The clinically approved drugs amiodarone, dronedarone and verapamil inhibit filovirus cell entry

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Received 4 December 2013; returned 21 January 2014; revised 2 March 2014; accepted 7 March 2014

Objectives: Filoviruses such as Ebola virus and Marburg virus cause a severe haemorrhagic fever syndrome in humans for which there is no specific treatment. Since filoviruses use a complex route of cell entry that depends on numerous cellular factors, we hypothesized that there may be drugs already approved for human use for other indications that interfere with signal transduction or other cellular processes required for their entry and hence have anti-filoviral properties.

Methods: We used authentic filoviruses and lentiviral particles pseudotyped with filoviral glycoproteins to identify and characterize such compounds.

Results: We discovered that amiodarone, a multi-ion channel inhibitor and adrenoceptor antagonist, is a potent inhibitor of filovirus cell entry at concentrations that are routinely reached in human serum during anti-arrhythmic therapy. A similar effect was observed with the amiodarone-related agent dronedarone and the L-type calcium channel blocker verapamil. Inhibition by amiodarone was concentration dependent and similarly affected pseudoviruses as well as authentic filoviruses. Inhibition of filovirus entry was observed with most but not all cell types tested and was accentuated by the pre-treatment of cells, indicating a host cell-directed mechanism of action. The New World arenavirus Guanarito was also inhibited by amiodarone while the Old World arenavirus Lassa and members of the Rhabdoviridae (vesicular stomatitis virus) and Bunyaviridae (Hantaan) families were largely resistant.

Conclusions: The ion channel blockers amiodarone, dronedarone and verapamil inhibit filoviral cell entry.

Keywords: haemorrhagic fever, cationic amphiphiles, calcium channels

Introduction

Members of the Filoviridae family, which includes Marburg virus (MARV) and several species of Ebola virus, are enveloped filament-shaped viruses with a non-segmented negative-sense RNA genome. Infection of humans causes a severe haemorrhagic fever syndrome. Most cases occur in resource-poor settings in sub-Saharan Africa, with case fatality rates in the range of 42%–90%. 

Monocytes, macrophages and dendritic cells are thought to be sites of viral replication during the early and later stages of infection yet viral amplification also occurs in endothelial cells and many other tissues. Consistent with rapid spread to a broad range of cell types and tissues in humans, filoviruses have been found to readily enter into a broad range of cultured cell types, with the notable exception of lymphocytes. It has emerged over recent years that the filoviral route of cell entry is complex. Interaction between the target cell and the incoming virion is mediated on the viral side by heterotrimers of the filoviral glycoprotein (GP) subunits 1 (GP1) and 2 (GP2) that are generated by the furin-mediated cleavage of a single precursor GP (GP0) and remain linked by a disulfide bond. Numerous factors on the surface of host cells have been reported to interact with GP1/GP2. These include the folate receptor, members of the Tyro3 family of receptor tyrosine kinases (Axl, Dtk, Mer) and T cell immunoglobulin and mucin domain 1, although the relevance of the...
folate receptor for filovirus entry was later disputed.\textsuperscript{13,16} In addition, numerous C-type lectins, calcium-dependent carbohydrate-binding molecules, including the asialoglycoprotein receptor,\textsuperscript{15} DC-SIGN and DC-SIGNR,\textsuperscript{16,17} human macrophage galactose-type C-type lectin\textsuperscript{18} and liver and lymph node sinusoidal endothelial cell C-type lectin\textsuperscript{19} have been reported to interact with GP\textsubscript{3} and promote filovirus entry.

Following host cell binding, filoviruses are taken up into the cell most likely through macropinocytosis.\textsuperscript{20,21} The low pH-dependent cathepsin B/L-mediated cleavage of filovirus GP is then required for fusion with a late endosomal membrane.\textsuperscript{22} In addition, the endosomal cholesterol transporter Niemann–Pick C1 (NPC1) acts as an essential intracellular receptor.\textsuperscript{23,24} This intricate multistep route of viral entry is likely to require some form of coordination, which may take advantage of cellular signalling, as has been shown for coxsackie group B viruses\textsuperscript{25} and hepatitis C virus.\textsuperscript{26} Indeed, the phosphoinositide-3 kinase/Akt pathway as well as protein kinase C and small cellular GTPases have been implicated in filovirus entry.\textsuperscript{27}

Although (as discussed below) several experimental antifiloviral approaches have been reported, no vaccine or specific antiviral treatment has yet been established. Given low case numbers and geographical restriction to resource-limited regions, industry-sustained drug development programmes are unlikely. Nonetheless, there is a clear unmet clinical need from naturally occurring cases as well as an additional potential need given that filoviruses are considered to be CDC category A bioterrorism agents (www.bt.cdc.gov/bioterrorism). Given the complex filoviral route of entry, we hypothesized that drugs which perturb cellular signalling networks and are approved for other indications might also interfere with filovirus entry. We performed a small-scale screen and found that amiodarone, a multi-ion channel inhibitor used clinically as an anti-arrhythmic agent, acts as a potent and specific inhibitor of filoviral cell entry. The concentrations of amiodarone that are required for filovirus inhibition are well within the range that is achieved in serum during anti-arrhythmic therapy in humans, i.e. 1.5–2.5 \(\mu\)g/mL.\textsuperscript{28}

### Materials and methods

#### Compounds

Pharmacological agents were purchased from Sanofi-Aventis (Frankfurt, Germany) (amiodarone), Sigma-Aldrich (Taufkirchen, Germany) (amiodarone, dronedarone, epigallocatechin-3-gallate (EGCG), ethosuximide, lidocaine, metoprolol], Merck Millipore (Darmstadt, Germany) (Z-Phe-Tyr[Bu]-diazomethylketone (FYdmk)], Toronto Research Chemicals in a 12-well format using 8 \(\times\) 10\(^5\) EAhy cells per well. Seeding numbers were adjusted for other cell lines. Transductions were carried out with polybrene (4 \(\mu\)g/mL) and with or without drugs. After 6 h, the medium was changed every 2 – 3 days.

Primary human hepatocytes were isolated using a modified two-step collagenase (Roche P, Mannheim, Germany) perfusion technique as previously reported\textsuperscript{10} and cultured in Williams’ medium E (all Biochrom AG, Berlin, Germany) supplemented with insulin (1 \(\mu\)M), dexamethasone (1 \(\mu\)M), penicillin/streptomycin, sodium pyruvate, HEPES buffer, l-glutamine and 5% FCS. The generation of macrophages from primary human monocytes has recently been described.\textsuperscript{31} Briefly, Ficoll gradient-purified human monocytes from peripheral blood mononuclear cells were cultured in RPMI 1640 medium with 7.5% human fibrin-depleted plasma and 1% penicillin/streptomycin for 24 h. Cells were then resuspended in X-Vivo 10 medium supplemented with 1% human fibrin-depleted plasma and 1% penicillin/streptomycin, seeded and allowed to differentiate for at least 7 days. The medium was changed every 2 – 3 days.

#### DNA constructs

The plasmids CSFlucW2 encoding firefly luciferase in the context of a gutted lentiviral genome, HIV gag-pol, pCDNA3.1 and vesicular stomatitis virus (VSV) G-protein (GTV-V) that are the basis for the production of lentiviral pseudoparticles have previously been described,\textsuperscript{32,32} as has the plasmid pCAGGS-MARVGp.\textsuperscript{33} The plasmids pVR1012-GP(Z), pVR1012-GP(R), pVR1012-GP(S) and pVR1012-GP(IC) encoding the GP of Zaire Ebola virus (EBOV) as well as Reston, Sudan and Ivory Coast (Tai Forrest) Ebola virus, respectively, were a kind gift from Drs Gary Nabel and Anthony Sanchez (NIH, Bethesda, USA). The plasmid pCMV-LassaGP encoding the GP of Lassa virus was a kind gift from Dr Francois-Loic Cosset (Inserm U758, Lyon, France). The plasmid pWRGHTN-Mix encoding the GP of Hantaan virus was a kind gift from Dr Jay Hooper (USAMRDC, Fort Detrick, USA). The plasmid INH-95551 encoding the GP of the New World arenavirus Guanarito was a kind gift from Drs Hyeryun Choe (Harvard Medical School, Boston, USA) and Stefan Kunz (University of Lausanne, Switzerland).

#### Pseudoparticle production and transduction

Pseudoparticles were generated by co-transfection of plasmids encoding: (i) a gutted lentiviral genome containing the firefly luciferase gene (CSFlucW2); (ii) HIV gag-pol; and (iii) the desired envelope GP. The day before transfection, 8 \(\times\) 10\(^5\) 293T cells were seeded in a 35 mm well. The next day, a total of 1 \(\mu\)g of DNA was transfected per well using polyethylenemine. The medium was replaced after 6 h. Supernatants were harvested at 48 h and 72 h after transfection, pooled and filtered (0.45 \(\mu\)m pore size), and then used immediately or stored at 4 \(^\circ\)C (<1 week) or –80 \(^\circ\)C (>1 week). Pseudoparticle transduction assays were performed in a 12-well format using 8 \(\times\) 10\(^3\) EAHy cells per well. Seeding numbers were adjusted for other cell lines. Transductions were carried out with polybrene (4 \(\mu\)g/mL) and with or without drugs. After 6 h, the medium was exchanged. After 72 h, cells were lysed and luciferase was measured as previously described.\textsuperscript{34} To separate the virus from the drug, we used an Amicon Ultra-15 centrifugal device with a 100 Kd cut-off (Millipore). In this device, pre-treated pseudovirus was washed with 10 mL of drug-free media three times by centrifugation at 3000 rpm.

#### Authentic filovirus production and infection

All work with the infectious Mayinga strain of EBOV (GenBank accession number NC002549) was performed under the highest safety precautions in the biosafety level 4 (BSL-4) facility at the Institute of Virology, Philipps-University Marburg, Germany. Vero E6 cells were infected with EBOV at a multiplicity of infection (moi) of 1 TCID\textsubscript{50}/cell.\textsuperscript{35} EBOV particles were purified from the supernatant of infected cells at 72 h post-infection by centrifugation over a sucrose cushion for 90 min at 30000 rpm, 4 \(^\circ\)C in a Beckman ultracentrifuge using a SW32 rotor (Beckman Coulter, Palo Alto, CA, USA). Pellets were resuspended in PBS. Amiodarone was mixed with concentrated EBOV
particles with an moi of 1.5 TCID<sub>50</sub>/cell and transferred to EAhy cells. After 1 h of incubation, the inoculum was removed and replaced by fresh DMEM supplemented with 3% FCS. At 20 h post-infection, cells were fixed in 4% paraformaldehyde for 48 h, removed from the BSL-4 laboratory and subjected to quantitative immunofluorescence analysis. Immunostaining of infected cells was performed as described below.

**Immunofluorescence staining**

Immunofluorescence analyses were carried out as previously described. For the detection of nucleocapsid (NP)-induced inclusion bodies in EBOV-infected EAhy cells (after fixation of the cells with 4% paraformaldehyde in DMEM for 48 h), we used a monoclonal anti-EBOV NP antibody and a secondary FITC-coupled goat anti-mouse antibody.

**Statistical analysis**

Numerical comparisons between groups were made by unpaired two-sided Student’s t-test. Differences with P values below 0.05 are referred to as significant. P < 0.05 and P < 0.01 are indicated by single and double asterisks throughout. GraphPad Prism software (La Jolla, CA, USA) was used to fit concentration–response curves and determine the 50% inhibitory concentration (IC<sub>50</sub>).

**Results**

**Identification of amiodarone as an inhibitor of filovirus GP-driven cell entry**

Based on a literature review, we selected 15 drugs for the initial screen. Drugs were chosen that met several of the following selection criteria: (i) a known safety profile in humans; (ii) known to perturb cell signalling processes; (iii) recognized antiviral properties against viruses other than members of the Filoviridae; and (iv) coverage of a broad range of indications and drug classes. Of these 15 drugs, 14 are approved by the EMA and FDA for various indications; one drug, the protein kinase C inhibitor sotrastaurin, is in advanced clinical development as an immunosuppressive agent for use in organ transplant recipients. Human endothelium-derived EAhy cells were transduced with pseudoparticles bearing either EBOV GP or MARV GP in the presence or absence of drugs. Drug concentrations tested were based on serum levels achievable in humans. Four concentrations were tested per drug and two rounds of screening were performed. The cathepsin B and L inhibitor FYdmk, known to potently inhibit EBOV GP-mediated cell entry, was included as a positive control (Figure 1). While most drugs had no major effect on filovirus GP-mediated cell entry, amiodarone was found to reduce the detectable signal by over 99%, and thus more strongly than FYdmk, which achieved 86%–98% inhibition.

**Concentration–response relationship of amiodarone inhibition of filoviral cell entry**

Amiodarone-mediated inhibition of EBOV and MARV GP-bearing pseudoparticles showed an IC<sub>50</sub> of 1.38 μg/mL (2.02 μM) and 1.18 μg/mL (1.73 μM), respectively (Figure 2a). We then exposed EAhy cells stably expressing firefly luciferase to different concentrations of amiodarone to test for cytotoxic and anti-proliferative effects. A 50% signal reduction (CC<sub>50</sub>) was seen at 16.69 μg/mL (25.9 μM) (Figure 2b). This corresponds to a calculated therapeutic index of 12 and 14 for EBOV and MARV, respectively. In a ‘worst case’ scenario (assuming that the true IC<sub>50</sub> is 1×SD above and CC<sub>50</sub> 1×SD below our determination), the index is still >5 for both EBOV and MARV.

**Amiodarone inhibition of authentic Ebola virus**

To assess the effect of amiodarone on authentic filovirus entry, EAhy cells were exposed to purified EBOV in the presence of different concentrations of amiodarone for 1 h. The medium was exchanged, and 20 h later cells were fixed with paraformaldehyde and stained for EBOV NP protein. DAPI was used as a counterstain. There was a clear concentration-dependent reduction in the percentage of NP-positive cells while the overall cell number was unchanged (Figure S1, available as Supplementary data at JAC Online). Significant inhibition was observed at amiodarone concentrations of 0.5 μg/mL or higher (Figure 3). On averaging all the experiments performed, the IC<sub>50</sub> was 0.25 μg/mL, corresponding to a calculated therapeutic index of above 50. Of note, the apparently flatter slope of the concentration response curve is most likely due to the fact that experiments performed on separate occasions were averaged. Thus, authentic filoviruses may be more sensitive to amiodarone inhibition than pseudoparticles bearing filoviral GP.

**Amiodarone inhibition of cell entry mediated by other viral GPs**

Next we aimed to assess whether amiodarone inhibits entry driven by the GPs of all filovirus species and whether entry mediated by the GPs from other viral families may be affected.
Pseudoparticles bearing GP of the Ebola virus species Tai Forest, Reston, Sudan and Zaire, as well as MARV, were similarly inhibited by amiodarone (Figure 4a). Thus, amiodarone is a blocker of cell entry mediated by viral GPs from across the Filoviridae family.

Among a broader range of human pathogenic enveloped viruses that enter target cells through endocytosis and in a pH-dependent manner, we observed a significant inhibition of pseudoviruses bearing the GP of the New World arenavirus Guanarito (Figure 4b). VSV-G- (Rhabdoviridae family), Lassa virus GP- (Old World arenavirus) and Hantaan (Bunyaviridae family) virus GP-pseudotyped lentiviruses were affected to a lesser extent. Since all pseudoviruses have the same lentiviral NP and reporter genome, these differences strongly support the fact that amiodarone exerts its inhibitory effect on viral cell entry, i.e. a replication cycle step up to the point of fusion of the viral envelope with a cellular membrane.

Effects of amiodarone pre-treatment of target cells

We next tested the effect of target cell pre-treatment. Amiodarone was present either 1 h before the cells were washed three times and then EBOV or MARV pseudoparticles were added to the cells, or during the 6 h when the cells were exposed to the pseudoparticles, or both (Figure 5a). We observed the most marked inhibition when the drug was present throughout the experiment, i.e. from 1 h prior to addition of pseudoviruses until 6 h after, followed by the set-up where amiodarone was present only during the cell entry phase. In the case of MARV, there was also significant inhibition when the drug was present only before the pseudoparticles were added to the cells. This is suggestive of a cell-directed mechanism of action. However, the effect on the target cells appears to be reversible upon removal of the drug.

![Figure 2](https://academic.oup.com/jac/article-abstract/69/8/2123/2911060)

**Figure 2.** Amiodarone toxicity and concentration–response curves. (a) EAhy cells were transduced with pseudoparticles bearing EBOV (upper panel) or MARV (lower panel) GP in the presence of increasing concentrations of amiodarone. Individual data points represent the mean ± SD of n = 3 independent replicates from a representative of three independent experiments. The IC50 ± SD is indicated. The x-axis indicating the amiodarone concentration has a log scale. (b) EAhy cells stably expressing firefly luciferase were exposed to the indicated concentrations of amiodarone for 6 h. Then drug-containing medium was replaced with fresh medium without the drug. After 72 h, the cells were lysed, luciferase activity was measured and the CC50 was determined. Individual data points represent the mean ± SD of n = 3 independent replicates from a representative of three independent experiments.

![Figure 3](https://academic.oup.com/jac/article-abstract/69/8/2123/2911060)

**Figure 3.** Amiodarone inhibition of authentic EBOV infection. EAhy cells were exposed to purified Zaire Ebola virus in the presence or absence of amiodarone at the indicated concentrations. After 20 h cells were fixed and stained for Ebola NP protein. The percentage of cells infected with authentic EBOV in the absence of drug was set to 100%. Means ± SD from n = 3 independent experiments are shown. Significant inhibition is indicated by asterisks (*P < 0.05, **P < 0.01).
**Amiodarone inhibits filovirus entry**

Moreover, when EBOV pseudovirus was incubated with a high concentration (4.5 µg/mL) of amiodarone and then washed in 100 kDa filter devices in order to remove drug, we observed a subsignificant 52% reduction of infectivity relative to VSV-G pseudoviruses (Figure S2, available as Supplementary data at JAC Online). Next we assessed whether EAhy cells could be adapted to amiodarone by growing them in the presence of 1.5 µg/mL amiodarone for 2 weeks prior to experimentation. Cell growth was largely unaltered and there were no obvious morphological alterations. We observed a comparable degree of inhibition of EBOV and MARV pseudoparticles, suggesting that prolonged exposure to amiodarone does not lead to compensatory changes in the host cell (Figure 5b).

**Effect of amiodarone on filoviral entry into different cell lines and primary cells**

We next evaluated the amiodarone inhibition of cell entry mediated by filoviral GP in a range of different target cells. There was significant inhibition in all cell lines tested, although there appeared to be a trend towards a more pronounced effect on cell lines of endothelial origin compared with epithelial cell lines, with cell lines of fibroblast origin appearing least sensitive (Figure 6). Filoviral GP-mediated entry into primary human umbilical vein endothelial cells and in macrophages derived from primary human monocytes was significantly inhibited at amiodarone concentrations below 1 µg/mL for both MARV and EBOV GP while amiodarone had no effect on the transduction of primary hepatocytes (Figure S3, available as Supplementary data at JAC Online). These cell type-specific differences are also in keeping with a host cell-targeted mechanism of action of amiodarone.

**The multi-channel inhibitor dronedarone as well as some calcium channel inhibitors share the anti-filoviral effect of amiodarone**

Amiodarone inhibits or otherwise modulates a number of cellular targets that include potassium channels, sodium channels, calcium channels and α- and β-adrenergic receptors. We used more specific pharmacological agents to test whether the observed anti-filoviral effect was associated with any of the known pharmacodynamic properties of amiodarone. Dronedarone, a newer drug with a pharmacodynamic profile similar to amiodarone, showed a marked concentration-dependent inhibition of MARV and EBOV GP-bearing pseudoparticles similar to amiodarone (Figure 7a). The L-type calcium channel blocker verapamil similarly inhibited filovirus GP-mediated entry, although higher absolute and molar concentrations were required (Figure 7b). Conversely, the selective T-type calcium channel blocker ethosuximide had no effect. The sodium channel blocker lidocaine, the β₁-selective adrenoreceptor antagonist metoprolol, and the non-selective β-blocker and potassium channel blocker sotalol were also without detectable effects (Figure 7c). Drug concentrations were chosen based on plasma levels reported to be achievable in humans. Relevant toxicity or anti-proliferative effects at the concentrations used were excluded using an EAhy cell line stably expressing a luciferase reporter (Figure S4, available as Supplementary data at JAC Online). Thus, several agents that are either non-specific ion channel inhibitors (amiodarone, dronedarone) or inhibitors of L-type calcium channels (verapamil) inhibit cell entry mediated by filoviral GPs, while other agents possessing some of the other multiple pharmacodynamic effects of amiodarone do not.

**Discussion**

In this paper we describe the identification of amiodarone and other drugs that act as inhibitors of ion channels (dronedarone, verapamil) as inhibitors of filovirus cell entry. We showed that amiodarone at concentrations that are routinely reached in human serum when amiodarone is employed clinically acts as a host cell-targeting agent that blocks viral entry.

In the absence of approved treatments, the management of filoviral haemorrhagic fever is largely limited to supportive care and containment. Mortality is very high in resource-poor settings, and even when modern intensive care is available, treatment is...
Amiodarone (1.5 μg/mL) was present in the cell culture medium 1 h before (Pre) and/or during (During) the 6 h of infection as indicated. Means ± SD of n=6 independent replicates from a representative of two independent experiments are shown. (b) Standard EAhy cells (Std) or EAhy cells that had previously been cultured in the presence of amiodarone (1.5 μg/mL) (Adapt) were transduced with pseudoparticles bearing EBOV or MARV GPs in the presence or absence of amiodarone (1.5 μg/mL). Means ± SD of n=4 independent replicates from a representative of two independent experiments are shown. Significant inhibition is indicated by asterisks (*P < 0.05, **P < 0.01).

Figure 5. Effect of target cell pre-treatment. (a) EAhy cells were transduced with pseudoparticles bearing EBOV or MARV GPs. Amiodarone (1.5 μg/mL) was present in the cell culture medium 1 h before (Pre) and/or during (During) the 6 h of infection as indicated. Means ± SD of n=6 independent replicates from a representative of two independent experiments are shown. Significant inhibition is indicated by asterisks (*P < 0.05, **P < 0.01).
properties. Amiodarone is a pleiotropic drug known to target potassium channels, sodium channels, calcium channels, and α- and β-adrenergic receptors. When testing other agents with a narrower range of molecular target, only the L-type calcium channel blocker verapamil exhibited an anti-filoviral effect. These findings may suggest a role for calcium currents in filoviral entry. While their role is more obvious in excitable tissues such as muscle and neuronal cells, L-type calcium channels are also present in many non-excitable cells including endothelial and epithelial cells. Calcium fluxes can cause rapid shifts in intracellular calcium levels and are an important part of cellular signalling processes, most notably maybe the phospholipase C/1,4,5-inositol

![Figure 6. Amiodarone inhibition of EBOV GP-mediated entry into different cell types. The indicated cell lines were transduced with pseudoparticles bearing EBOV GP in the presence or absence of amiodarone. Values are normalized to absence of the drug and to the signal detected with VSV-G in order to control for effects on cell proliferation. Means ± SD of n = 3 independent replicates from a representative of two independent experiments are shown. Significant inhibition is indicated by asterisks (*P < 0.05, **P < 0.01).](image)

![Figure 7. Effect of specific ion channel blockers on filoviral entry. (a) EAhy cells were transduced with EBOV (upper panels) or MARV (lower panels) pseudoparticles in the presence of the indicated concentrations of dronedarone. Individual data points represent the mean ± SD of n = 3 independent replicates from a representative of three independent experiments. (b) Transduction in the presence of calcium channel blockers. For each drug, a lower and a higher concentration was used as follows: ethosuximide, 100 and 300 μg/mL; verapamil, 20 and 60 μg/mL. Individual data points represent the mean ± SD of n = 3 independent replicates from a representative of three independent experiments. (c) Transduction in the presence of the sodium channel blocker lidocaine (5 and 15 μg/mL), the β-receptor blocker metoprolol (0.2 and 0.6 μg/mL) and the potassium channel blocker/β-receptor blocker sotalol (3 and 9 μg/mL). Individual data points represent the mean ± SD of n = 3 independent replicates from a representative of three independent experiments.](image)
trisphosphate/diacylglycerol pathway. Thus, interference with the calcium-mediated cell signalling events required for the orchestration of filoviral entry is another plausible mechanism. Interestingly, it has very recently been reported that gabapentin, verapamil and other inhibitors of voltage-gated calcium channels, as well as the siRNA-mediated knockdown of calcium channel subunits, inhibit infection by the New World arenavirus Junin.

Ongoing work aims to test these hypotheses and determine the exact mechanism of filovirus inhibition by amiodarone and other anti-arrhythmic agents. The work presented here shows that a limited-scale screening of drugs with a known safety profile in humans can reveal novel antiviral properties that may be useful in addressing rare yet severe infections for which drug discovery programmes will likely not be initiated. The chances of identifying potentially useful agents may be best for viruses that employ complex cell entry routes such as filoviruses. The discovery of such unexpected antiviral properties in known drugs with cellular targets may at the same time offer novel insights into the molecular mechanisms of the virus-host interaction and new therapeutic approaches.

Acknowledgements
We thank Hyeryun Choe, Francois-Loic Cosset, Jay Hooper, Stefan Kunz, Gary Noble, Charles Rice and Anthony Sanchez for providing reagents and Sandra Westhaus for help with data analysis.

Funding
This work was supported by an ‘Emmy Noether’ Fellowship from Deutsche Forschungsgemeinschaft to T. V. H. (HA4394/2-1).

Transparency declarations
The authors declare that they have no conflicts of interest relevant to this work.

Supplementary data
Figures S1 to S4 are available as Supplementary data at JAC Online (http://jac.oxfordjournals.org/).

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