize with eGFP-labeled caveolae. Dil-EbolaΔVP30 virions (left panel) or Dil-Ebola VLPs (right panel) were adsorbed to Cav1-eGFP-expressing Vero cells for 30 min on ice. The cells were then incubated for 15 min at 37°C and the co-localization of Dil-labeled viral particles with eGFP-labeled caveolae was analyzed by using confocal laser scanning microscope. Insets show enlargements of the boxed areas. Scale bars, 10 μm. (B) Effect of Cav1 down-regulation on the internalization of Dil-labeled Ebola virions. Vero cells were transfected with control siRNA (left panels) or siRNA to down-regulate Cav1 expression (right panels). The efficiency of Cav1 down-regulation was analyzed by use of immunofluorescent.
staining 48 h post-transfection (lower panels) and western blot analysis (C). Labeled Ebola VLPs were adsorbed to the siRNA-transfected cells for 30 min on ice 48 h post-transfection. After incubation for 2 h at 37 ºC, surface-bound virions were removed by the addition of trypsin for 5 min at 37 ºC and the internalization of Ebola VLPs was analyzed by using confocal laser scanning microscope (upper panels). Outlines of individual cells were drawn. Scale bars, 10 μm. (D) Quantitative analysis of the internalization of Dil-labeled Ebola virions in siRNA-transfected cells. Each experiment was performed in triplicate and the results are presented as the mean ± SD. (E) Internalization of Dil-labeled Ebola virions in cells lacking Cav1. Dil-labeled EbolaΔVP30 virions were adsorbed to Cav1-deficient Huh7 cells for 30 min on ice. The internalization of Dil-EbolaΔVP30 virions was analyzed 2 h after the temperature shift to 37 ºC. Outlines of individual cells were drawn. Scale bar, 10 μm. (F) Effect of dynasore on the internalization of Dil-labeled Ebola virions. Vero cells were treated with DMSO (left panel) or dynasore (right panel) for 30 min at 37 ºC. Labeled Ebola VLPs were adsorbed to the cells for 30 min on ice and incubated for 2 h at 37 ºC in the presence of DMSO or dynasore. Surface-bound virions were removed by trypsin and the internalization of Dil-virions was analyzed by using confocal laser scanning microscope. Dynasore treatment interfered with the internalization of Alexa Fluor 633-Tf (green in right panel), attesting to its presence of DMSO or dynasore. Surface-bound virions were removed by trypsin and the internalization of DiI-virions was analyzed by using confocal microscopy (upper panels). Outlines of individual cells were drawn. Scale bar, 10 μm. (G) Quantitative analysis of the internalization of Dil-labeled Ebola virions in dynasore-treated Vero cells. The internalized Dil-virions were analyzed in 10 individual DMSO- or dynasore-treated cells. Each experiment was performed in triplicate and the results are presented as the mean ± SD.

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Macropinocytosis-associated events occur during Ebola virion internalization

Constitutive macropinocytosis occurs in specific cell types such as dendritic cells and macrophages [18,19,20]; however, in epithelial cells, it is initiated in response to growth factor stimulation [21,22] or expression of ruffling kinases [23,24,25]. To assess whether Ebola virions activate macropinocytosis to allow EBOV to be internalized into the cells, we asked whether the virions accelerated the uptake of a macropinocytosis marker, Dex Mw 10K. In the presence of Ebola virions, the uptake of Dex Mw 10K was accelerated (Figure 6A and S13), and this event was inhibited by EIPA. Co-localization of Dil-EbolaΔVP30 and Alexa Fluor-Dex Mw 10K was also observed (Figure 6B).

The Rho GTPases (Rac1 and Cdc42), protein kinase C (PKC), and Pak1 are involved in the regulation of macropinocytosis [23,24,27,29,30]. Therefore, we examined the role of Rac1 by use of dominant-negative Rac1 (dnRac1) [89]. Expression of eGFP-fused dnRac1 inhibited the internalization of Ebola virions (red) into cells by 80% (Figure 6C, lower right panel; Figure 6D) compared with that of eGFP-fused wild-type Rac1 (wtRac1) (Figure 6C upper right panel; Figure 6D). dnRac1 expression also interfered with the uptake of Dex Mw 10K (blue) (Figure 6C, lower middle panel), indicating that expression of dnRac1 inhibited macropinocytosis. The role of PKC in the internalization of Ebola virions was tested by use of the specific PKC inhibitor staurosporine [90]. Staurosporine reduced the internalization of Dil-virions (red bars in Figure 6E and left panels in Figure S14A) and Dex Mw 10K (blue bars in Figure 6E and right panels in Figure S14A) by 80% and 70%, respectively. The effect of down-regulation of Cdc42, and Pak1 by siRNAs on Ebola VLP uptake was also tested. Down-regulation at the mRNA level was assessed by RT-PCR (Figure 6F). Knockdown of Cdc42 and Pak1 appreciably interfered with DiI-Ebola VLP internalization (red
Figure 3. Internalized Dil-EBOV particles co-localize with the macropinosome marker sorting nexin (SNX) 5. (A) Time-lapse analysis of the co-localization of Dil-labeled viral particles with eGFP-SNX5. Dil-EbolaΔVP30 virions (upper panels) or Dil-influenza virus (lower panels) were adsorbed to eGFP-SNX5-expressing Vero cells for 30 min on ice. The cells were then incubated at 37°C and time-lapse images were acquired at 20-second intervals over a period of 20 min by using confocal laser scanning microscope. Still frames at the indicated times (min) after the temperature shift are shown. Scale bars: 5 μm.

B

% co-localization of Dil-virions with eGFP-SNX5

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Ebola virus is internalized via macropinocytosis.
shift to 37 °C are shown. Virions co-localizing with SNX5 are indicated by arrows. Scale bars, 5 μm. (B) Co-localization efficiency of EBOV particles with SNX5. Shown are the co-localization efficiencies of Dil-EbolaVP30 (blue bars), Dil-Ebola VLPs (yellow bars), and Dil-influenza virus (red bars) with eGFP-SNX5 at the indicated time points after the temperature shift to 37 °C. The number of Dil-labeled virions co-localized with eGFP-SNX5-positive vesicles was measured in 10 individual cells and the percentage of co-localization in the total Dil-virions is shown for each time point. Each experiment was performed in triplicate and the results are presented as the mean ± SD.

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bars in Figure 6G and left panels in Figure S14B) and also reduced the uptake of Dex Mw 10K (blue bars in Figure 6G and right panels in Figure S14B). Since plasma membrane ruffling precedes macropinocytosis [14,15,16], we monitored ruffling formation in the internalization of Dil-virions by use of Vero cells expressing eGFP-actin [91]. Time-lapse analysis revealed that prominent plasma membrane ruffling was associated with Dil-labeled virions after the temperature-shift (Figure 6H and Video S7). Appreciable actin rearrangement was not observed in the absence of EBOV virions (Figure S15 and Video S8). Together, these results demonstrate that Ebola virions stimulate macropinocytosis along with the activation of the cellular factors involved in actin polymerization that allow the virions to be internalized.

Internalization of EBOV particles is GP-dependent

Our data indicate that the EBOV particle internalization occurs via macropinocytosis, whereas previous studies suggest that clathrin- or caveolin-dependent endocytosis mediate the internalization of wild-type EBOV and EBOV GP-pseudotyped VSV or retroviruses [50,57,58,59]. To determine if these conflicting findings result from differences in assay systems (i.e., use of pseudotype viruses) and/or experimental conditions used, we tested whether a VSV pseudotyped with EBOV GP (VSVΔG-GP) was internalized by macropinocytosis. Although VSV is known to be internalized via the clathrin-dependent pathway [6], Dil-labeled VSVΔG-GP virions did not co-localize with CLCa-eGFP or Cav1-eGFP (Figure S16), whereas Dil-labeled VSVΔG-G virions co-localized with CLCa-eGFP (Figure S17). By contrast, Dil-labeled VSVΔG-GP virions co-localized with eGFP-SNX5 (Figure 7A, left panel), indicative of macropinocytosis. No significant co-localization with eGFP-SNX5 was observed for a Dil-controlled control virion possessing the VSV G glycoprotein (Dil-VSVΔG-G; Figure 7A, right panel). EbolaΔVP30 particles possessing authentic morphologies (blue bars in Figure 7B) and VSV pseudotyped with EBOV GP (green bars in Figure 7B) co-localized with eGFP-Rab7-positive vesicles with similar kinetics, indicating that the smaller size of the VSV virions relative to that of the Ebola virions did not affect the kinetics of internalization. The kinetics of Dil-VSVΔG-G trafficking to late endosomes/lysosomes (red bars in Figure 7B) was consistent with a previous study of authentic VSV [92]. EIPA, which specifically interferes with macropinocytosis, blocked the co-localization of eGFP-Rab7 with Dil-labeled VSVΔG-GP (green bars in Figure 7C), but not with Dil-VSVΔG-G (red bars in Figure 7C). The PI3K inhibitors significantly reduced the co-localization of eGFP-Rab7 with Dil-labeled VSVΔG-GP (green bars in Figure 7C) but not with VSVΔG-G (red bars in Figure 7C), which is consistent with previous findings [93].

The effect of these inhibitors was further assessed in a viral infection system by use of a VSV pseudovirion encoding eGFP. Vero cells were pre-treated with one of the inhibitors and then infected with VSVΔG-G (green bars in Figure 7D) or VSVΔG*-G (red bars in Figure 7D) in the presence of the inhibitors. The infection efficiency of each pseudovirus was determined by measuring the number of GFP-positive cells. EIPA blocked the infection of VSVΔG-G (green bars in Figure 7D), but not VSVΔG*-G (red bars in Figure 7D). The PI3K inhibitors reduced the infection of VSVΔG-GP (green bars in Figure 7D) but not VSVΔG*-G (red bars in Figure 7D), which is consistent with the results of the co-localization of Dil-VSV pseudovirions and SNX5 (Figure 7C). These findings demonstrated that in this viral infection system, VSV pseudotyped with EBOV GP is internalized by macropinocytosis, as are EbolaΔVP30 and Ebola VLPs. Therefore, regardless of the size of the virions, our data indicate that EBOV GP induces receptor-dependent macropinocytosis, unlike those in a previous report which showed that macropinocytosis is receptor-independent [32]. Our finding is consistent with a recent report describing receptor-dependent macropinocytosis in adenovirus type 3 [33].

Discussion

Viruses accomplish cell entry by hijacking the cellular endocytic machinery. In this study, with EBOV particles that resemble authentic EBOV, the data lead us to conclude that EBOV is internalized into host cells via macropinocytosis in a viral GP-dependent manner.

Our conclusion that EBOV is internalized via macropinocytosis is based on the following observations: (i) the internalized viral particles co-localize with a marker of macropinosomes, SNX5 (Figure 3); (ii) the internalization of viral particles was blocked by inhibitors of actin polymerization and PI3K, which are known players in macropinocytosis and also by a specific inhibitor of macropinocytosis, EIPA (Figure 5); (iii) the internalization of Ebola virions accelerated the uptake of a specific cargo for macropinosomes in a viral GP-dependent manner.

Two findings, the inability to enter cells of Ebola VLPs lacking GP (Figure S2) and the macropinocytic uptake of VSV particles pseudotyped with EBOV GP (Figure 7), support a role for GP in the macropinocytic internalization of EBOV particles. Macropinocytosis was thought to be receptor-independent [32] until a recent study showed that Ad3 entry via macropinocytosis requires receptors (CD46 and integrins) [33]. This finding, together with our observations, supports the concept of receptor-mediated macropinocytic pathways. The exact mechanism of GP-mediated macropinocytosis remains to be elucidated; however, mannose-binding lectin, a potential EBOV co-receptor [43], is known to accelerate macropinocytosis and phagocytosis for the uptake of apoptotic cells and bacteria into macrophages [94,95]. In addition, integrins, which are also potential EBOV co-receptors [47], play an important role in Ad3 entry via macropinocytosis [33]. Thus, macropinocytosis is likely initiated through GP interaction with EBOV co-receptors on the cell surface (Figure 8).
Figure 4. Internalized Dil-labeled EBOV particles are transported to endosomes. (A) Internalized Dil-labeled Ebola virions are transported to Rab7-positive vesicles. Dil-Ebola virions were adsorbed to eGFP-Rab7-expressing Vero cells for 30 min on ice. The cells were then incubated at 37°C and images were acquired at the indicated time points. Shown are representative images at 0 (left panel) and 120 min (right panel) after the temperature shift. Dil-labeled virions that co-localize with Rab7-positive vesicles are indicated by arrows. Insets show enlargements of the boxed areas. Scale bars, 10 μm. (B) Co-localization efficiency of EBOV particles with Rab7-positive vesicles. The co-localization efficiencies of Dil-EbolaΔVP30 and Ebola VLP are shown.
Recently, one study demonstrated that the entry of Ebola VLPs and pseudovirions depends on the PI3K-Akt signaling pathway and Rac1 [99]. PI3K and its effectors are responsible for ruffling and macrophagocytosis [23,31]. Rac1 is also critical for the induction of actin filament accumulation at the plasma membrane, which leads to membrane ruffling and macrophagocytosis [27]. Moreover, membrane-bound Rac1 localizes to macropinosomes [26,27,28]. Other study demonstrated that overexpression of RhoC GTPase facilitated wild-type EBOV entry and VSV pseudotyped with EBOV GP [96]. Although a role of RhoC in viral entry has not been specifically characterized, the overexpression of RhoC resulted in increased dextran uptake and in formation of increased actin organization [96], suggesting that RhoC plays a role in EBOV entry mediated via macropagocytosis. Taken together with our findings, these observations support the model of EBOV entry through macropinosocytosis.

Clathrin-mediated endocytosis was thought to contribute to EBOV entry based on findings that specific inhibitors of clathrin-mediated endocytosis blocked the expression of viral antigens in EBOV-infected cells [59]. However, some of these inhibitors caused severe cytotoxicity, which may have induced the down-regulation of viral antigen expression [59]. Recently, by using specific inhibitors of clathrin-mediated endocytosis, a dominant-negative Eps15, which abrogates CCP formation, and siRNA for CHC, a possible role for the clathrin-dependent pathway in the internalization of retrovirus pseudovirions with EBOV GP was suggested [60]. The discrepancy between this study and ours may originate from the difference in pseudotype systems (retrovirus versus VSV or Ebola virions) and specific cell types [60]. Our data demonstrate that down-regulation of cellular CHC, which specifically blocks clathrin-mediated endocytosis, does not interfere with the internalization of Ebola virions which resemble authentic EBOV in their morphology into Vero cells (Figure 1B).

Caveolae- and lipid raft-mediated endocytosis were also thought to play a role in EBOV entry because FR-ζ, a potential coreceptor of filovirus entry, localizes to lipid rafts and is internalized through lipid raft-associated caveolae [40]. However, the role of FR-ζ in EBOV entry remains controversial [51,97]. The internalization of EBOV GP-pseudotyped virions was sensitive to the depletion of cholesterol, a major component of caveolae and lipid rafts [50,57,58]; however, cholesterol is also required for membrane ruffling and macrophagocytosis [98]. Moreover, the internalization of Ebola virions into cells transfected with siRNA for Cav1 (Figure 2B and 2C) or that lacked Cav1 (Figure 2D), argues against a role for caveolae-mediated endocytosis in EBOV entry.

One study [59] ruled out macropinocytic uptake of wild-type EBOV based on the use of an amiloride; however, the concentration of the drug used was one tenth of that typically used and may not have allowed the authors to detect an effect of this anti-macropinocytic drug on EBOV internalization.

After internalization, EBOV particles traffic to late endosomes, as suggested by their co-localization with Rab7-positive vesicles (Figure 4). This finding is consistent with previous studies that identified low pH- and cathepsin B/L-requirements for the internalization of EBOV and pseudovirions with EBOV GP into host cells [50,51,52,53,54,55,56].

Currently, no antivirals or vaccines are available for EBOV infections. Since viral entry is an attractive target for therapeutic intervention, it is imperative that we understand the mechanism of EBOV cell entry. Our finding that EBOV is likely internalized through macrophagocytosis may stimulate the development of compounds that interfere with the EBOV internalization process.

**Materials and Methods**

**Plasmids and reagents**

Human CLCa, Cav1, and Rab7 genes were amplified by RT-PCR from total RNA derived from HeLa cells, and subcloned into pEGFP-N1 or pEGFP-C1 plasmids (Clontech, Mountain View, USA). The EGF-SNX5 and eGFP-actin expression plasmid was a kind gift from Drs Rohan D. Teasdale (University of Queensland, Brisbane, Australia) and David Knecht (University of Connecticut, respectively). The eGFP-fused genes were cloned into a moloney murine leukemia virus-based retrovirus plasmid [99], a kind gift from Dr. Bill Sugden (University of Wisconsin-Madison, Madison, USA). Expression plasmids for eGFP-fused wild-type and dominant-negative Rac1 were purchased from Addgene (Cambridge, USA). Dil, Alexa Fluor 633-labeled Tf and Alexa Fluor 647-labeled DexMw 10K were purchased from Invitrogen (Carlsbad, USA). Dynasore, Cytochalasin D, Wortmannin, LY-294002 hydrochloride, EIPA, and Staurosporine were purchased from Sigma-Aldrich (St. Louis, USA). Antibodies for human clathrin heavy chain and Caveolin 1 were purchased from Abcam (Cambridge, UK).

**Cell culture and transfection**

African green monkey kidney epithelial Vero cells were grown in minimum essential medium (MEM) supplemented with 10% fetal bovine serum (FBS), L-glutamine, vitamins, nonessential amino acids, and antibiotics. A Vero cell line stably expressing the EBOV VP30 protein [62] was maintained in complete MEM containing 5 µg/ml puromycin (Sigma-Aldrich), Human embryonic kidney 293T cells and human hepatoblastoma cell line Huh7 cells were grown in high-glucose Dulbecco’s modified Eagle’s medium (DMEM) containing 10% FBS and antibiotics. Cells were maintained at 37°C in 5% CO2. Plasmid transfections in Vero cells were carried out with FuGene HG (Roche, Basel, Switzerland).

**Retroviral infection**

Recombinant retroviruses for the expression of CLCa-eGFP, Cav1-eGFP, eGFP-SNX5, -actin and -Rab7, were produced and purified as previously described [99]. For retroviral infections, Vero cells were grown to 20%–30% confluence, at which point the culture medium was replaced with ice-cold MEM supplemented with 10% FBS and 20 mM Hepes (pH 7.4), and the cells were incubated with viral stocks (107–108 infectious units/ml) for 1 h at 4°C at a multiplicity of infection (m.o.i) of 5. After being washed twice with complete medium, the cells were cultured in complete medium for 48 h.

**Purification and fluorescent-labeling of viral particles**

For the purification of EbolaΔVP30, Vero cells stably expressing VP30 were infected with EbolaΔVP30 stock [62] at a m.o.i of 0.1 in MEM containing 4% BSA and 2% FBS. EbolaΔVP30-containing culture medium was harvested 5 days post-infection and centrifuged at 3,500 rpm for 15 min to remove
Figure 5. Effect of macropinocytosis inhibitors on the co-localization of Dil-labeled viral particles with Rab7-positive vesicles. Vero cells expressing eGFP-Rab7 were pretreated with cytochalasin D (CytoD), wortmannin (Wort), LY294002, or EIPA for 30 min at 37°C as described in the Materials and Methods. Dil-EbolaΔVP30 virions, Dil-Ebola VLPs and Dil-influenza virus were adsorbed to the cells for 30 min on ice. The cells were then incubated at 37°C in the presence of inhibitors for 2 h. As a control, DMSO-treated cells were incubated with labeled EBOV particles. Representative images of the co-localization of Dil-EbolaΔVP30 virions with eGFP-Rab7-positive vesicles are indicated by arrows. Scale bars, 10 μm. (B) shows a graphic representation of the data. The number of Dil-labeled EbolaΔVP30 virions that co-localize with eGFP-Rab7-positive vesicles is shown (A). Dil-labeled EbolaΔVP30 virions that co-localize with eGFP-Rab7-positive vesicles are indicated by arrows. Scale bars, 10 μm. (B) shows a graphic representation of the data. The number of Dil-labeled EbolaΔVP30 virions (blue bars), Ebola VLPs (yellow bars) and influenza virions (red bars) co-localized with eGFP-Rab7-positive vesicles was measured in 10 individual cells and the percentage of co-localization in the total Dil-virions is shown for each time point. Each experiment was carried out in triplicate and the results are presented as the mean ± SD.

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Figure 6. Macropinocytosis-associated events occur during Ebola virion internalization. (A) The effect of the internalization of Dil-labeled Ebola VLPs on dextran uptake. Vero cells were incubated with 0.5 mg/ml Alexa Fluor 647-Dex Mw 10K in the absence or presence of Ebola VLPs for 60 min at 37°C. The uptake of Alexa Fluor 647-Dex Mw 10K was analyzed by using flow cytometry. The effect of EIPA pretreatment was assessed in parallel. Each experiment was performed in triplicate and the results are presented as the mean ± SD. (B) Co-localization of internalized Dil-labeled Ebola VLPs and Dex Mw 10K. Dil-EbolaΔVP30 was adsorbed to Vero cells for 30 min on ice. The cells were cultured in the presence of 0.5 mg/ml Alexa Fluor 647-Dex Mw 10K for 10 min at 37°C. Co-localization of Dil-virions (red) and Alexa Fluor-Dex Mw 10K (green) was analyzed by using confocal laser scanning microscope. Co-localized virions are shown by arrows. Outlines of individual cells were drawn. Scale bar, 10 μm. (C) Effect of a dominant-negative form of Rac1 on the
internalization of DiI-labeled Ebola virions. The eGFP-fused, wild-type Rac1 (wtRac1, upper panels) or the dominant-negative form of Rac1 (dnRac1, lower panels) was expressed in Vero cells. DiI-labeled Ebola VLPs were adsorbed to the cells for 30 min on ice. After incubation for 2 h at 37°C, surface-bound virions were removed by trypsin and the internalization of DiI-virions was analyzed by using confocal laser scanning microscopy. Expression of dnRac1 interfered with the internalization of Alexa Fluor 647-Dex Mw 10K (blue; lower middle panel), attesting to its functionality. Scale bars, 10 μm. (D) Quantitative analysis of the internalization of DiI-labeled Ebola virions in wtRac1 or dnRac1-expressed Vero cells. The internalized Di-I-virions were measured in 10 individual wtRac1 or dnRac1-expressed cells. Each experiment was performed in triplicate and the results are presented as the mean ± SD. (E) Effect of PKC inhibitors on the internalization of DiI-labeled Ebola virions. Vero cells were treated with DMSO or staurosporine (Stauro) for 30 min at 37°C. Labeled Ebola VLPs were adsorbed to the cells for 30 min on ice and incubated for 2 h at 37°C in the absence or presence of inhibitor. Surface-bound virions were removed by trypsin and the internalization of Di-I-virions was analyzed by using confocal laser scanning microscope. The internalized Di-I-virions were analyzed in 10 individual DMISO- or staurosporine-treated cells (red bars). The efficiency of Alexa Fluor-Dex Mw 10K uptake in inhibitor-treated cells was measured by using flow cytometry (blue bars). Each experiment was performed in triplicate and relative uptake efficiencies are presented as the mean ± SD (red bars). Staurosporine treatment interfered with the internalization of Alexa Fluor 633-Tf (blue bars), attesting to its functionality. (F) The down-regulation of Cdc42 and Pak1 by siRNA. The efficiencies of Cdc42 and Pak1 knock-down were assessed by use of RT-PCR. Total cellular RNA was isolated from siRNA-transfected Vero cells 48 h post-transfection by using TRI reagent (Sigma-Aldrich) according to the manufacturer’s instructions. cDNA synthesis was measured by using flow cytometry (blue bars). Each experiment was performed in triplicate and relative uptake efficiencies are presented as the mean ± SD. The internalization of Di-I-labeled Ebola virions is associated with plasma membrane ruffling. Di-I-Ebola VLPs were adsorbed to eGFP-actin-expressing Vero cells for 30 min on ice. The cells were then incubated at 37°C and time-lapse images were acquired at 15-second intervals over a period of 10 min by using confocal laser scanning microscope. Still frames at the indicated times (sec) after the temperature shift to 37°C are shown. Scale bar, 10 μm.

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Ebolavirus Is Internalized via Macropinocytosis

cell debris. The virions were precipitated through a 30% sucrose cushion by centrifugation at 11,000 rpm for 1 h at 4°C with an SW28 rotor (Beckman, Fullerton, USA). Precipitated virions were resuspended in TNE buffer [10 mM Tris-HCl (pH 7.6), 100 mM NaCl, 1 mM EDTA], and fractionated by use of a 25%–30% Nicodenz (Nycome Pharma AS, Oslo, Norway) gradient in TNE buffer at 27,000 rpm for 2.5 h at 4°C with an SW40 rotor (Beckman). The purification efficiency was confirmed by Coomassie Brilliant Blue staining and western blot analysis with antibodies to VP40 and NP. The infected titer was determined by plaque assay, as described previously [62].

For purification of Ebola VLPs, equal amounts of the expression plasmids for EBOV VP40 [100,101], VP30 [102], NP [100], and GP [100,101] were transfected into 293T cells by using TransIT LT-1 (Mirus, Madison, USA). Forty-eight hours post-transfection, the culture supernatants were harvested and released VLPs were purified, as described above. Incorporation of viral proteins in the purified VLPs was confirmed by western blot analysis with antibodies to VP40, GP, and NP, and the morphology of the VLPs was confirmed by negative staining (Figure S3).

Influenza virus A/PR/8/34 was prepared and purified as described previously [102]. VSV pseudotyped with EBOV GP (VSVAG™-GP) was generated as described previously [61] and purified as described above. Protein concentrations of the individual virion fractions were measured by use of a Bradford protein assay kit (BioRad, Hercules, USA). Viral particles were fluorescently labeled as described by Sakai et al. [67]. Briefly, 1 ml of fractionated virions (100 μg/ml) was incubated with 6 μl of 100 μM stock solution of DiI in the dark for 1 h at room temperature with gentle agitation.

Imaging of the internalization of DiI-labeled viral particles in live cells

For real-time imaging of the internalization of DiI-labeled viral particles, Vero cells expressing CLCa-eGFP, Cav1-eGFP, eGFP-SNX5, eGFP-actin or eGFP-Rab7 were cultured in 35 mm glass-bottom culture dishes (MatTek corporation, Ashland, USA), washed in 1 ml of phenol red-free MEM (Invitrogen) containing 2% FBS and 4% BSA, and incubated with DiI-labeled virions in 50 μl of the same medium on ice for 30 min. The cells were washed with the ice-cold medium and incubated for various times in a temperature-controlled chamber on the stage of a confocal laser scanning microscope (LSM510 META, Carl Zeiss, Oberko-chen, Germany); the chamber was maintained at 37°C with a humidified atmosphere of 5% CO2. Images were collected with a 40x oil objective lens (C-Apochromat, NA = 1.2, Carl Zeiss) and acquired by using LSM510 software (Carl Zeiss). For presentation in this manuscript, all images were digitally processed with Adobe Photoshop. For co-localization analysis, the images were acquired randomly, the number of DiI-labeled virions that co-localized with eGFP-SNX5 or eGFP-Rab7-positive vesicles were measured in 10 individual cells (approximately 10–20 dots/cell), and the percentage of co-localization in the total Di-I-virions was determined for each time point. Each experiment was performed in triplicate and the results are presented as the mean ± standard deviation.

siRNA treatment

Target sequences corresponding to the human CHC [103], Cav1 [104], and Cdc42 [105] -coding sequences were selected, respectively (Table S1), and synthesized (Dharmacon, Lafayette, USA or Qiagen, Hilden, Germany). siRNA for Pak1 down-regulation was purchased from Cell Signaling (Trask Lane, USA). Synthesized siRNA was transfected into Vero cells by using TransIT-TKO (Mirus, Madison, USA). For analysis of the efficiencies of internalization of Ebola virions, Di-I-virions were adsorbed to the siRNA-transfected cells 48 h post-transfection, as described above, and then incubated for 2 h at 37°C. Unin-ternalized surface-bound virions were removed by the addition of 0.25% trypsin for 5 min at 37°C and the number of Di-I-virions in 10 individual cells was counted. Each experiment was performed in triplicate and the results are presented as the mean ± SD.

The efficiency of CHC and Cav1 down-regulation was assessed by immunofluorescent staining with antibodies specific to CHC and Cav1 (Abcam, Cambridge, UK). The down-regulation of endogenous Cav1 was also examined by western blot analysis by using an antibody specific to Cav1 (Abcam). The efficiencies of Cdc42 and Pak1 [106] were assessed by RT-PCR with oligonucleotides to amplify each gene (Table S1).
Figure 7. Macropinocytic internalization of Ebola virions is GP-dependent. (A) Co-localization of SNX5 with VSV pseudotyped with EBOV GP. Labeled VSV particles pseudotyped with EBOV GP (DiI-VSVΔG-GP) or VSV G (DiI-VSVΔG-G) were adsorbed to eGFP-SNX5-expressing Vero cells for 30 min on ice. The cells were then incubated at 37°C and time-lapse images were acquired at 20-second intervals over a period of 30 min by using confocal laser scanning microscope. Still frames of DiI-VSVΔG-GP (left panel) and DiI-VSVΔG-G (right panel) at 10 min after the temperature shift are shown. DiI-pseudovirions that co-localize with eGFP-SNX5 are indicated by arrows. Scale bars, 10 μm. (B) Graphic representation of the co-localization of EBOV GP-pseudotyped VSV virions with Rab7-positive vesicles. Co-localization of DiI-VSVΔG-GP (green bars) with Rab7-positive vesicles was analyzed at the indicated time points as indicated in the Materials and Methods. Experiments were performed in triplicate and the results are presented as the mean ± standard deviation. Results obtained for DiI-EbolaΔVP30 (blue bars) and DiI-VSVΔG-G (red bars) are shown for
Inhibitor treatment

Vero cells or Vero cells expressing eGFP-Rab7 were pretreated with 100 μM dynasore (Sigma-Aldrich), 2 μM cytochalasin D (Sigma-Aldrich), 50 μM LY294002 hydrochloride (Sigma-Aldrich), 50 nM wortmannin (Sigma-Aldrich), 100 μM EIPA (Sigma-Aldrich) or 100 nM staurosporine (Sigma-Aldrich) for 30 min at 37°C. Dilabeled virions were adsorbed to the cells for 30 min on ice. The cells were then incubated at 37°C in the presence of inhibitors for 2 h. Co-localization of Dil-pseudovirions with eGFP-Rab7-positive vesicles was analyzed as described in the Materials and Methods. Experiments were carried out in triplicate and the results are presented as the mean ± standard deviation. (D) Effect of macropinocytosis inhibitors on the infectivity of VSV pseudovirions. Vero cells were treated with individual inhibitors for 30 min at 37°C and infected with VSVΔG*-GP (green bars) or VSVΔG*-G (red bars) in the presence of the inhibitor. 1 h post-infection, surface-bound virions were removed by trypsin and the cells were cultured for 24 h in the absence of inhibitors. The infection efficiency of each pseudovirus was determined by measuring the number of GFP-positive cells using conventional fluorescent microscope. Each experiment was performed in triplicate and the relative infection efficiencies are presented as the mean ± SD.

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Figure 8. Model of GP-dependent EBOV cell entry.

For EBOV cell entry, the binding of GP to cellular receptor(s) may activate cellular actin modulators (PI3K, small GTPases, PKC and Pak1), which trigger the actin-dependent membrane ruffling that leads to macropinocytosis. The virions are then internalized via macropinocytosis. Macropinosomes containing the virions are eventually fused to Rab7-positive late endosomes/lysosome (late maturation), resulting in the fusion of the viral envelope with the endosomal membrane in a low pH- and cathepsin-dependent manner.

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were incubated at 37°C. The cells were washed with the same medium and subsequently fixed in 4% PBS-buffered paraformaldehyde. The co-localization of Alexa Fluor-Tf with CLCa-eGFP was analyzed by use of confocal laser scanning microscope. The inset shows an enlargement of the boxed area. Scale bar, 1 μm.

Methods for supporting information files

Methods for supporting information files are described in Text S1.

Supporting Information

Figure S1 The effect of adsorption temperature on Ebola virion internalization. DiI-labeled Ebola VLPs were adsorbed to Vero cells grown in 35 mm glass-bottom culture dishes for 30 min on ice (4°C), room temperature (r.t.), or 37°C in parallel. The cells were then incubated for 2 h at 37°C. Surface-bound virions were removed by trypsin and the internalization of the DiI-virions was measured in 10 individual cells by use of confocal laser scanning microscope. Each experiment was performed in triplicate and the results are presented as the mean ± SD. Found at: doi:10.1371/journal.ppat.1001121.s001 (3.40 MB TIF)

Figure S2 Visualization of the internalization of DiI-labeled EBOV particles in live cells. (A) DiI-labeled Ebola-VLPs (red; left panel) or control VLPs lacking GP [EboV VLPs (-GP)] (red; right panel) were absorbed to Vero cells for 30 min on ice. The cells were incubated at 37°C and time-lapse images were acquired at 20-second intervals over a period of 20 min by using a confocal laser scanning microscope. Still frames at the indicated times (min) after the temperature shift to 37°C are shown. Individual cells are highlighted. Initial positions of individual viral particles are shown as white dots. Scale bars, 10 μm. (B) DiI-labeled Ebola VLPs (red; left panel) or Ebola VLPs (-GP) (red; right panel) were absorbed to Vero cells for 30 min on ice. The cells were then incubated for 30 min at 37°C. Images were collected by taking 10–15 optical slices of z-stack in 0.16 μm steps and the cross-sectional views were processed with LSM510 software. Outlines of individual cells were drawn. Scale bars, 10 μm. Found at: doi:10.1371/journal.ppat.1001121.s002 (1.04 MB TIF)

Figure S3 filamentous morphologies of Ebola VLPs. Ebola VLPs released into the supernatants of 293T cells expressing EBOV VP40, NP and GP were purified as described in the Materials and Methods and then negatively stained with 1% uranyl acetate. Filamentous particles of various lengths with surface spikes can be seen. Scale bar, 1 μm. Found at: doi:10.1371/journal.ppat.1001121.s003 (3.91 MB TIF)

Figure S4 Transferrin and cholera toxin subunit B are co-localized with CLCa-eGFP and Cav1-eGFP, respectively. (Left panel) Vero cells expressing CLCa-eGFP were incubated with 2 μg/ml Alexa Fluor 594-Transferrin (Tf) (red) for 30 min on ice. The cells were then incubated for 3 min at 37°C and subsequently fixed in PBS-buffered 4% paraformaldehyde. The co-localization of Alexa Fluor-Tf with CLCa-eGFP was analyzed by using confocal laser scanning microscope. The inset shows an enlargement of the boxed area. Scale bar, 1 μm. (Right panel) Vero cells expressing Cav1-eGFP were incubated with 2 μg/ml Alexa Fluor 647-cholera toxin subunit B (CtxB) (purple) for 30 min on ice. The cells were then incubated for 60 min at 37°C and subsequently fixed in PBS-buffered 4% paraformaldehyde. The co-localization of Alexa Fluor-CtxB with Cav1-eGFP was analyzed by use of confocal laser scanning microscope. The inset shows an enlargement of the boxed area. Scale bar, 10 μm. Found at: doi:10.1371/journal.ppat.1001121.s004 (6.50 MB TIF)

Figure S5 The effect of trypsin on the internalization of DiI-labeled virions. Labeled Ebola VLPs were adsorbed to Vero cells grown in 35 mm glass-bottom culture dishes for 30 min on ice. (A) The cells were treated with (middle and right panels) or without (left panel) 0.25% trypsin for 5 min at 37°C before (middle panel) and after (right panel) incubation for 2 h at 37°C followed by an additional incubation at 37°C for 1 h. The internalization of DiI-virions was analyzed by using confocal laser scanning microscope. Outlines of individual cells were drawn. Scale bars, 10 μm. (B) The internalized DiI-virions were measured in 10 individual cells. Each experiment was performed in triplicate and the results are presented as the mean ± SD (lower panels). Found at: doi:10.1371/journal.ppat.1001121.s005 (0.70 MB TIF)

Figure S6 Dex Mw 10K associates with macropinosomes but not with CCPs and caveolae. Vero cells expressing eGFP-SNX5 (A), CLCa-eGFP (B, left panel), or Cav1-eGFP (B, right panel) were incubated with 0.5 mg/ml Alexa Fluor 647-Dex Mw 10K for 10 min at 37°C. The co-localization of Alexa Fluor-Dex Mw 10K (purple) with eGFP-SNX5, CLCa-eGFP, or Cav1-eGFP was analyzed by using confocal laser scanning microscope. The inset shows an enlargement of the boxed area. Scale bars, 10 μm. Found at: doi:10.1371/journal.ppat.1001121.s006 (3.31 MB TIF)

Figure S7 Endogenous SNX5 and Rab7 co-localize with Ebola VLPs. (A) Vero cells were incubated with Ebola VLPs for 30 min on ice. The cells were then incubated for 10 min at 37°C and subsequently fixed in 4% PBS-buffered paraformaldehyde. Endogenous SNX5 (green) and Ebola VLPs (red) were immuno-
stained by using an anti-SNX5 goat polyclonal antibody (Abcam) and an anti-VP40 rabbit polyclonal antibody, as well as Alexa Fluor 488- and 594-labeled secondary antibodies, respectively. Scale bar, 10 μm. (B) Vero cells were incubated with Ebola VLPs for 30 min on ice. The cells were then incubated for 10 min at 37°C and subsequently fixed in 4% PBS-buffered paraformaldehyde. Endogenous Rab7 (green) and Ebola VLPs (red) were immunostained by using an anti-Rab7 mouse monoclonal antibody (Abcam) and an anti-VP40 rabbit polyclonal antibody, as well as Alexa Fluor 488- and 594-labeled secondary antibodies, respectively. Scale bar, 10 μm.

Found at: doi:10.1371/journal.ppat.1001121.s007 (1.21 MB TIF)

Figure S8 Internalized Dex Mw 10K co-localizes with Rab7-positive vesicles. Vero cells expressing eGFP-Rab7 were incubated with 0.5 mg/ml Alexa Fluor 647-Dex Mw 10K for 30 min at 37°C. The co-localization of internalized Dex Mw 10K (purple) with GFP-Rab7 was analyzed by using laser scanning confocal microscope. The inset shows an enlargement of the boxed area. Scale bar, 10 μm.

Found at: doi:10.1371/journal.ppat.1001121.s008 (2.21 MB EPS)

Figure S9 Effect of NH4Cl on internalized Dil-labeled EBOV virions. Vero cells expressing eGFP-Rab7 were pretreated with 20 mM NH4Cl for 30 min at 37°C (right panel), or left untreated (Control; left panel). Dil-EbolaAVP30 virions (red) were adsorbed to Vero cells expressing eGFP-Rab7 for 30 min on ice in the presence or absence of NH4Cl. Cells were then incubated for 4 h at 37°C in the presence or absence of NH4Cl and the internalized Dil-EbolaAVP30 virions were analyzed by using confocal laser scanning microscope. The insets show enlargements of the boxed areas. Scale bars, 10 μm.

Found at: doi:10.1371/journal.ppat.1001121.s009 (1.14 MB TIF)

Figure S10 Dil-Ebola VLPs possessing a fusion-deficient GP mutant (F535R) co-localized with eGFP-Rab7-positive vesicles but failed to fuse with the membrane of Rab7-positive vesicles. Dil-Ebola VLPs possessing GP mutant (F535R) [Ebola VLP (GP-F535R) (red) were adsorbed to eGFP-Rab7-expressing Vero cells for 30 min on ice. The cells were then incubated for 4 h at 37°C and the co-localization of Dil-virions with eGFP-Rab7 was analyzed by using confocal laser scanning microscope. Insert shows enlargements of the boxed areas. Scale bar, 10 μm.

Found at: doi:10.1371/journal.ppat.1001121.s010 (3.17 MB EPS)

Figure S11 Effect of macropinocytosis inhibitors on the uptake of Dex Mw 10K. (A) Vero cells were pretreated with 2 μM cytochalasin D (CytoD), 50 μM wortmannin (Wort), 50 μM LY294002 hydrochloride, or 100 μM EIPA for 30 min at 37°C. Vero cells were incubated with 0.5 mg/ml AlexaFluor 647-Dex Mw 10K for 60 min at 37°C in the presence of inhibitors, harvested by trypsin, washed twice with ice-cold PBS and fixed with 4% PBS-buffered paraformaldehyde for 10 min at room temperature. As a control, Vero cells were treated with DMSO. The mean fluorescence intensities in the cells were analyzed by using flow cytometry. Each experiment was performed in triplicate and the mean fluorescence intensity is presented as the mean ± SD. (B) Representative images are shown. Outlines of individual cells are drawn. Scale bar, 10 μm.

Found at: doi:10.1371/journal.ppat.1001121.s011 (17.87 MB TIF)

Figure S12 Effect of macropinocytosis inhibitors on the co-localization of Dil-labeled influenza viruses with Rab7-positive vesicles. Vero cells expressing eGFP-Rab7 were pretreated with cytochalasin D (CytoD), wortmannin (Wort), LY294002, or EIPA for 30 min at 37°C. Dil-influenza viruses (red) were adsorbed to the cells for 30 min on ice, then incubated at 37°C for 2 h in the presence of inhibitors. As a control, DMSO-treated cells were incubated with Dil-influenza viruses (Control). Representative images acquired 2 h after the temperature shift are shown. Dil-influenza virions that co-localized with eGFP-Rab7-positive vesicles are indicated by arrows. Scale bars, 10 μm.

Found at: doi:10.1371/journal.ppat.1001121.s012 (1.73 MB TIF)

Figure S13 The effect of the internalization of Dil-labeled Ebola VLPs on dextran uptake. Vero cells, grown on cover slips, were incubated with 0.5 mg/ml Alexa Fluor 647-Dex Mw 10K in the absence or presence of Ebola VLPs for 60 min at 37°C. The uptake of Alexa Fluor 647-Dex Mw 10K was analyzed by using confocal laser scanning microscope. The effect of EIPA pretreatment was assessed in parallel. Scale bars, 10 μm.

Found at: doi:10.1371/journal.ppat.1001121.s013 (0.82 MB TIF)

Figure S14 The effect of PKC, Cdc42, and Pak1 on the internalization of Ebola VLPs and Dex Mw 10K. (A) Effect of PKC inhibitors on the internalization of Dil-labeled Ebola virions and Dex 10K. Vero cells were treated with DMSO or staurosporine (Stauro) for 30 min at 37°C. Labeled Ebola VLPs were adsorbed to the cells for 30 min on ice and incubated for 2 h at 37°C in the absence or presence of inhibitor. Alexa Fluor-Dex Mw 10K was incubated for 2 h at 37°C in the absence or presence of inhibitor. Surface-bound virions or Dex Mw 10K were removed by trypsin and the internalization of Dil-virions (left panels) or Dex Mw 10K (right panels) was analyzed by using confocal laser scanning microscope. Outlines of individual cells are drawn. Scale bars, 10 μm. (B) Effect of down-regulation of Cdc42 and Pak1 on the internalization of Dil-labeled Ebola virions and Dex Mw 10K. Vero cells were transfected with control (Cont) non-targeting siRNA or siRNA to down-regulate Cdc42 and Pak1 expression. Labeled Ebola VLPs were adsorbed to the siRNA-transfected cells for 30 min on ice, 48 h post-transfection, and incubated for 2 h at 37°C. Alexa Fluor-Dex Mw 10K was incubated for 2 h at 37°C, 48 h post-transfection. After incubation for 2 h at 37°C, surface-bound virions or Dex Mw 10K were removed by trypsin for 5 min at 37°C. The internalization of Dil-virions (left panels) or Dex Mw 10K (right panels) was analyzed by using confocal laser scanning microscope. Outlines of individual cells are drawn. Scale bars, 10 μm.

Found at: doi:10.1371/journal.ppat.1001121.s014 (1.12 MB TIF)

Figure S15 Significant membrane ruffling was not observed in the absence of EBOV virions. eGFP-actin-expressing Vero cells were placed on ice for 30 min. The cells were then incubated at 37°C and time-lapse images were acquired at 15-second intervals over a 10 min time period by using a confocal laser scanning microscope. Still frames at the indicated times (sec) after the temperature shift to 37°C are shown. Scale bar, 10 μm.

Found at: doi:10.1371/journal.ppat.1001121.s015 (0.93 MB TIF)

Figure S16 Dil-labeled VSV pseudotyped with EBOV GP did not co-localize with CLCa-eGFP and Cav1-eGFP. Dil-VSV pseudotyped with EBOV GP [VSV*G-GP] (red) were adsorbed to CLCa-eGFP- or Cav1-eGFP-expressing Vero cells for 30 min on ice. The cells were then incubated for 10 min at 37°C and the co-localization of internalized Dil-virions with CLCa-eGFP or Cav1-eGFP was analyzed by use of confocal laser scanning microscope. Scale bars, 10 μm.

Found at: doi:10.1371/journal.ppat.1001121.s016 (5.80 MB TIF)

Figure S17 Dil-labeled VSV pseudotyped with VSV-G co-localized with CCPs. Dil-VSV pseudotyped with VSV-G (VSV*G-G) virions (red) were adsorbed to CLCa-eGFP-expressing
Vero cells for 30 min on ice. The cells were then incubated for 10 min at 37°C and the co-localization of internalized Dil-pseudovirions with CLCa-eGFP was analyzed by use of confocal laser scanning microscope. Dil-pseudovirions that co-localized with CLCa-eGFP are indicated by arrows. Scale bar, 10 µm. 

**Table S1** Summary of siRNA target sequence and oligonucleotide sequence for RT-PCR

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<th>Target Sequence</th>
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**Text S1** Supporting materials and methods

**Video S1** Dil-labeled Ebola-VLPs were efficiently internalized into cells after a temperature shift. Dil-labeled Ebola VLPs were adsorbed to Vero cells for 30 min on ice. Cells were then incubated for 15 min at 37°C and images were collected every 20 seconds by confocal laser scanning microscope. Ebola VLPs (red) were internalized immediately after the temperature shift.

**Video S2** Dil-labeled Ebola-VLPs lacking GP were not internalized into cells after a temperature shift. Dil-labeled Ebola VLPs that lacked EBOV GP were adsorbed to Vero cells for 30 min on ice. Cells were then incubated for 15 min at 37°C and images were collected every 20 seconds by confocal laser scanning microscope. Ebola VLPs (red) remained stationary after the temperature shift.

**Video S3** Dil-labeled Ebola-VLPs were not associated with CLCa-eGFP. Dil-labeled EbolaVP30 virions were adsorbed to Vero cells expressing CLCa-eGFP for 30 min on ice. Cells were then incubated for 15 min at 37°C and images were collected every 20 seconds by confocal laser scanning microscope. Co-localization of CLCa-eGFP (green) with DiI-virions (red) was not observed.

**Video S4** Dil-labeled Ebola-VLPs were not associated with Cav1-eGFP. Dil-labeled EbolaVP30 virions were adsorbed to Vero cells expressing Cav1-eGFP for 30 min on ice. Cells were then incubated for 15 min at 37°C and images were collected every 20 seconds by confocal laser scanning microscope. Co-localization of Cav1-eGFP (green) with DiI-virions (red) was not observed.

**Video S5** Internalized Dil-labeled EbolaVP30 virions were co-localized with eGFP-SNX5. Dil-labeled EbolaVP30 virions were adsorbed to Vero cells expressing eGFP-SNX5 for 30 min on ice. Cells were then incubated for 15 min at 37°C and images were collected every 20 seconds by confocal laser scanning microscope. Dil-EbolaVP30 virions (red) co-localized with eGFP-SNX5 (green).

**Video S6** Internalized Dil-labeled influenza virus virions were not co-localized with eGFP-SNX5. Dil-labeled influenza virions were adsorbed to Vero cells expressing eGFP-SNX5 for 30 min on ice. Cells were then incubated for 15 min at 37°C and images were collected every 20 seconds by confocal laser scanning microscope. Co-localization of eGFP-SNX5 (green) with DiI-influenza virions (red) was not observed.

**Video S7** Internalization of Dil-labeled EbolaVP30 virions was associated with plasma membrane ruffling. DiI-labeled EbolaVP30 virions were adsorbed to Vero cells expressing eGFP-actin for 30 min on ice. Cells were then incubated for 10 min at 37°C and images were collected every 10 seconds by confocal laser scanning microscope. Internalization of Dil-EbolaVP30 virions (red) was associated with plasma membrane ruffling (green). 

**Video S8** Plasma membrane ruffling was not observed in the absence of Ebola virions. Vero cells expressing eGFP-actin was placed on ice for 30 min. Cells were then incubated for 10 min at 37°C and images were collected every 10 seconds by confocal laser scanning microscope. Plasma membrane ruffling was not observed in this condition.

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**Author Contributions**

Conceived and designed the experiments: AN YK. Performed the experiments: AN MI SW. Analyzed the data: AN SW GN YK. Contributed reagents/materials/analysis tools: MI SW TN KT PH YK. Wrote the paper: AN GN.

**References**


Ebolavirus Is Internalized via Macropinocytosis