Compounds with therapeutic potential against novel respiratory 2019 coronavirus

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Abstract

Currently, the expansion of the novel human respiratory coronavirus (known as: SARS-CoV-2, COVID-2019, or 2019-nCoV) has stressed the need for therapeutic alternatives to alleviate and stop this new epidemic. The previous epidemics of high-morbidity human coronaviruses, such as the acute respiratory syndrome coronavirus (SARS-CoV) in 2003, and the Middle East respiratory syndrome corona virus (MERS-CoV) in 2012, prompted the characterization of compounds that could be potentially active against the currently emerging novel coronavirus SARS-CoV-2. The most promising compound is remdesivir (GS-5734), a nucleotide analog prodrug currently in clinical trials for treating Ebola virus infections. Remdesivir inhibited the replication of SARS-CoV and MERS-CoV in tissue cultures, and it displayed efficacy in non-human animal models. In addition, a combination of the human immunodeficiency virus type 1 (HIV-1) protease inhibitors, lopinavir/ritonavir, and interferon beta (LPV/RTV-INFb) were shown to be effective in patients infected with SARS-CoV. LPV/RTV-INFb also improved clinical parameters in marmosets and mice infected with MERS-CoV. Remarkably, the therapeutic efficacy of remdesivir appeared to be superior to that of LPV/RTV-INFb against MERS-CoV in a transgenic humanized mice model. The relatively high mortality rates associated with these three novel human coronavirus infections, SARS-CoV, MERS-CoV, and SARS-CoV-2, has suggested that pro-inflammatory responses might play a role in the pathogenesis. It remains unknown whether the generated inflammatory state should be targeted. Therapeutics that target the coronavirus alone might not be able to reverse highly pathogenic infections. This minireview aimed to provide a summary of therapeutic compounds that showed potential in fighting SARS-CoV-2 infections.

On December 30, 2019, a cluster of 27 pneumonia cases (including 7 severe cases) of unknown origin emerged in Wuhan (Hubei, China) and were reported to the National Health Commission of China (1). In the early stages of this pneumonia, patients developed severe acute respiratory infection symptoms, and some patients rapidly developed acute respiratory distress syndrome (2). Real time RT-PCR and deep sequencing analysis from lower respiratory tract samples identified a novel human coronavirus, now called SARS-CoV-2 (3–5). By the end of January, 2020, nearly 50,000 confirmed cases were reported in China, and the first confirmed cases were reported in Thailand, Nepal, Republic of Korea, USA, Singapore, France, Viet Nam, Canada, Australia, Malaysia, Germany, UAE, Finland, Italy, Cambodia, Sri Lanka, the Russian Federation, Spain, Sweden, India, and the Philippines. Among the patients with confirmed cases, most were aged 30–80 years and had mild infections (80%). The fatality rate was around 2% (6).

Coronaviruses can cause different types of infections in diverse animals. In humans, they mainly produce respiratory tract infections, as observed with SARS-CoV and MERS-Cov (7, 8). Sequencing and phylogenetic analyses have shown that the novel SARSCoV-2 virus is closely related to a group of human SARS-like coronaviruses and bat SARS-related coronaviruses (9–11). The origin of SARSCoV-2 remains unclear; it is unknown how it was first transmitted to humans. The high prevalence of SARS-related coronaviruses in bats has suggested that a bat coronavirus might have jumped into a civet or some other mammal, and from there to humans, which started the former 2003 SARS epidemic. Initial confirmed cases of SARSCoV-2 were associated with Huanan seafood and live animal markets. However, no animal source has been identified to date, and spillover events may continue to occur. Although bats might be the

source of SARSCoV-2, it is critical to identify the intermediate species to stop the current spread and to prevent future human SARS-related coronavirus epidemics.

A key question is whether the current SARSCoV-2 epidemic is similar to other SARS outbreaks or whether it shows different features. The epidemiological and clinical characteristics of SARSCoV-2 indicate that this new outbreak is different from the 2003-SARS. SARSCoV-2 displays higher transmissibility and lower mortality compared to the 2003-SARS (1, 3, 4). SARSCoV-2 has shown efficient intra-familial spread (4). The asymptomatic period of SARSCoV-2 infections oscillates between 2 and 14 days, and some individuals probably transmit the virus without developing any disease symptoms. It remains to be elucidated whether this virus replicates more readily in the upper airway than SARS-CoV and MEERS-CoV and whether it is similar to other human coronaviruses (HCoV) that cause colds, but not pneumonia. It will be necessary to identify molecular determinants that mediate transmission from animal to human, and from human to human. Of note, in the novel SARS-CoV-2, the nucleotide sequence of the external ectodomain in the spike protein receptor-binding domain is different from that of the 2003 SARS-CoV. When individual bat coronavirus spike genes were introduced into SARS-CoV infectious clones, the SARS-CoV/bat-CoV spike viruses could bind to the human, bat, or civet angiotensin converting enzyme 2 (ACE2) cellular receptor (12). Understanding the interaction between this novel SARS-CoV-2 spike protein and the host ACE2 receptor might reveal how this virus overcame the species barrier between animals and humans. As discussed below, this information might promote the design of effective antivirals.

To predict new zoonotic coronavirus jumps across species and to understand the rate of virus spread among people, it is crucial to determine whether SARSCoV-2 is mutating to improve its binding to human receptors for infection. As an RNA virus, SARS-CoV-2 has intrinsic genetic variability, which results in a high mutation rate. Moreover, coronaviruses have the largest genomes (~30 kb) among RNA viruses. However, part of their sequence encodes a proofreading 3' exonuclease that can increase replication fidelity (13). It has been suggested that any adaptation in the SARS-CoV-2 sequence that might make it more efficient at transmitting from person to person might also increase its virulence (14). However, this mechanism could lead to a genetic bottleneck, known as Muller's ratchet, which could significantly decrease viral fitness, (15). Muller's ratchet predicts that, when mutation rates are high and a significant proportion of mutations are deleterious, a type of irreversible ratchet mechanism will gradually reduce the mean fitness of small populations of asexual organisms. Because genetic bottlenecks for RNA viruses often occur during respiratory droplet transmissions, the SARS-CoV-2 is expected to become less virulent through human to human transmissions (16).

From the public health perspective, we urgently need to develop an effective vaccine and antiviral therapeutics to stop the SARS-CoV-2 epidemic. Moreover, social and economic issues generated by this epidemic also call for rapid interventions. This review focuses on the potential of repurposing preexisting compounds that might provide new opportunities for treating people infected with SARS-CoV-2. Previous work with SARS-CoV and MERS-CoV has provided an opportunity to accelerate the identification of meaningful therapies for fighting the

novel SARS-CoV-2 epidemic. Nevertheless, we must be aware that, currently, no compound that targets SARS-CoV or MERS-CoV has moved beyond phase 1 trials.

The most promising antiviral for fighting SARS-CoV-2 is remdesivir (GS-5734). Remdesivir is an adenosine nucleotide analogue prodrug with broad-spectrum antiviral activity against filoviruses, paramyxoviruses, pneumoviruses, and pathogenic coronaviruses, like SARS-CoV and MERS-CoV (17). Pharmacokinetic studies have been completed and clinical trials are ongoing for testing remdesivir efficacy in treating Ebola virus (18). Previous studies have indicated that nucleotide analogues generally show low efficacy against coronaviruses, due to the virus exonuclease proofreading enzyme. Nevertheless, remdesivir was effective against SARS-CoV, MERS-CoV, and bat-CoV strains (17). In tissue cultures, remdesivir displayed half-maximum effective concentrations (EC50s) of 0.069 for SARS-CoV and 0.074 μM for MERS-CoV. Of note, tissue culture studies have shown that remdesivir is also active in the submicromolar EC50 range against a number of highly divergent coronaviruses, including the endemic human CoVs, OC43 (HCoV-OC43) and 229E (HCoV-229E). Thus, remdesivir has broad-spectrum anti-CoV activity (19). In a mouse model of SARS-CoV pathogenesis, prophylactic and early therapeutic administration of remdesivir significantly reduced the lung viral load. Viral titers were reduced by >2 orders of magnitude on day 4 or 5 post infection. Remdesivir improved the clinical signs of disease and respiratory function compared to untreated control animals (17). Comparable results were obtained with MERS-CoV in prophylactic studies carried out with a MERS-CoV mouse transgenic model. In that model, a humanized MERS-CoV receptor (dipeptidyl peptidase 4, hDPP4) was expressed and carboxylesterase 1c (Ces1c) was deleted to improve the

pharmacokinetics of nucleotide prodrugs (20). Remdesivir specificity for coronavirus was demonstrated by propagating the virus in tissue culture. After 23 passages in the presence of drug, two mutations were identified (F276L and V553L) in the viral RNA-dependent RNA polymerase gene. These mutations increased the replication capacity of the virus in the presence of remdesivir (21). However, these amino acid changes decreased the viral fitness and attenuated SARS-CoV pathogenesis in mice (21). The efficacy of prophylactic and therapeutic remdesivir treatment was recently tested in a nonhuman primate (rhesus macaque) model of MERS-CoV infection (22). When prophylactic remdesivir treatment was initiated 24 h prior to inoculation, MERS-CoV was prevented from inducing clinical disease and inhibited from replicating in respiratory tissues, which prevented the formation of lung lesions. Similar results were obtained when therapeutic remdesivir treatment was initiated at 12 h after virus inoculation (22). Human safety data are available for remdesivir (18); thus, human trials can be initiated for testing the efficacy of this compound against novel coronaviruses.

Therapies that are approved by the Food and Drug Administration (FDA) have been evaluated for antiviral activity against SARS-CoV and MERS-CoV. For example, lopinavir (LPV), a human immunodeficiency virus 1 (HIV-1) protease inhibitor, was combined with ritonavir (RTV) to increase the LPV half-life. LPV/RTV was shown to be effective against SARS-CoV in patients and in tissue culture. The estimated EC50 in fetal rhesus kidney-4 cells was 4 µg/ml (23). LPV/RTV also reduced weight loss, clinical scores, viral titers, and disease progression in marmosets infected with MERS-CoV (24). Nevertheless, the antiviral activity of LPV against MERS-CoV in

tissue culture remains controversial. No optimal EC50 was found in Vero cells (25), but an EC50 of 8 μM was reported in Huh7 cells (26).

Clinical observations in animals and humans showed that MERS-CoV infections were mediated by both virus replication and host inflammatory responses. Those findings led to explorations of combination therapies that included types I and II interferons (IFN I and II). Interferon beta (IFNb) displayed the best efficacy, with EC50s of 1.37-17 IU/ml, for reducing MERS-CoV replication in tissue culture (25, 27). Similar to LPV/RTV, clinical improvements with IFNb were observed in common marmosets infected with MERS-CoV (24). In the Kingdom of South Arabia, an ongoing randomized control trial (MIRACLE Trial) was initiated to determine whether the combination of LPV/RTV and IFNb could improve clinical outcomes in MERS-CoV infections (28). Importantly, another controlled trial was launched in China to test the efficacy of LPV/RTV and IFNα-2b in hospitalized patients with SARS-CoV-2 infections (ChiCTR2000029308).

The prophylactic and therapeutic properties of remdesivir and LPV/RTV-IFNb were compared in a humanized transgenic mouse MERS-CoV infection model (29). Remdesivir improved pulmonary function, reduced lung viral loads, and ameliorated severe lung pathology. In contrast, prophylactic LPV/RTV-IFNb only slightly reduced viral loads and did not impact other disease parameters, and therapeutic LPV/RTV-IFNb improved pulmonary function, but did not reduce virus replication or severe lung pathology (29). Overall, these results indicated that remdesivir showed more potential than LPV/RTV-IFNb for treating MERS-CoV infections.

Antimicrobial Agents and Chemotherapy

Ribavirin, a guanosine analogue, is an antiviral compound used to treat several virus infections, including respiratory syncytial virus, hepatitis C virus, and some viral hemorrhagic fevers. In most cases, ribavirin is combined with IFN. Ribavirin was first marketed in 1980 for the treatment of respiratory syncytial virus in children. Although promising results were obtained with ribavirin and IFNα-2b in a MERS-CoV rhesus macaque model (30), data have been conflicting on patients with MERS-CoV infections that were treated with a combination of ribavirin and IFN (either α2a or β1) (31). However, ribavirin reduces hemoglobin concentrations, an undesirable side effect in patients with respiratory disorders. This feature reduces its potential as an antiviral against SARS-CoV-2.

Work with influenza virus has shown that monoclonal and polyclonal antibodies can be useful prophylactic and therapeutic tools. Several antibodies have been shown to bind influenza virus hemagglutinin and inhibit virus replication (12). For example, human immunoglobulin G1 (IgG1) monoclonal antibody (MHAA4549A) binds to a highly conserved epitope on the stalk of influenza A hemagglutinin. In a phase 2 human influenza A virus challenge study, MHAA4549A significantly reduced the clinical symptoms and viral burden relative to placebo (32). Another example is VIS410, a monoclonal antibody engineered to target all known influenza A strains. A phase 2a trial showed that VIS410 had some clinical benefits (33). Current development efforts in monoclonal and polyclonal antibodies against coronaviruses are mainly targeting MERS-CoV. In a phase 1 clinical trial, a human polyclonal antibody, SAB-301, which is generated in trans-chromosomic cattle, was found to be safe and well tolerated in healthy participants. (34). However, therapeutic treatment with human monoclonal antibodies did not protect against the

189 severe disease or the loss of lung function induced by MERS-CoV in animal models (20). The
190 lack of viral sequence homology among different human coronaviruses suggests that current
191 investigational antibody-based therapeutics will not be effective against novel virus variants.
192 Nevertheless, immune-based therapies should be not discarded, when considering future
193 treatments for novel coronaviruses.
194
195 Another potential treatment option could be the use of novel coronavirus sera prepared from
196 the blood of patients in convalescence (convalescent sera). Passive immunization is well
197 established for viral infection prophylaxis. Polyclonal antibody products have been licensed that
198 target cytomegalovirus, hepatitis B virus, and varicella-zoster virus. A meta-analysis of reports
199 on the 1918 influenza A (H1N1) epidemic concluded that early administration of convalescent
200 blood products reduced the absolute risk of pneumonia-related death from 37% to 16% (35).
201 Nevertheless, the appropriate titer of convalescent sera antibody that is required for
202 therapeutic efficacy against SARS-CoV-2 remains to be determined. Moreover, additional
203 studies performed with influenza virus have produced controversial results regarding the
204 clinical benefit of administering high titers of anti-influenza immunoglobulins (36). Finally, it
205 remains unclear whether a sufficient pool of potential donors is feasible. Work carried out with
206 MERS-CoV showed that sera from patients recovering from infections did not contain sufficient
207 antibody titers for therapeutic use (37).
208
209 Another interesting therapeutic alternative that was previously explored with influenza virus is
210 to target cellular components involved in the host inflammatory response to the infection. For

example, the activation of the inflammatory response to an infection can induce a cytokine outburst that results in an acute lung injury. An example of a therapy for this type of infection has been to target the cellular toll-like receptor 4 (TLR4) with specific antibodies. TLR4 is a transmembrane protein that belongs to the pattern recognition receptor (PRR) family. The prototype pathogen-associated molecular pattern (PAMP) that TLR4 recognizes is the gram-negative bacteria, endotoxin, lipopolysaccharide (LPS). TLR4 has been implicated in the pathology associated with other infections and with tissue damage caused by non-infectious insults. TLR4 activation leads to the NF-κB intracellular signaling pathway and inflammatory cytokine production, which activate the innate immune system. Interestingly, TLR4-null mice were highly resistant to infection by the mouse-adapted influenza A virus (38). Thus, protection against influenza infections was achieved by targeting TLR4 with small molecule antagonists, like TAK-242, or with anti-TLR4-specific antibodies (39, 40). Indeed, targeting a cellular protein would overcome the drawbacks associated with virus or coronavirus genetic heterogeneity.

The high mortally rates observed in some emerging respiratory diseases induced by viruses like MERS-CoV, SARS-CoV, and novel influenza A strains (H5N1) has given rise to the hypothesis that the pro-inflammatory response might be involved in the disease pathogenesis. Consequently, immunosuppressants (e.g., corticosteroids) might be used as an adjunct for treating severe forms of the disease. However, the therapeutic use of immunosuppressants is not free of controversy. To date, no conclusive results have been found for the effects of immunosuppressants in severe influenza virus infections (12). Furthermore, the use of corticosteroids to treat influenza virus has been associated with an increased risk of

233 superinfection, prolonged viral replication, and an increased risk of death (41). In contrast,
234 corticosteroid treatment for MERS-CoV infections was not significantly associated with
235 mortality, although a delay in MERS-CoV RNA clearance was observed (42). Further studies
236 should be performed to clarify the potential clinical benefit of prescribing immunosuppressants
237 for coronavirus infections.
238
239 To end this minireview, we will discuss an interesting potential antiviral strategy. The spike
240 protein of SARS-CoV mediates viral entry into target cells. Intriguingly, the cleavage and
241 activation of the SARS-CoV spike protein by a host cell protease is essential for infectious viral
242 entry (43). This host protease could be a type II transmembrane serine protease, TMPRSS2,
243 which was shown to cleave and activate SARS-CoV spike protein in cell cultures. Therefore,
244 TMPRSS2 is a potential a target for antiviral interventions. For example, the serine protease
245 inhibitor, camostat mesylate, inhibits the enzymatic activity of TMPRSS2 (44). Recently, K11777,
246 a cysteine protease inhibitor, was shown in tissue cultures to inhibit SARS-CoV and MERS-CoV
247 replication in the sub-nanomolar range (45). Future tissue culture and animal model studies
248 should be conducted to clarify the potential antiviral activity of targeting TMPRSS2.
249
250 By the end of February 2020, two months after the first cases of SARS-CoV-2 were reported in
251 China, several hundreds of new infection cases had been registered, mainly in other Asian
252 regions and Europe. This news has strongly suggested that we are in the thick of a SARS-CoV-2
253 pandemic. Social alarm and health authorities have called for the development of therapeutic
254 alternatives for fighting the current, and possibly new, coronavirus epidemics. Animal models

and clinical studies are urgently needed for evaluating the effectiveness and safety of promising antiviral compounds that target the virus and/or the immunopathology involved in the host responses. The identification and characterization of novel compounds and therapeutic alternatives will be required to better control this probable pandemic outbreak.

Funding. This work was supported by the Spanish Ministry of Science and Innovation [SAF2016–75277-R].

Conflicts of interest. The author declares no conflict of interest.

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