Short Communication

Cyclosporin A inhibits the replication of diverse coronaviruses

Adriaan H. de Wilde,[1] Jessika C. Zevenhoven-Dobbe,[1] Yvonne van der Meer,[1] Volker Thiel,[2,3] Krishna Narayanan,[4] Shinji Makino,[4] Eric J. Snijder[1] and Martijn J. van Hemert[1]

Correspondence
Martijn J. van Hemert
m.j.van_hemert@lumc.nl

[1]Molecular Virology Laboratory, Department of Medical Microbiology, Center of Infectious Diseases, Leiden University Medical Center, Leiden, The Netherlands

[2]Institute of Immunobiology, Kantonal Hospital St Gallen, St Gallen, Switzerland

[3]Vetsuisse Faculty, University of Zürich, Zürich, Switzerland

[4]Department of Microbiology and Immunology, University of Texas Medical Branch, Galveston, Texas, USA

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Low micromolar, non-cytotoxic concentrations of cyclosporin A (CsA) strongly affected the replication of severe acute respiratory syndrome coronavirus (SARS-CoV), human coronavirus 229E and mouse hepatitis virus in cell culture, as was evident from the strong inhibition of GFP reporter gene expression and a reduction of up to 4 logs in progeny titres. Upon high-multiplicity infection, CsA treatment rendered SARS-CoV RNA and protein synthesis almost undetectable, suggesting an early block in replication. siRNA-mediated knockdown of the expression of the prominent CsA targets cyclophilin A and B did not affect SARS-CoV replication, suggesting either that these specific cyclophilin family members are dispensable or that the reduced expression levels suffice to support replication.

The 2003 outbreak of severe acute respiratory syndrome (SARS) sparked a renewed interest in coronaviruses, a group of positive-strand RNA viruses that can cause respiratory or gastrointestinal disease in humans and livestock (reviewed by Perlman & Netland, 2009). Several inhibitors of coronavirus enzymes (reviewed by Tong, 2009) and compounds that inhibit replication in cell culture have been described (Kono *et al.*, 2008; te Velthuis *et al.*, 2010b; Vincent *et al.*, 2005), but effective treatment for coronavirus infections is currently unavailable (Stockman *et al.*, 2006). An inherent risk of the use of inhibitors directed against viral functions is the development of antiviral resistance, owing to the rapid adaptive evolution of RNA viruses. Coronavirus replication relies on a variety of host factors (de Haan & Rottier, 2006; Vogels *et al.*, 2011; Zhang *et al.*, 2010), which also constitute potentially interesting targets for antiviral therapy, as resistance is less likely to develop when host factors are targeted instead of viral proteins.

While aiming to identify host factors involved in SARS-coronavirus (SARS-CoV) replication, we established that the drug cyclosporin A (CsA) inhibited coronavirus replication. CsA affects the function of many members of the cyclophilin family, which consists of peptidyl-prolyl isomerases that act as chaperones and facilitate protein folding (reviewed by Davis *et al.*, 2010). CsA was previously reported to inhibit the replication of human immunodeficiency virus (Briggs *et al.*, 1999), vesicular stomatitis virus (VSV; Bose *et al.*, 2003), hepatitis C virus (HCV; Nakagawa *et al.*, 2004, 2005; Watashi *et al.*, 2003) and other flaviviruses (Kambara *et al.*, 2011; Qing *et al.*, 2009).

Initially, by using GFP-expressing recombinant coronaviruses, we investigated the effect of CsA on the replication of representatives of different coronavirus genera: human coronavirus 229E (HCoV-229E), mouse hepatitis virus (MHV) and SARS-CoV. In order to rigorously evaluate the inhibitory potential of the drug, each of these viruses was tested in single-cycle, high-m.o.i. experiments, in which the drug was added upon removal of the inoculum at 1 h post-infection (p.i.). Experiments were performed in a 96-well plate format and GFP expression was quantified by using a Berthold Mithras plate reader. When using SARS-CoV-GFP (Sims *et al.*, 2008) and Vero E6 cells (m.o.i. of 10), a CsA dose range of 0 to 64 μM was used and cells were fixed at 18 h p.i. CsA inhibited SARS-CoV–GFP replication in a dose-dependent manner, with GFP expression becoming undetectable upon treatment with 16 μM CsA (Fig. 1a, upper panel). Cell viability was not affected at any of the CsA concentrations tested (Fig. 1a, lower panel). To confirm that CsA also inhibits SARS-CoV replication in human cells, the experiment was repeated using 293/ACE2 cells, which stably express the SARS-CoV receptor ACE2

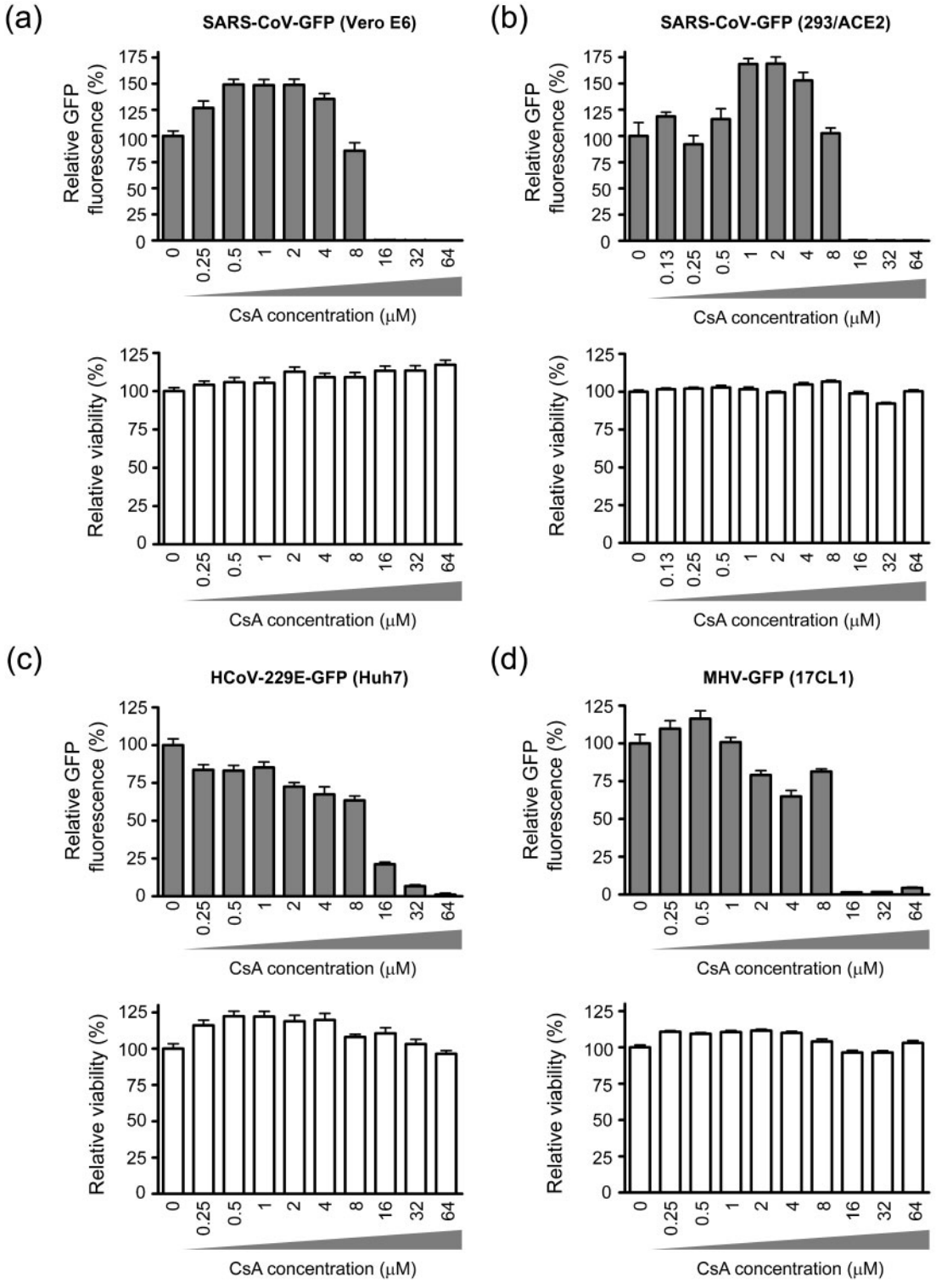

Fig. 1. CsA inhibits the replication of GFP-expressing recombinant coronaviruses. Vero E6 cells (a) or 293/ACE2 cells (b) were infected with SARS-CoV–GFP at an m.o.i. of 10 and at 1 h p.i. the inoculum was replaced by medium containing different CsA concentrations. Cells were fixed at 18 h p.i. and GFP reporter expression was measured and normalized to the signal in control cells (100 %), which were treated with DMSO, the solvent used for CsA (upper panels, grey bars). Huh7 cells infected with HCoV-229E–GFP were treated with CsA from 1 h p.i. onwards and were fixed for GFP measurements at 24 h p.i. (c, upper panel). 17CL1 cells were infected with MHV–GFP, treated with CsA from 1 to 18 h p.i., and GFP fluorescence was quantified (d, upper panel). The effect of CsA treatment on the viability of the various cell lines used, compared with untreated control cells (a–d, lower panels) was determined by using a CellTiter 96 AQ_{ueous} MTS assay (Promega). Graphs show the results (mean and SD) of a representative quadruplicate experiment. All experiments were repeated at least twice.

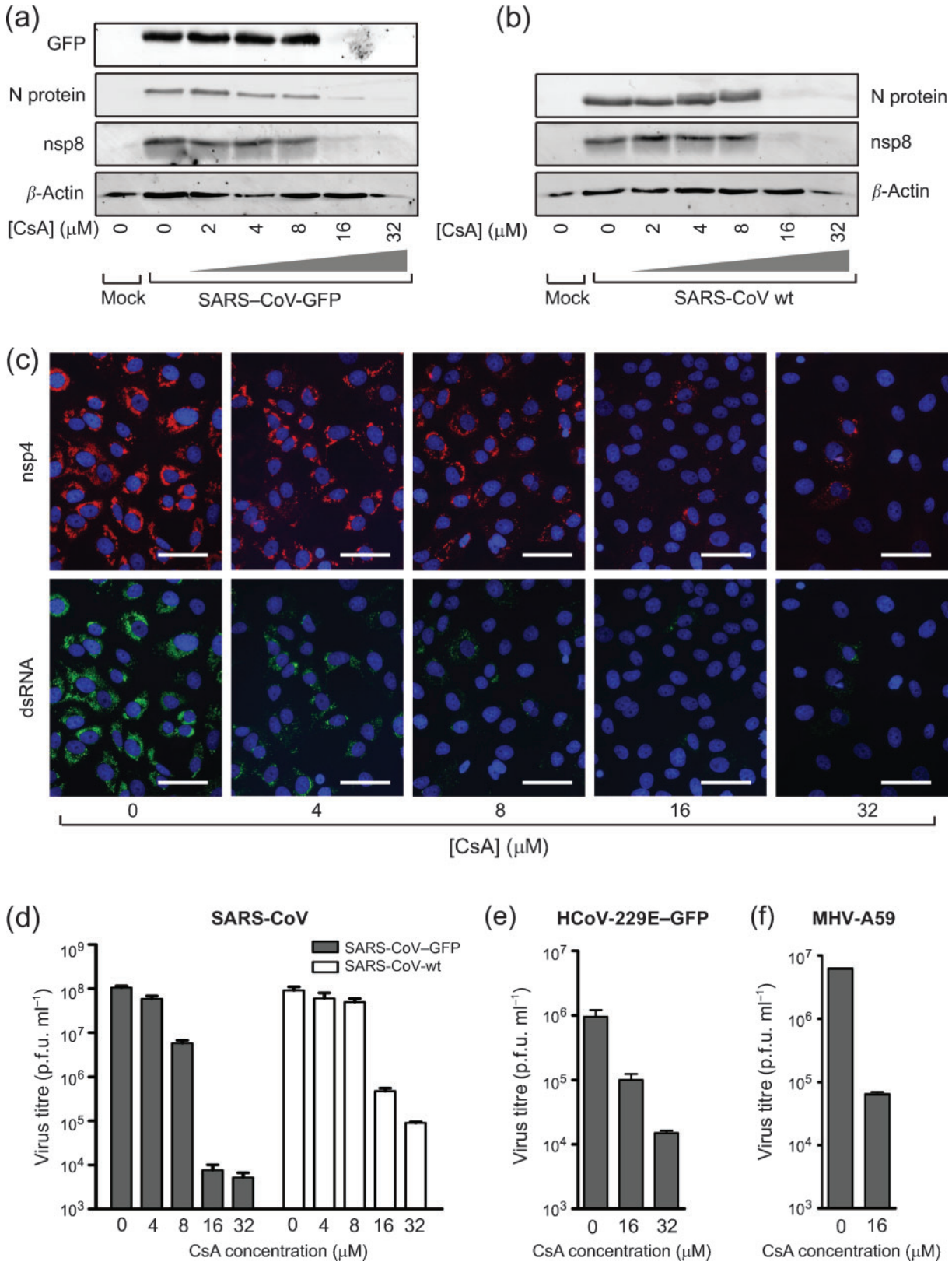
(a)
GFP
N protein
nsp8
β-Actin
[CsA] (μM)
0
0
2
4
8
16
32
Mock
SARS–CoV-GFP
(b)
N protein
nsp8
β-Actin
[CsA] (μM)
0
0
2
4
8
16
32
Mock
SARS-CoV wt
(c)
nsp4
dsRNA
0
4
8
16
32
[CsA] (μM)
(d)
SARS-CoV
SARS-CoV–GFP
SARS-CoV-wt
Virus titre (p.f.u. ml−1)
CsA concentration (μM)
(e)
HCoV-229E–GFP
Virus titre (p.f.u. ml−1)
CsA concentration (μM)
(f)
MHV-A59
Virus titre (p.f.u. ml−1)
CsA concentration (μM)

Fig. 2. CsA treatment inhibits coronavirus protein and RNA synthesis, and the production of infectious progeny. Vero E6 cells were infected with SARS-CoV–GFP (a) or wt SARS-CoV (b) and treated with CsA from 1 to 10 h p.i. Viral protein expression was analysed by Western blotting using polyclonal rabbit antisera against nsp8 (van Hemert *et al.*, 2008), the N protein (Knoops *et al.*, 2010) and GFP, as indicated next to the panels. β-Actin, detected with a rabbit antiserum (Sigma), was used as loading control. (c) Immunofluorescence analysis of Vero E6 cells infected with SARS-CoV (m.o.i. 10) and treated from 1 to 10 h p.i. with the CsA concentration indicated below each panel. Cells were stained with an anti-SARS-CoV nsp4 rabbit antiserum (upper panel; van Hemert *et al.*, 2008) or an anti-dsRNA mAb (lower panel; Knoops *et al.*, (2008)). Bar, 50 μm. (d) Vero E6 cells infected with SARS-CoV–GFP (grey bars) or wt SARS-CoV (white bars) were treated with various concentrations of CsA from 1 h p.i. onwards, and virus titres in the culture supernatant were determined at 16 h p.i. by plaque assay on Vero E6 cells. Huh7 cells infected with HCoV-229E–GFP (e) or 17CL1 cells infected with MHV-A59 (f) were treated with CsA from 1 h p.i. onwards, and infectious-progeny titres were determined at 30 h p.i. and 8 h p.i., respectively. The graphs show the mean of two independent duplicate experiments.

(Kamitani *et al.*, 2006). Indeed, in these cells, CsA inhibited SARS-CoV–GFP replication to the same extent as in Vero E6 cells (Fig. 1b).

To investigate whether CsA also inhibits the replication of other coronaviruses, Huh7 cells infected with HCoV-229E-GFP (Cervantes-Barragan *et al.*, 2010) and 17CL1 cells infected with MHV–GFP (Das Sarma *et al.*, 2002) were treated with CsA at 1 h p.i. and GFP expression was quantified at 24 and 18 h p.i., respectively (Fig. 1c, d, upper panels). As in the case of SARS-CoV–GFP, MHV–GFP replication was strongly inhibited by 16 μM CsA. HCoV-229E–GFP appeared to be somewhat less sensitive, as complete inhibition of GFP expression required 32 μM CsA (Fig. 1c). The viability of 17CL1 and Huh7 cells was not affected by the CsA concentrations used (Fig. 1c, d, lower panels). It should be noted that SARS-CoV replication appeared to be somewhat enhanced by low doses of CsA ($\leqslant$4 μM).

Western blot analysis of SARS-CoV–GFP-infected Vero E6 cells that were treated with 0 to 32 μM CsA from 1 to 10 h p.i. showed that expression of SARS-CoV non-structural protein (nsp) 8, nucleocapsid (N) protein and GFP was strongly reduced in cells treated with 16 μM CsA (Fig. 2a). This suggested that CsA treatment strongly inhibited an early step in the SARS-CoV replicative cycle. To verify the inhibitory effect of CsA with wild-type (wt) SARS-CoV, we repeated the experiments using the Frankfurt-1 isolate (Fig. 2b) and found that the expression of nsp8 and N protein was barely detectable upon treatment with 16 μM CsA. At lower CsA concentrations, little effect on viral protein synthesis was observed, indicating that the replication of recombinant and wt SARS-CoV is equally sensitive to CsA treatment. The steep dose–response curve, showing a strong reduction in SARS-CoV replication between 8 and 16 μM CsA, is in line with the observations made for several other positive-strand RNA viruses, such as HCV (Ishii *et al.*, 2006; Nakagawa *et al.*, 2004; Watashi *et al.*, 2003).

The conclusions from the Western blot studies were further substantiated by immunofluorescence labelling of nsp4 and dsRNA in SARS-CoV-infected cells, as markers for viral protein and RNA synthesis, respectively (Fig. 2c). Hardly any nsp4 or dsRNA was detectable upon treatment with 16 μM CsA and the immunolabelling for these markers was visibly reduced when 8 or 4 μM CsA was given. Remarkably, approximately 1–5 % of the infected cells remained SARS-CoV positive by immunofluorescence analysis, even at CsA concentrations of up to 64 μM, suggesting that they were somehow insensitive to CsA treatment and remained capable of supporting a certain level of SARS-CoV replication. Compared with untreated cells, the signals for nsp4 and dsRNA were clearly reduced in these cells, although – probably due to the relatively high avidity of the antibodies used – the N protein remained readily detectable (data not shown), thus suggesting that SARS-CoV replication was indeed impaired, although not fully blocked.

To assess whether CsA treatment also affected the production of infectious progeny, virus titres were determined for supernatants harvested at 16 h p.i. from CsA-treated Vero E6 cultures infected with wt SARS-CoV or SARS-CoV–GFP (Fig. 2d). CsA dramatically reduced progeny titres, with a 16 μM CsA dose resulting in approximately 4- and 3-log reductions for SARS-CoV–GFP and wt SARS-CoV, respectively. These data correlate well with the barely detectable expression of GFP, nsp4, nsp8 and N protein after treatment with 16 μM CsA (Figs 1a and 2a–c). The 3–4 log reduction in progeny titre also suggested that the low percentage of cells that remained SARS-CoV positive by immunofluorescence assay upon treatment with 16 μM CsA produced reduced levels of infectious progeny. CsA also affected HCoV-229E–GFP titres (Fig. 2e), although a 32 μM CsA concentration was required to achieve a 2-log reduction. Progeny titres of MHV, the most rapidly replicating of the three coronaviruses tested, were also reduced by 2 logs upon treatment with 16 μM CsA (Fig. 2f). Also, as observed for SARS-CoV-infected cells, a subpopulation of the HCoV-229E-infected Huh7 and MHV-infected 17CL1 cells appeared to be resistant to CsA treatment.

CsA inhibits the peptidyl-prolyl isomerase activity of several members of the cyclophilin family (Davis *et al.*, 2010). Specifically, cyclophilin A (CypA) (Bose *et al.*, 2003; Kaul *et al.*, 2009; Liu *et al.*, 2009; Manel *et al.*, 2010) and cyclophilin B (CypB) (Kambara *et al.*, 2011; Watashi *et al.*, 2005) have been reported to enhance the replication of several viruses. Furthermore, CypA was identified as an

interaction partner of the SARS-CoV N protein (Luo *et al.*, 2004). CsA might exert its inhibitory effect on coronavirus replication by inhibiting cyclophilin function or, alternatively, by direct inhibition of a virus-specific function. A direct inhibitory effect on the activity of the SARS-CoV nsp12 RNA-dependent RNA polymerase was excluded by using an *in vitro* assay and recombinant nsp12 (data not shown; te Velthuis *et al.*, 2010a). We next analysed the effect of siRNA-mediated knock-down of cellular CypA and CypB expression (for 48 h) on the replication of SARS-CoV–GFP in 293/ACE2 cells. Western blot analysis of cells transfected with siRNAs targeting CypA and CypB confirmed that protein levels were significantly reduced, to approximately 25 % of the original level (Fig. 3a). Depletion of CypA or CypB did not affect cell viability (Fig. 3b), but also did not significantly inhibit the replication of SARS-CoV–GFP in 293/ACE2 cells, compared with infected cells transfected with a non-targeting control siRNA (Fig. 3c). These data suggest that these specific cyclophilins, which have been implicated in the replication of other viruses, are not required for SARS-CoV replication. Alternatively, the remaining cyclophilin levels in siRNA-treated cells may suffice to support normal virus replication.

In conclusion, CsA inhibits the replication of diverse coronaviruses at non-cytotoxic, low-micromolar concentrations. Treatment of infected cells with 16 μM CsA strongly reduced viral and reporter gene expression of SARS-CoV–GFP, the amount of dsRNA in infected cells and the virus titre in culture supernatants (by >3 logs). In cells infected with HCoV-229E–GFP and MHV–GFP, reporter gene expression and the production of infectious progeny were also significantly decreased upon CsA treatment. Compared with other RNA viruses (Briggs *et al.*, 1999; Kambara *et al.*, 2011; Nakagawa *et al.*, 2004; Paeshuyse *et al.*, 2006; Watashi *et al.*, 2003), somewhat higher CsA concentrations were required to block coronavirus replication (16 versus 0.5–3 μM), suggesting that coronaviruses are less sensitive to CsA treatment. However, we cannot exclude that this may be in part due to differences in experimental set-up, including the cells and high m.o.i. used, and whether or not cells were pretreated with CsA (Ishii *et al.*, 2006; Liu *et al.*, 2009; Qing *et al.*, 2009).

The inhibitory effect of CsA and its analogues and the role of cyclophilins in virus replication have been studied in considerable detail for HCV and several other RNA viruses. In the case of HCV, cyclophilin inhibitors lacking the undesirable immunosuppressive properties of CsA – NIM811, Debio-025 and SCY-635 – are currently being tested in clinical trials (Flisiak *et al.*, 2008, 2009; Lawitz *et al.*, 2011). Several mechanism-of-action studies on the

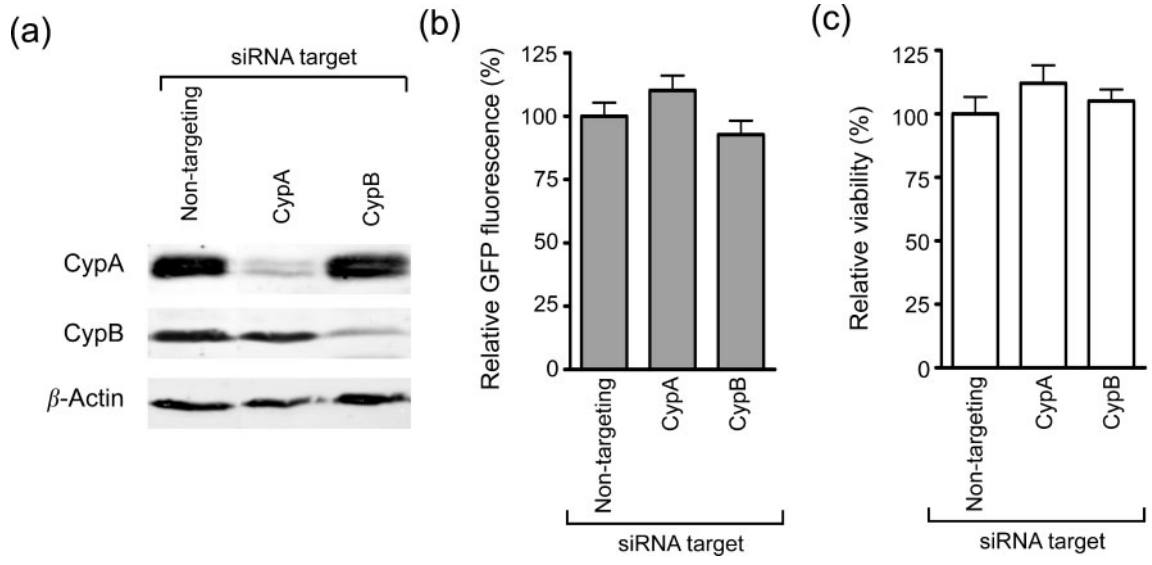

Fig. 3. SARS-CoV–GFP replication in Cyclophilin A- or B-depleted cells. By using DharmaFECT1 (Dharmacon), 293/ACE2 cells were transfected with siRNAs (ON-Target PLUS pools; Dharmacon) targeting CypA and CypB mRNAs. Non-targeting siRNA and siRNA targeting GAPDH expression were used as negative and positive controls for transfection and depletion efficiency, respectively. (a) Expression levels of CypA (upper panel) and CypB (middle panel), in cells transfected with the siRNA pools indicated below the lanes, were analysed by Western blotting by using specific antisera (Abcam). β-Actin, detected with a rabbit antiserum (Sigma), was used as a loading control. (b) The viability of cells transfected with the various siRNAs was monitored by using a CellTiter 96 AQ_{ueous} MTS assay (Promega). Data were normalized to the mean MTS assay value of cells transfected with non-targeting control siRNAs (100 %). (c) Forty-eight hours after siRNA transfection, cells were infected with SARS-CoV–GFP and 24 h later cells were fixed and GFP fluorescence was quantified. The level of GFP expression was normalized to that in infected cells transfected with non-targeting siRNA.

inhibitory effect of CsA identified mainly CypA and CypB as being involved in virus replication. CypA was found to interact with HCV NS2 (Ciesek *et al.*, 2009), NS5A (Chatterji *et al.*, 2010; Coelmont *et al.*, 2010; Fernandes *et al.*, 2010) and NS5B (Chatterji *et al.*, 2009), and was shown to be required for HCV replication. Furthermore, CypA was found to interact functionally with West Nile virus NS5 (Qing *et al.*, 2009) and VSV N protein (Bose *et al.*, 2003). In addition, an interaction between CypB and Japanese encephalitis virus NS4A (Kambara *et al.*, 2011) was documented, and CypB also appears to be a functional regulator of the HCV polymerase (Watashi *et al.*, 2005). Also Cyp-40 was found to play a role in HCV replication (Gaither *et al.*, 2010; Goto *et al.*, 2009).

Although the exact mechanism by which CsA inhibits coronavirus replication remains to be established, it is likely that the drug also interferes with functional interactions between viral proteins and one or multiple members of the large cyclophilin family. If this indeed proves to be true, it will be interesting to explore the potential of these host proteins for the development of a coronavirus-wide antiviral strategy.

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References

Bose, S., Mathur, M., Bates, P., Joshi, N. & Banerjee, A. K. (2003). Requirement for cyclophilin A for the replication of vesicular stomatitis virus New Jersey serotype. *J Gen Virol* **84**, 1687–1699.

Briggs, C. J., Ott, D. E., Coren, L. V., Oroszlan, S. & Tözsér, J. (1999). Comparison of the effect of FK506 and cyclosporin A on virus production in H9 cells chronically and newly infected by HIV-1. *Arch Virol* **144**, 2151–2160.

Cervantes-Barragan, L., Züst, R., Maier, R., Sierro, S., Janda, J., Levy, F., Speiser, D., Romero, P., Rohrlich, P. S. & other authors (2010). Dendritic cell-specific antigen delivery by coronavirus vaccine vectors induces long-lasting protective antiviral and antitumor immunity. *MBio* **1**, e00171–e00110.

Chatterji, U., Bobardt, M., Selvarajah, S., Yang, F., Tang, H., Sakamoto, N., Vuagniaux, G., Parkinson, T. & Gallay, P. (2009). The isomerase active site of cyclophilin A is critical for hepatitis C virus replication. *J Biol Chem* **284**, 16998–17005.

Chatterji, U., Lim, P., Bobardt, M. D., Wieland, S., Cordek, D. G., Vuagniaux, G., Chisari, F., Cameron, C. E., Targett-Adams, P. & other authors (2010). HCV resistance to cyclosporin A does not correlate with a resistance of the NS5A-cyclophilin A interaction to cyclophilin inhibitors. *J Hepatol* **53**, 50–56.

Ciesek, S., Steinmann, E., Wedemeyer, H., Manns, M. P., Neyts, J., Tautz, N., Madan, V., Bartenschlager, R., von Hahn, T. & Pietschmann, T. (2009). Cyclosporine A inhibits hepatitis C virus nonstructural protein 2 through cyclophilin A. *Hepatology* **50**, 1638–1645.

Coelmont, L., Hanoulle, X., Chatterji, U., Berger, C., Snoeck, J., Bobardt, M., Lim, P., Vliegen, I., Paeshuyse, J. & other authors (2010). DEB025 (Alisporivir) inhibits hepatitis C virus replication by preventing a cyclophilin A induced *cis–trans* isomerisation in domain II of NS5A. *PLoS ONE* **5**, e13687.

Das Sarma, J., Scheen, E., Seo, S. H., Koval, M. & Weiss, S. R. (2002). Enhanced green fluorescent protein expression may be used to monitor murine coronavirus spread *in vitro* and in the mouse central nervous system. *J Neurovirol* **8**, 381–391.

Davis, T. L., Walker, J. R., Campagna-Slater, V., Finerty, P. J., Paramanathan, R., Bernstein, G., MacKenzie, F., Tempel, W., Ouyang, H. & other authors (2010). Structural and biochemical characterization of the human cyclophilin family of peptidyl-prolyl isomerases. *PLoS Biol* **8**, e1000439.

de Haan, C. A. & Rottier, P. J. (2006). Hosting the severe acute respiratory syndrome coronavirus: specific cell factors required for infection. *Cell Microbiol* **8**, 1211–1218.

Fernandes, F., Ansari, I. U. & Striker, R. (2010). Cyclosporine inhibits a direct interaction between cyclophilins and hepatitis C NS5A. *PLoS ONE* **5**, e9815.

Flisiak, R., Horban, A., Gallay, P., Bobardt, M., Selvarajah, S., Wiercinska-Drapalo, A., Siwak, E., Cielniak, I., Higersberger, J. & other authors (2008). The cyclophilin inhibitor Debio-025 shows potent anti-hepatitis C effect in patients coinfected with hepatitis C and human immunodeficiency virus. *Hepatology* **47**, 817–826.

Flisiak, R., Feinman, S. V., Jablkowski, M., Horban, A., Kryczka, W., Pawlowska, M., Heathcote, J. E., Mazzella, G., Vandelli, C. & other authors (2009). The cyclophilin inhibitor Debio 025 combined with PEG IFNα2a significantly reduces viral load in treatment-naïve hepatitis C patients. *Hepatology* **49**, 1460–1468.

Gaither, L. A., Borawski, J., Anderson, L. J., Balabanis, K. A., Devay, P., Joberty, G., Rau, C., Schirle, M., Bouwmeester, T. & Mickanin, C. (2010). Multiple cyclophilins involved in different cellular pathways mediate HCV replication. *Virology* **397**, 43–55.

Goto, K., Watashi, K., Inoue, D., Hijikata, M. & Shimotohno, K. (2009). Identification of cellular and viral factors related to anti-hepatitis C virus activity of cyclophilin inhibitor. *Cancer Sci* **100**, 1943–1950.

Ishii, N., Watashi, K., Hishiki, T., Goto, K., Inoue, D., Hijikata, M., Wakita, T., Kato, N. & Shimotohno, K. (2006). Diverse effects of cyclosporine on hepatitis C virus strain replication. *J Virol* **80**, 4510–4520.

Kambara, H., Tani, H., Mori, Y., Abe, T., Katoh, H., Fukuhara, T., Taguwa, S., Moriishi, K. & Matsuura, Y. (2011). Involvement of cyclophilin B in the replication of Japanese encephalitis virus. *Virology* **412**, 211–219.

Kamitani, W., Narayanan, K., Huang, C., Lokugamage, K., Ikegami, T., Ito, N., Kubo, H. & Makino, S. (2006). Severe acute respiratory syndrome coronavirus nsp1 protein suppresses host gene expression by promoting host mRNA degradation. *Proc Natl Acad Sci U S A* **103**, 12885–12890.

Kaul, A., Stauffer, S., Berger, C., Pertel, T., Schmitt, J., Kallis, S., Zayas, M., Lohmann, V., Luban, J. & Bartenschlager, R. (2009). Essential role of cyclophilin A for hepatitis C virus replication and virus production and possible link to polyprotein cleavage kinetics. *PLoS Pathog* **5**, e1000546.

Knoops, K., Kikkert, M., Worm, S. H., Zevenhoven-Dobbe, J. C., van der Meer, Y., Koster, A. J., Mommaas, A. M. & Snijder, E. J. (2008). SARS-coronavirus replication is supported by a reticulovesicular network of modified endoplasmic reticulum. *PLoS Biol* **6**, e226.

Knoops, K., Swett-Tapia, C., van den Worm, S. H., Te Velthuis, A. J., Koster, A. J., Mommaas, A. M., Snijder, E. J. & Kikkert, M. (2010). Integrity of the early secretory pathway promotes, but is not required for, severe acute respiratory syndrome coronavirus RNA synthesis and virus-induced remodeling of endoplasmic reticulum membranes. *J Virol* **84**, 833–846.

Kono, M., Tatsumi, K., Imai, A. M., Saito, K., Kuriyama, T. & Shirasawa, H. (2008). Inhibition of human coronavirus 229E infection in human epithelial lung cells (L132) by chloroquine: involvement of p38 MAPK and ERK. *Antiviral Res* **77**, 150–152.

Lawitz, E., Godofsky, E., Rouzier, R., Marbury, T., Nguyen, T., Ke, J., Huang, M., Praestgaard, J., Serra, D. & Evans, T. G. (2011). Safety, pharmacokinetics, and antiviral activity of the cyclophilin inhibitor NIM811 alone or in combination with pegylated interferon in HCV-infected patients receiving 14 days of therapy. *Antiviral Res* **89**, 238–245.

Liu, Z., Yang, F., Robotham, J. M. & Tang, H. (2009). Critical role of cyclophilin A and its prolyl-peptidyl isomerase activity in the structure and function of the hepatitis C virus replication complex. *J Virol* **83**, 6554–6565.

Luo, C., Luo, H., Zheng, S., Gui, C., Yue, L., Yu, C., Sun, T., He, P., Chen, J. & Shen, J. (2004). Nucleocapsid protein of SARS coronavirus tightly binds to human cyclophilin A. *Biochem Biophys Res Commun* **321**, 557–565.

Manel, N., Hogstad, B., Wang, Y., Levy, D. E., Unutmaz, D. & Littman, D. R. (2010). A cryptic sensor for HIV-1 activates antiviral innate immunity in dendritic cells. *Nature* **467**, 214–217.

Nakagawa, M., Sakamoto, N., Enomoto, N., Tanabe, Y., Kanazawa, N., Koyama, T., Kurosaki, M., Maekawa, S., Yamashiro, T. & Chen, C.-H. (2004). Specific inhibition of hepatitis C virus replication by cyclosporin A. *Biochem Biophys Res Commun* **313**, 42–47.

Nakagawa, M., Sakamoto, N., Tanabe, Y., Koyama, T., Itsui, Y., Takeda, Y., Chen, C. H., Kakinuma, S., Oooka, S. & other authors (2005). Suppression of hepatitis C virus replication by cyclosporin a is mediated by blockade of cyclophilins. *Gastroenterology* **129**, 1031–1041.

Paeshuyse, J., Kaul, A., De Clercq, E., Rosenwirth, B., Dumont, J. M., Scalfaro, P., Bartenschlager, R. & Neyts, J. (2006). The non-immunosuppressive cyclosporin DEBIO-025 is a potent inhibitor of hepatitis C virus replication *in vitro*. *Hepatology* **43**, 761–770.

Perlman, S. & Netland, J. (2009). Coronaviruses post-SARS: update on replication and pathogenesis. *Nat Rev Microbiol* **7**, 439–450.

Qing, M., Yang, F., Zhang, B., Zou, G., Robida, J. M., Yuan, Z., Tang, H. & Shi, P. Y. (2009). Cyclosporine inhibits flavivirus replication through blocking the interaction between host cyclophilins and viral NS5 protein. *Antimicrob Agents Chemother* **53**, 3226–3235.

Sims, A. C., Burkett, S. E., Yount, B. & Pickles, R. J. (2008). SARS-CoV replication and pathogenesis in an *in vitro* model of the human conducting airway epithelium. *Virus Res* **133**, 33–44.

Stockman, L. J., Bellamy, R. & Garner, P. (2006). SARS: systematic review of treatment effects. *PLoS Med* **3**, e343.

te Velthuis, A. J., Arnold, J. J., Cameron, C. E., van den Worm, S. H. & Snijder, E. J. (2010a). The RNA polymerase activity of SARS-coronavirus nsp12 is primer dependent. *Nucleic Acids Res* **38**, 203–214.

te Velthuis, A. J., van den Worm, S. H., Sims, A. C., Baric, R. S., Snijder, E. J. & van Hemert, M. J. (2010b). Zn^{2+} inhibits coronavirus and arterivirus RNA polymerase activity *in vitro* and zinc ionophores block the replication of these viruses in cell culture. *PLoS Pathog* **6**, e1001176.

Tong, T. R. (2009). Drug targets in severe acute respiratory syndrome (SARS) virus and other coronavirus infections. *Infect Disord Drug Targets* **9**, 223–245.

van Hemert, M. J., van den Worm, S. H., Knoops, K., Mommaas, A. M., Gorbalenya, A. E. & Snijder, E. J. (2008). SARS-coronavirus replication/transcription complexes are membrane-protected and need a host factor for activity *in vitro*. *PLoS Pathog* **4**, e1000054.

Vincent, M. J., Bergeron, E., Benjannet, S., Erickson, B. R., Rollin, P. E., Ksiazek, T. G., Seidah, N. G. & Nichol, S. T. (2005). Chloroquine is a potent inhibitor of SARS coronavirus infection and spread. *Virol J* **2**, 69.

Vogels, M. W., van Balkom, B. W., Kaloyanova, D. V., Batenburg, J. J., Heck, A. J., Helms, J. B., Rottier, P. J. & de Haan, C. A. (2011). Identification of host factors involved in coronavirus replication by quantitative proteomics analysis. *Proteomics* **11**, 64–80.

Watashi, K., Hijikata, M., Hosaka, M., Yamaji, M. & Shimotohno, K. (2003). Cyclosporin A suppresses replication of hepatitis C virus genome in cultured hepatocytes. *Hepatology* **38**, 1282–1288.

Watashi, K., Ishii, N., Hijikata, M., Inoue, D., Murata, T., Miyanari, Y. & Shimotohno, K. (2005). Cyclophilin B is a functional regulator of hepatitis C virus RNA polymerase. *Mol Cell* **19**, 111–122.

Zhang, L., Zhang, Z. P., Zhang, X. E., Lin, F. S. & Ge, F. (2010). Quantitative proteomics analysis reveals BAG3 as a potential target to suppress severe acute respiratory syndrome coronavirus replication. *J Virol* **84**, 6050–6059.