Broad-spectrum antivirals for the emerging Middle East respiratory syndrome coronavirus

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Accepted 27 September 2013
Available online 3 October 2013

KEYWORDS
Coronavirus; Middle East; Mycophenolic acid; Interferon; Ribavirin; Antiviral

Summary  Objectives: Middle East respiratory syndrome coronavirus (MERS-CoV) has emerged to cause fatal infections in patients in the Middle East and traveler-associated secondary cases in Europe and Africa. Person-to-person transmission is evident in outbreaks involving household and hospital contacts. Effective antivirals are urgently needed.

Methods: We used small compound-based forward chemical genetics to screen a chemical library of 1280 known drugs against influenza A virus in Biosafety Level-2 laboratory. We then assessed the anti-MERS-CoV activities of the identified compounds and of interferons, nelfinavir, and lopinavir because of their reported anti-coronavirus activities in terms of cytopathic effect inhibition, viral yield reduction, and plaque reduction assays in Biosafety Level-3 laboratory.

Results: Ten compounds were identified as primary hits in high-throughput screening. Only mycophenolic acid exhibited low EC\textsubscript{50} and high selectivity index. Additionally, ribavirin and interferons also exhibited in-vitro anti-MERS-CoV activity. The serum concentrations achievable at therapeutic doses of mycophenolic acid and interferon-\textbeta 1b were 60–300 and 3–4 times higher than the concentrations at which in-vitro anti-MERS-CoV activities were demonstrated, whereas...
Introduction

A novel lineage C betacoronavirus, previously known as human coronavirus EMC/2012 and later renamed as Middle East respiratory syndrome coronavirus (MERS-CoV), has emerged in the Arabian Peninsula since April 2012 to cause a "severe acute respiratory syndrome (SARS)-like" disease in 136 laboratory-confirmed cases with 58 fatalities in 9 countries in the Middle East, Europe, and North Africa as of 4 October 2013.1–5 Animal-to-human transmission has been suspected in view of MERS-CoV’s close phylogenetic relatedness to other lineage C betacoronaviruses found in bats in Hong Kong, Mexico, Europe, and Africa,6–13 and its broad species tropism in various animal cell lines including those of bats, primates, pigs, civets, and rabbits.14,15 Recently, a serological study of major livestock suggested dromedary camels to be a possible host based on the high prevalence of MERS-CoV neutralizing antibodies in dromedary camels from Oman.16 However, targeted studies are needed to confirm this finding and its possible relevance to human cases of MERS-CoV infection as most cases did not have contact with camels and the virus has not been isolated in animals yet. The epidemic continues to evolve with recent outbreaks occurring among epidemiologically-linked household contacts in the Kingdom of Saudi Arabia, the United Kingdom, Italy, and Tunisia, and hospital contacts in the Kingdom of Saudi Arabia, Jordan, the United Kingdom, and France providing evidence for MERS-CoV’s potential for person-to-person transmission.17–23

Unlike most other human coronavirus infections which are generally mild, most patients with MERS have suffered from rapidly progressive pneumonia with some also developing acute renal failure, hepatic dysfunction, gastrointestinal upset, pericarditis, disseminated intravascular coagulation, and/or cytopenias.2,24 The resulting crude mortality rate of nearly 50% in documented cases far exceeded those seen in all other human coronavirus infections including SARS despite aggressive supportive treatment including extracorporeal membrane oxygenation in some of the MERS cases. While mild and asymptomatic cases have been recognized,2,19,24 these recent case clusters signify a global health threat especially in view of the unusual clinical severity of MERS, travel of infected persons to other countries and influx of religious pilgrims to the Kingdom of Saudi Arabia, and the lack of proven effective specific antiviral treatment.

After our initial success in applying chemical genetics in probing novel targets and compounds for antiviral development,25 we started looking for broad-spectrum antiviral compounds that may be active against both influenza A viruses and coronaviruses, the two viral pathogens responsible for causing the recent 2009 pandemic and large-scale epidemics.9 While neuraminidase inhibitors such as oseltamivir and zanamivir remain effective against most seasonal and avian influenza A viruses,26–30 proven antiviral therapeutic options for coronavirus infections is lacking. Given the limited time available to develop novel antiviral agents in this evolving epidemic, we attempted to provide an alternative solution by identifying potential broad-spectrum antiviral agents against MERS-CoV and influenza A viruses by a small compound-based forward chemical genetics approach using chemical libraries consisting of 1280 drug compounds already marketed or having reached clinical trials in the United States, Europe, or Asia (Microsource Discovery Systems, USA).31 We then assessed the anti-MERS-CoV activities of the identified drug compounds in cell culture by cytopathic effect (CPE) inhibition, viral yield reduction, and plaque reduction assay (PRA) assays, as well as drug cytotoxicity.

Materials and methods

Viruses

A clinical isolate of MERS-CoV was kindly provided by R. Fouchier, A. Zaki, and colleagues.3 The isolate was amplified by one additional passage in Vero cells to make working stocks of the virus (4 × 10^5 TCID_{50}/ml). All experimental protocol involving live MERS-CoV isolate followed the standard operating procedures of the approved Biosafety Level-3 facility as we previously described.3 The influenza A/WSN/1933 (H1N1) virus was expanded in chick embryo as we previously described.25

Chemical reagents and high-throughput screening (HTS)

A total of 1280 pre-existing drug compounds (Microsource Discovery Systems) were screened against influenza A/WSN/1933 (H1N1) virus. High-throughput screening (HTS) was carried out in a fully automated Beckman Coulter Core System (Beckman Coulter, USA) integrated with a Kendro robotics CO_{2} incubator (Thermo Fisher Scientific) at Chemical Genetics Unit, Department of Microbiology, Research Center of Infection and Immunology, Li Ka Shing Faculty of Medicine, the University of Hong Kong as we previously described with modifications.25 Briefly, compounds were added in 96-well microtitre plates (TPP) in duplicate with a final concentration of 10 μM or 100 μM and 20,000 Madin–Darby canine kidney (MDCK) cells per well in 100 μl complete Eagle’s minimal essential medium (EMEM) supplemented with 1% heat-inactivated FBS. Cells were then inoculated at an MOI of 0.01 with influenza A/WSN/1933 (H1N1) virus for detection of broad-spectrum antivirals. After infection, the plates were incubated for 37 °C with 5% CO_{2} and monitored daily using a Leica DM inverted light microscope for virus-induced CPE. Drugs that...
gave full protection of MDCK cells (no CPE) were selected for further evaluation with MERS-CoV in a Biosafety Level-3 laboratory.

The cytotoxicity of selected drug (Ribavirin: 1600–0.1 μg/ml; IntronA 75,000–4.58 IU/ml; Avonex: 75,000–4.58 IU/ml; Rebif: 250,000–15.26 IU/ml; Betaferon: 50,000–3.05 IU/ml; MMF: 32–0.25 μg/ml) was determined by thiazolyl blue tetrazolium bromide (MTT) assay according to manufacturer’s instructions. The endpoint was the 50% effective cytotoxic concentration (TC50).

MERS-CoV CPE inhibition assay

The drug compounds identified as primary hits showing a EC50 of less than or equal to 50 μM and a selectivity index of more than 100 were diluted with serum free MEM and added to confluent Vero cells in 96-well culture plates in triplicate for 2 h at 37 °C. After incubation, the drug containing media was removed, and MERS-CoV at 0.0001 MOI was added together with fresh drug-compound media to each well containing approximately 60,000 cells. Following 1 h adsorption at 37 °C, the virus-compound mixture was removed and the cells were washed 2 times with MEM to remove unbound virus. Subsequently, media with antiviral compounds were added to the cells for further incubation for 72 h at 37 °C in a 5% CO2 humidified environment. CPE was examined by inverted light microscopy, and 50 μl of supernatant was collected for virus quantification, as we previously described with modifications.14 Thereafter, 50 μl of serum free MEM and 10 μl of 5 mg/ml MTT solution (prepared in 1 × PBS, filtered) were added to the wells. The monolayers were incubated as above for 4 h (away from light). Finally, 100 μl of 10% SDS with 0.01 M HCl was added and further incubated at 37 °C with 5% CO2 overnight. The activity was read at OD570 with reference wavelength at OD640. The interferon and non-interferon drug compound with the lowest 50% effective inhibitory concentration (EC50) and highest selectivity index were selected for combination studies using the CPE inhibition assay.

MERS-CoV virus yield reduction and plaque reduction assays

For the drug compounds with antiviral activity in the MTT assay, further evaluation by quantitative virus yield reduction and plaque reduction assays (PRA) was performed. Virus yield quantification was performed by quantitative RT-PCR using total nucleic acid extracted from culture supernatants of the Vero cells infected by MERS-CoV on day 3 post-infection as we previously described.14 PRA was performed as we previously described with modifications.32 Briefly, it was performed in duplicate in 24-well tissue culture plates (TPP). The Vero cells were seeded at 1 × 105 cells/well in MEM (Invitrogen) with 10% FBS on the day before carrying out the assay. After 16–24 h incubation, 70–100 plaque-forming units (PFU) of MERS-CoV virus were added to the cell monolayer with or without the addition of drug compounds and the plates further incubated for 2 h at 37 °C in 5% CO2 atmosphere before removal of unbound viral particles by aspiration of the media and washing once with MEM. Monolayers were then overlaid with media containing 1% low melting agarose (Cambrex) in MEM and appropriate concentrations of drug compounds and incubated as above for 72 h. Next, the wells were fixed with 10% formaldehyde (BDH) overnight. After removal of the agarose plugs, the monolayers were stained with 0.7% crystal violet (BDH) and the plaques counted. The percentage of plaque inhibition relative to the control (without the addition of compound) plates was determined for each drug compound concentration. The EC50 and the 50% cellular cytotoxicity concentration (CC50) were calculated using Sigma plot (SPSS) in an Excel add-in ED50V10. The PRA were carried out in triplicate and repeated twice for confirmation.

Results

High-throughput screening (HTS)

Ten drugs compounds, namely mycophenolic acid, fluconamic acid, tolenamic acid, meclofenamate sodium, mefenamic acid, ribavirin, mercaptopurine, pyrimethamine, emetine, and estradiol were identified as primary hits with protective results in chemical library screening against influenza A/WSN/1933 (H1N1) virus (Table 1). Neuraminidase inhibitors were not identified because they were not included in the chemical library. Amantadine was not identified because the virus strain had an M2 gene mutation (S31N) conferring drug resistance. Using both EC50 and TC50 as the hit selection criteria, only mycophenolic acid exhibited a low EC50 of <10 μM with a high selectivity index of >100. Mercaptopurine, which is a competitive, selective, and reversible inhibitor of the SARS-CoV papain-like protease,37 demonstrated a high EC50 of Z6.5 and low selectivity index of 4.

MERS-CoV CPE inhibition assay

In addition to mycophenolic acid (Sigma–Aldrich, USA), ribavirin (Tianxin Pharmaceutical, China), Intron A (recombinant interferon-β2b, Schering-Plough, USA), Avonex (recombinant interferon-β1a, Biogen Idec, Denmark), Rebif (recombinant interferon-β1a, Merck Serono, Italy), Betaferon (recombinant interferon-β1b, Bayer Schering Pharma, Germany), Imukin (recombinant interferon-γ1b, Boehringer Ingelheim, Germany), nelfinavir mesylate hydrate (Agouron Pharmaceuticals, USA), and lopinavir (Abbott, USA) were also tested in the MTT assays because of their documented in vitro anti-SARS-CoV activities in previous reports.34–37 Among them, only mycophenolic acid, ribavirin, Intron A, Avonex, Rebif, and Betaferon showed anti-MERS-CoV activity at the tested concentrations (Table 2). CPE was completely absent in Vero cells infected with MERS-CoV on day 3 post-infection at concentrations of ≥0.063 μg/ml for mycophenolic acid and ≥100 μg/ml for ribavirin, and was decreased but not absent in the tested concentrations of Intron A, Avonex, Rebif, or Betaferon (Table 3). Combination studies showed that the EC50 of mycophenolic acid was lowered by 1.7–2.8 times in the presence of 6.25–12.5 IU/ml of
Betaferon, and that the EC$_{50}$ of Betaferon was lowered by 1.1–1.8 times in the presence of 0.016–0.063 mg/ml of mycophenolic acid (Table 2).

**MERS-CoV virus yield reduction**

The mean baseline viral load in the cell culture supernatants without drugs was 12.110$^{±}$0.003 log$_{10}$ copies/ml. There was a 50% reduction in viral load as compared to the baseline in cell culture supernatants inoculated with each of the six drugs (Fig. 1). There was a >2-log reduction in viral load in cell culture supernatants inoculated with mycophenolic acid, ribavirin, Rebif, and Betaferon. There was >1-log reduction in the viral load in cell culture supernatants at 40 IU/ml of Betaferon and >3-log reduction at the highest concentration of 50,000 IU/ml (Fig. 1c). The largest reduction in viral load at clinically relevant drug levels was a nearly 4-log reduction at 16 µg/ml of mycophenolic acid.

**MERS-CoV PRA**

Mycophenolic acid, ribavirin, and Rebif achieved 100% plaque reduction at concentrations of 6.4 µg/ml, 400 µg/ml, and 62,500 IU/ml respectively (Figs. 2 and 3). The maximum percentages of plaque reduction achieved by Intron A, Avonex, and Betaferon were 76.2% at 70,000 IU/ml, 70.2% at 5000 IU/ml, and 66.6% at Table 1

<table>
<thead>
<tr>
<th>Drug in compound</th>
<th>EC$_{50}$ (µM)$^a$</th>
<th>TC$_{50}$ (µM)$^a$</th>
<th>Selectivity index</th>
<th>Bioactivity</th>
<th>Serum concentration (µg/ml) [oral dose]</th>
</tr>
</thead>
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<tr>
<td>Mycophenolic acid</td>
<td>0.24</td>
<td>170.00</td>
<td>708.00</td>
<td>Anti-neoplastic</td>
<td>Mycophenolate mofetil: 10–50 [1 g] Mycophenolate sodium: 26.1 [720 mg]</td>
</tr>
<tr>
<td>Flufenamic acid</td>
<td>6.30</td>
<td>79.16</td>
<td>12.60</td>
<td>Anti-inflammatory, analgesic</td>
<td>6–20 [200 mg]</td>
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<td>Tolafenamic acid</td>
<td>7.94</td>
<td>64.00</td>
<td>8.00</td>
<td>Anti-inflammatory, analgesic</td>
<td>4.1 [300 mg]</td>
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<tr>
<td>Mefenamic acid</td>
<td>30.00</td>
<td>200.00</td>
<td>4.00</td>
<td>Anti-inflammatory, analgesic</td>
<td>10 [1 g]</td>
</tr>
<tr>
<td>Meclomenamate sodium</td>
<td>45.00</td>
<td>100.00</td>
<td>2.00</td>
<td>Anti-inflammatory, antipyretic</td>
<td>4.8 [100 mg tds]</td>
</tr>
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<td>Ribavirin</td>
<td>2.00</td>
<td>168.00</td>
<td>8.00</td>
<td>Antiviral</td>
<td>2.2 [4 weeks of 600 mg bd]</td>
</tr>
<tr>
<td>Mercaptopurine</td>
<td>26.50</td>
<td>100.00</td>
<td>4.00</td>
<td>Anti-neoplastic, purine anti-metabolite</td>
<td>0.09 [50 mg/m$^2$]</td>
</tr>
<tr>
<td>Pyrimethamine</td>
<td>3.10</td>
<td>5.40</td>
<td>1.80</td>
<td>Anti-malarial</td>
<td>0.55 [1500/75 mg of sulfadoxine/pyrimethamine]</td>
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<tr>
<td>Emetine</td>
<td>1.70</td>
<td>17.00</td>
<td>1.50</td>
<td>Inhibits RNA, DNA, and protein synthesis</td>
<td>0.001 [30 ml of syrup ipecac]</td>
</tr>
<tr>
<td>Estradiol</td>
<td>2.00</td>
<td>75.00</td>
<td>3.00</td>
<td>Estrogen</td>
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</table>

$^a$ Values represent activity against influenza A/WSN/1933 (H1N1) virus in MDCK cells.

<table>
<thead>
<tr>
<th>Drug in compound</th>
<th>EC$_{50}$</th>
<th>EC$_{90}$</th>
<th>EC$_{99}$</th>
<th>CC$_{50}$</th>
<th>Selectivity index$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mycophenolic acid</td>
<td>0.17$^{±}$0.03</td>
<td>2.61$^{±}$0.34</td>
<td>4.86$^{±}$0.57</td>
<td>&gt;32</td>
<td>&gt;195.12</td>
</tr>
<tr>
<td>With 6.25 IU/ml Betaferon</td>
<td>0.10$^{±}$0.01</td>
<td>0.06$^{±}$0.01</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>With 12.5 IU/ml Betaferon</td>
<td>9.99$^{±}$2.97</td>
<td>107.06$^{±}$11.24</td>
<td>183.17$^{±}$11.97</td>
<td>&gt;1600</td>
<td>&gt;152.98</td>
</tr>
<tr>
<td>Ribavirin</td>
<td>6709.79$^{±}$1747.97</td>
<td>184015.75$^{±}$90145.01</td>
<td>371242.78$^{±}$255482.32</td>
<td>&gt;75,000</td>
<td>&gt;11.73</td>
</tr>
<tr>
<td>Intron A (IU/ml)</td>
<td>5073.33$^{±}$7333.86</td>
<td>179949.17$^{±}$138588.37</td>
<td>708919.75$^{±}$840503.36</td>
<td>&gt;75,000</td>
<td>&gt;35.19</td>
</tr>
<tr>
<td>Avonex (IU/ml)</td>
<td>480.54$^{±}$183.85</td>
<td>2473.86$^{±}$576.35</td>
<td>3599.06$^{±}$778.81</td>
<td>15,625</td>
<td>27.08</td>
</tr>
<tr>
<td>Rebif (IU/ml)</td>
<td>17.64$^{±}$1.09</td>
<td>93.31$^{±}$10.07</td>
<td>135.70$^{±}$15.96</td>
<td>3125</td>
<td>249.09</td>
</tr>
</tbody>
</table>

$^a$ Selectivity index defined as ratio of CC$_{50}$/EC$_{50}$. 

Potential antiviral agents for MERS-CoV infection
Table 3 MERS-CoV-induced cytopathic effects in Vero cells on day 3 post-infection at different concentrations of mycophenolic acid, ribavirin, and interferons.

<table>
<thead>
<tr>
<th>Drug concentration</th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
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<tr>
<td>Mycophenolic acid (μg/ml)</td>
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</tr>
<tr>
<td>0.001</td>
<td>4+</td>
<td>4+</td>
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<tr>
<td>0.004</td>
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<tr>
<td>0.016</td>
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<td>1+</td>
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<tr>
<td>0.063</td>
<td>−</td>
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<td>−</td>
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<tr>
<td>0.250</td>
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<td>−</td>
<td>−</td>
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<tr>
<td>1.000</td>
<td>−</td>
<td>−</td>
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</tr>
<tr>
<td>4.000</td>
<td>−</td>
<td>−</td>
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<tr>
<td>16.000</td>
<td>−</td>
<td>−</td>
<td>−</td>
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<tr>
<td>Ribavirin (μg/ml)</td>
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<tr>
<td>0.098</td>
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<td>4+</td>
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<tr>
<td>3125.000</td>
<td>T</td>
<td>T</td>
<td>T</td>
</tr>
</tbody>
</table>

Table 3 (continued)

<table>
<thead>
<tr>
<th>Drug concentration</th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>12,500.000</td>
<td>T</td>
<td>T</td>
<td>T</td>
</tr>
<tr>
<td>50,000.000</td>
<td>T</td>
<td>T</td>
<td>T</td>
</tr>
</tbody>
</table>

Remarks: -, negative; 1+ is defined as 1%–25% involvement; 2+ is defined as >25%–50% involvement; 3+ is defined as >50%–75% involvement; 4+ is defined as >75% involvement; T, drug-induced toxic effects in Vero cells.

400 IU/ml respectively (Fig. 3). In PRA, Betaferon achieved 40–50% plaque reduction at 40 IU/ml (Fig. 3c).

Discussion

Novel antiviral targets for SARS coronavirus and influenza A virus have been identified previously using small compound-based forward chemical genetics approaches similar to ours.25,26,38 In this study, we identified ten compounds among approved drugs with as primary hits in chemical library screening that possess antiviral activities. Some may offer potential therapies in the evolving MERS-CoV epidemic. Influenza A/WSN/1933 (H1N1) virus, instead of MERS-CoV, was used for initial screening because its manipulation did not require a Biosafety Level III laboratory. Other human betacoronaviruses such as HCoV-OC43 and HCoV-HKU1 were not used because of their slow replication and low viral titres in cell culture.14 Among the 10 identified drug compounds, only mycophenolic acid exhibited an EC50 of <10 μM, which is a common cut-off value for lead compound detection, and a high selective index of >100. Additionally, we tested other agents reported to have in vitro activities against SARS-CoV and/or MERS-CoV,52,34,40 Imukin (interferon-γ1b) and the HIV protease inhibitors, nelfinavir mesylate hydrate and lopinavir, showed suboptimal EC50 in the initial CPE inhibition assay and were therefore not further evaluated. Together with mycophenolic acid, four other drug compounds in five preparations, namely ribavirin, Intron A, Avonex, Rebif, and Betaferon, showed in vitro anti-MERS-CoV activity of varying magnitude across four assays.

Mycophenolic acid is a selective, non-competitive, and reversible inhibitor of inosine-5′-monophosphate dehydrogenase (IMPDH). It inhibits the proliferation of T and B lymphocytes and production of immunoglobulins by depletion of the lymphocyte guanine and deoxyguanosine nucleotide pools.41 Its major clinical indication is prevention of graft rejection in solid organ and haematopoietic stem cell transplantations. In addition to potent immune-suppressive activity, mycophenolic acid also has broad activity in vivo and/or in animal models against different viruses including West Nile,42 Japanese encephalitis,43 yellow fever,44 dengue,45 Chikungunya,46 and possibly hepatitis B viruses.47 Furthermore, it inhibited the in vitro and in vivo replication of hepatitis C virus by augmentation of interferon-stimulated gene expression and depletion of guanosine.48,49 Combination treatment with interferon-α showed additive effects on interferon-stimulated gene expression and enhanced interferon-induced luciferase reporter activity.48 As for coronaviruses, mycophenolic acid...
was found to be ineffective against SARS-CoV in an animal model, although it did not significantly increase the viral load in the lungs of SARS-infected BALB/c mice as ribavirin did.\cite{note50} We are unaware of data on its activity against other human coronaviruses. Our study is the first to demonstrate the anti-coronavirus activity of mycophenolic acid against the novel MERS-CoV.

In addition to mycophenolic acid, our in vitro findings indicated that ribavirin, interferon-α, and interferon-β had anti-MERS-CoV activities in vitro. In the case of SARS-CoV, their antiviral activities in in vitro susceptibility tests had been conflicting.\cite{note34} None of them were tested systemically in large-scale randomized controlled trials and the results from clinical trials involving their use in SARS were often confounded with the concomitant use of corticosteroids.\cite{note51,note52} Although their clinical use in MERS-CoV infection has not been described, a recent study found that ribavirin had in vitro anti-MERS-CoV activity at very high concentrations which was potentiated when given together with interferon-β.\cite{note60} Another study showed that MERS-CoV is 50–100 times more sensitive to pegylated interferon-α than SARS-CoV in Vero cells, which is possibly related to the lineage-specific genetic differences between the two coronaviruses with MERS-CoV lacking the homolog of the SARS-CoV ORF6 protein responsible for the blockade of interferon-induced nuclear translocation of phosphorylated transcription factor STAT1.\cite{note53} Furthermore, the delayed and aberrant induction of inflammatory cytokines and chemokines by MERS-CoV might support the use of adjunctive immuno-modulatory treatment combined with antivirals in patients with MERS.\cite{note54,note55} Among the four preparations of interferons tested, Betaferon exhibited the lowest EC\textsubscript{50} of 17.64 IU/ml, which was below the mean peak serum concentration of 40 IU/ml after a subcutaneous dose of 16 million IU or an intravenous dose of 0.2 million to 64 million IU.\cite{note56} Although the other preparations of interferons also demonstrated in vitro anti-MERS-CoV activities, their EC\textsubscript{50} were generally above the peak serum concentrations achievable with usual therapeutic dosing. Combination treatment consisting of mycophenolic acid and Betaferon resulted in a 1.7–2.8-fold reduction in the EC\textsubscript{50} of mycophenolic acid in Vero cells with 6.25–12.5 IU/ml of Betaferon, and 1.1–1.8-fold reduction in the EC\textsubscript{50} of Betaferon in Vero cells with 0.016–0.063 µg/ml of mycophenolic acid. Our finding may provide the basis for combination mycophenolic acid and Betaferon in future clinical trials.

Compared with ribavirin and interferons, mycophenolic acid exhibits a number of attributes that support its practical use in MERS-CoV infection. It is commonly available in two forms, the prodrug mycophenolate mofetil and the salt mycophenolate sodium, and could be given orally.
or parenterally. The serum concentration of mycophenolic acid peaks at around 10–50 \( \mu g/ml \) after a 1000 mg oral dose of mycophenolate mofetil or 26.1 \( \mu g/ml \) after a 720 mg oral dose of mycophenolate sodium. These far exceed its EC50 of 0.17 \( \mu g/ml \) and is 60–300 times higher than the concentrations at which the replication of MERS-CoV is inhibited in cell culture and PRA.\(^{57}\) With average plasma elimination half-lives of 17.9 h and 16.6 h after a 1000 mg oral dose and 1500 mg intravenous dose of mycophenolate mofetil respectively,\(^{41}\) the usual regimens consisting of 1000 mg twice daily oral or 1500 mg twice daily intravenous mycophenolate mofetil would be sufficient to achieve levels well above the EC50 throughout the dosing interval. In contrast, the EC50 of ribavirin for MERS-CoV between 9.99 and 41.45 \( \mu g/ml \) is just marginally effective in some cell lines and greatly exceeds the drug’s serum concentration with usual oral doses. Peak concentrations with high intravenous doses may reach approximately 24 \( \mu g/ml \) in humans, but steady-state requires at least 4 weeks to achieve.\(^{40,58}\) Furthermore, the use of ribavirin, and hence also its combination with interferon-\(\alpha2b\), may be limited in the clinical setting, because a significant proportion of patients with MERS-CoV infection have developed acute renal failure often requiring renal replacement therapy.\(^{2,24}\) It has been suggested that systemic ribavirin should best be avoided in patients with a creatinine clearance of <50 ml/min because of the increased risk of haemolytic anaemia.\(^{59}\)

Although mycophenolic acid may also be associated with acute renal impairment, the dosage adjustment in such a setting is generally well established.\(^{41}\) The potent in vitro anti-MERS-CoV activity of mycophenolic acid may allow it to be used as a monotherapy if concomitant interferon is not available or tolerated by the patient. Finally, drug level monitoring for mycophenolate mofetil is generally available in most tertiary hospitals which are the usual referral centers for cases of severe MERS-CoV infections requiring intensive care facilities such as extracorporeal membrane oxygenation. However, the risk of immunosuppression at the onset of adaptive immune responses or polarization towards a deleterious Th1 response by mycophenolic acid needs to be considered.\(^{60}\) One possible approach is a short course of mycophenolate mofetil combined with an interferon, particularly interferon-\(\beta1b\), to provide synergistic antiviral and immune-enhancing effects against MERS-CoV. These options should be considered for study in randomized control clinical trials for this highly fatal disease.

There are a number of limitations in our study. Firstly, the cytotoxicity assay likely underestimated more subtle effects of candidate compounds on host cell growth and metabolism. For example, ribavirin inhibits replication of uninfected MDCK cells at concentrations of 10 \( \mu g/ml \) and above but does not cause overt cytotoxicity until much higher concentrations are reached.\(^{61,62}\) Secondly, we used Vero cells alone to study the antiviral activity of ribavirin. Vero cells have been described as being comparatively resistant to ribavirin due to their inefficient conversion of the drug into its mono- and tri-phosphate forms.\(^{63}\) However, we decided not to perform the experiment using
another cell line as this has been done in another recent report using Vero and LLC-MK2 cell lines which also demonstrated anti-MERS-CoV activity of high ribavirin concentrations similar to our findings. It would be important to extend these in vitro studies to human respiratory epithelial cell systems and explants.

To optimize treatment options for MERS-CoV infection, further studies on the anti-MERS-CoV activities of other potential anti-coronavirus agents which have been previously identified for SARS-CoV should be undertaken. Replication of many coronaviruses including SARS-CoV and MERS-CoV requires proteolytic processing of the replicase polyprotein by two viral cysteine proteases, a chymotrypsin-like protease (3CLpro) and a papain-like protease (PLpro). However, the protease inhibitors such as nelfinavir and lopinavir were not found to be active in our in vitro study. Helicase inhibitors are another group of agents with in vitro anti-SARS-CoV activities but their anti-MERS-CoV activities remain undetermined. Inhalational nitric oxide was used as rescue therapy for SARS and might be useful for treating MERS-CoV infection if organic nitric oxide donors such as S-nitro-N-acetylpentamidine also show anti-MERS-CoV activity. Anti-viral peptides or neutralizing antibodies designed against heptad repeat region 2 of S2 which may inhibit membrane fusion and cell entry of SARS-CoV could theoretically be harnessed for MERS-CoV since the S2 region shared significant homology amongst betacoronaviruses. Other agents with in vitro anti-SARS-CoV activities such as glycyrrhizin, baicalin, reserpine, aescin, valinomycin, niclosamide, aurantricarboxylic acid, mizoribine, indomethacin, chloroquine, and experimental agents like small interfering RNA (siRNA) and inhibitors targeting the binding interface between the S1 domain and receptor in vivo, should also be evaluated. We did not test these agents in this study because most of them have the problems of either not being commercially available or having therapeutic levels that are not easily achievable clinically. Recently, cyclophilin inhibitors, such as cyclosporine which is available commercially, have also been reported to exhibit anti-MERS-CoV and anti-coronavirus activity in cell culture and viral load studies. Further evaluation of its potential therapeutic effects of these commercially available agents with in vitro activity should be conducted in randomized clinical trials as good animal models for MERS are not widely available at this stage.

Acknowledgements

We thank Dr. Herman Tse for technical advice. This work is partly supported by the donations of Hui Hoy and Chow Sin.
Lan Charity Fund Limited, the Consultancy Service for Enhancing Laboratory Surveillance of Emerging Infectious Disease of the Department of Health, Hong Kong Special Administrative Region, China, and the National Science and Technology Major Project of China (grant 2012ZX10004-213-002).

Conflict of interests

The authors have no financial or any other conflicts of interest regarding the contents of the investigations.

References

Potential antiviral agents for MERS-CoV infection


47. Diamond MS, Zachariah M, Harris E. Mycophenolic acid inhibits dengue virus infection by preventing replication of viral RNA. Virology 2002;304:211–21.


