Are nucleotide inhibitors, already used for treating hepatitis C virus infection, a potential option for the treatment of COVID-19 compared with standard of care? A literature review

Anna Maria Spera

ORCID number: Anna Maria Spera 0000-0003-1292-3040.

Author contributions: Study conception and design, literature review, analysis and interpretation of data, drafting of manuscript and its critical revision was provided by Spera AM.

Conflict-of-interest statement: Authors declare no conflict of interests for this article.

Open-Access: This article is an open-access article that was selected by an in-house editor and fully peer-reviewed by external reviewers. It is distributed in accordance with the Creative Commons Attribution NonCommercial (CC BY-NC 4.0) license, which permits others to distribute, remix, adapt, build upon this work non-commercially, and license their derivative works on different terms, provided the original work is properly cited and the use is non-commercial. See: https://creativecommons.org/Licenses/by-nc/4.0/

Manuscript source: Invited manuscript

Specialty type: Infectious diseases

Country/Territory of origin: Italy

Abstract

Coronavirus disease 2019 (COVID-19) is global pandemic with various clinical presentations, ranging from cold to sometimes unrecoverable acute respiratory distress syndrome. Although urgently needed, currently there are no specific treatments for COVID-19. Repurposing existing pharmaceuticals to treat COVID-19 is crucial to control the pandemic. In silico and in vitro studies suggest that a nucleotide inhibitor called Sofosbuvir, has also antiviral activity against severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), apart from suppressing other positive-strand ribonucleic Acid viruses with conserved polymerase (hepatitis C virus). The aim of this study was to assess if Sofosbuvir improves clinical outcomes in patients with moderate or severe COVID-19. A comprehensive overview of scientific literature has been made. Terms searched in PubMed were: COVID-19, SARS-CoV-2, nucleotide inhibitors, pandemic, Sofosbuvir. Results clinical trials conducted among adults with moderate or severe COVID-19 were analyzed. Patients were divided in treatment and control arms, receiving Sofosbuvir plus standard care and standard care alone respectively. The addition of Sofosbuvir to standard care significantly reduced the duration of hospital stay compared with standard care alone in clinical trials examined. If efficacy of these repurposed, cheap and easily available drug against SARS-CoV-2 is further demonstrated, it could be essential to refine the treatment of COVID-19.

Key Words: COVID-19; SARS-CoV-2; Pandemic; Nucleotide inhibitors; Sofosbuvir; Coronavirus

©The Author(s) 2021. Published by Baishideng Publishing Group Inc. All rights reserved.
Core Tip: Coronavirus disease 2019 represents a terrible, still unsolved, global problem affecting not only the healthcare system but also the economic and social one. All countries are facing and fighting against this pandemic but there is still no specific treatment for its eradication. Recently some nucleotide inhibitors, already approved and employed for the treatment of hepatitis C virus infection, have been repurposed for treatment of severe acute respiratory syndrome coronavirus 2 infection, because of some common features among coronaviruses and hepatitis C virus. Herein briefly I focused on the effects of this compound on coronavirus disease 2019, based on its pharmacokinetic properties and on results of several completed clinical trials.

Citation: Spera AM. Are nucleotide inhibitors, already used for treating hepatitis C virus infection, a potential option for the treatment of COVID-19 compared with standard of care? A literature review. World J Virol 2021; 10(2): 53-61

URL: https://www.wjgnet.com/2220-3249/full/v10/i2/53.htm
DOI: https://dx.doi.org/10.5501/wjv.v10.i2.53

INTRODUCTION

Coronavirus disease 2019 (COVID-19) is an infection caused by a coronavirus (CoV), an enveloped positive-sense ribonucleic acid (RNA) virus with a crown-like appearance due to spike-like projections on its surface[1]. The identification of 27 cases of pneumonia of unknown etiology on 31 December 2019 in Wuhan City, China, revealed a new virus, severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), which causes COVID-19, as named by the World Health Organization (WHO)[2]. According to Zhou et al[3], SARS-CoV-2 can affect the respiratory, gastrointestinal, hepatic and central nervous system tracts of several organisms, such as humans, cattle, bats, rodents, birds and other wild animals. Given that COVID-19 has been preempted by two different events in the past (2002 and 2012) caused by crossover of animal betacoronaviruses to humans that resulted in severe disease, until the outbreak of severe acute respiratory syndromes, these zoonotic viruses were not considered highly pathogenetic to humans but only responsible for mild infections in immunocompetent people[4]. Such zoonotic spillover determines pathogen transmission from a vertebrate animal to a human. Furthermore, there is evidence of human-to-human virus transmission: Humans may change from hosts into new stable infection reservoirs[5].

Moreover, some people can act as superspreaders; overall, patients can be infectious not only during their symptomatic phase but also during their clinical recovery; as the viral loads found in the nasal cavity are higher than those of the throat, there is no difference in viral burden among symptomatic and asymptomatic patients, as Zou et al[6] recently clarified. According to Cheng et al[7], the receptor used by SARS-CoV-2 to enter the respiratory mucosa is angiotensin receptor 2 (ACE2), which is highly expressed in the Asian population; this finding may represent an interesting target for future therapeutic options, as reported. The clinical presentation of COVID-19 varies among individuals, ranging from an asymptomatic status to severe respiratory distress and multiorgan failure. SARS-CoV-2 also has neuroinvasive potential, as hypothesized by Li et al[8], entering the central nervous system, invading the olfactory nerve and bulb or the sensory fibers of the vagus nerve innervating the respiratory tract and thus causing hyposmia and dysgeusia. The disease can progress in a week to interstitial pneumonia, and in the worst cases, patients develop silent “happy” hypoxemia (respiratory failure without subjective perception of dyspnea) with evidence of hypocapnia by compensatory hyperventilation. Complications typically developed by elderly people and patients affected by underlying comorbidities include acute lung injury, acute respiratory distress syndrome, shock and acute kidney impairment[9]. Recovery begins in the 2nd or 3rd week, and the median duration of hospital stay for recovered patients is almost 10 d. Differential diagnosis of COVID-19 includes all types of respiratory viral infections, atypical organisms such as mycoplasma and chlamydia and bacterial infections[10].

INTRODUCTION

Coronavirus disease 2019 (COVID-19) is an infection caused by a coronavirus (CoV), an enveloped positive-sense ribonucleic acid (RNA) virus with a crown-like appearance due to spike-like projections on its surface[1]. The identification of 27 cases of pneumonia of unknown etiology on 31 December 2019 in Wuhan City, China, revealed a new virus, severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), which causes COVID-19, as named by the World Health Organization (WHO)[2]. According to Zhou et al[3], SARS-CoV-2 can affect the respiratory, gastrointestinal, hepatic and central nervous system tracts of several organisms, such as humans, cattle, bats, rodents, birds and other wild animals. Given that COVID-19 has been preempted by two different events in the past (2002 and 2012) caused by crossover of animal betacoronaviruses to humans that resulted in severe disease, until the outbreak of severe acute respiratory syndromes, these zoonotic viruses were not considered highly pathogenetic to humans but only responsible for mild infections in immunocompetent people[4]. Such zoonotic spillover determines pathogen transmission from a vertebrate animal to a human. Furthermore, there is evidence of human-to-human virus transmission: Humans may change from hosts into new stable infection reservoirs[5].

Moreover, some people can act as superspreaders; overall, patients can be infectious not only during their symptomatic phase but also during their clinical recovery; as the viral loads found in the nasal cavity are higher than those of the throat, there is no difference in viral burden among symptomatic and asymptomatic patients, as Zou et al[6] recently clarified. According to Cheng et al[7], the receptor used by SARS-CoV-2 to enter the respiratory mucosa is angiotensin receptor 2 (ACE2), which is highly expressed in the Asian population; this finding may represent an interesting target for future therapeutic options, as reported. The clinical presentation of COVID-19 varies among individuals, ranging from an asymptomatic status to severe respiratory distress and multiorgan failure. SARS-CoV-2 also has neuroinvasive potential, as hypothesized by Li et al[8], entering the central nervous system, invading the olfactory nerve and bulb or the sensory fibers of the vagus nerve innervating the respiratory tract and thus causing hyposmia and dysgeusia. The disease can progress in a week to interstitial pneumonia, and in the worst cases, patients develop silent “happy” hypoxemia (respiratory failure without subjective perception of dyspnea) with evidence of hypocapnia by compensatory hyperventilation. Complications typically developed by elderly people and patients affected by underlying comorbidities include acute lung injury, acute respiratory distress syndrome, shock and acute kidney impairment[9]. Recovery begins in the 2nd or 3rd week, and the median duration of hospital stay for recovered patients is almost 10 d. Differential diagnosis of COVID-19 includes all types of respiratory viral infections, atypical organisms such as mycoplasma and chlamydia and bacterial infections[10].
Clinical management of COVID-19 is based only on life support, treatment of symptoms and prevention of respiratory failure, as there are currently no registered drugs for treating this disease. Nevertheless, clinical trials based on antiviral, immunomodulatory and anti-inflammatory drugs are ongoing, moving from the SARS-CoV and MERS-CoV experience as well as in vitro observations. No conclusive evidence is available regarding the use of steroids; according to Russel et al[9] and Zhou et al[10], it is necessary to evaluate use on a case-by-case basis, considering both risks and benefits[11,12]. Lin et al[13] recommend the use of anticoagulation therapy at the early stage of the disease, particularly when the D-dimer value is 4 times higher than normal, as the infection and related factors can overactivate the coagulation cascade, possibly resulting in ischemic events and disseminated intravascular coagulation. The use of antiviral agents is controversial. In fact, although Chu et al[14], Lim et al[15] and Yao et al[16] demonstrated the efficacy of lopinavir/ritonavir (400/100 mg twice daily) against COVID-19, clinical evidence of its efficacy remains under debate. Al-Tawfiq et al[17] described the successful use of remdesivir, a nucleotide analog able to incorporate into the nascent viral RNA chain, causing its premature termination, but it is not yet recommended by the WHO[18]. Chloroquine and hydroxychloroquine, two drugs used for malaria and amoebiasis, demonstrate activity against SARS-CoV-2 in vitro and in animal models[19]. According to this study, the mechanism of action of these drugs seems to be an increase in endosomal pH, which prevents fusion between the virus and the host cell and also interferes with the ACE2 receptor targeted by the virus. Moreover, these drugs appear to have immunomodulatory activity. In addition to common side effects (nausea, vomiting, diarrhea, abdominal pain, extrapyramidal disorders), arrhythmogenic cardiotoxicity has been reported, and QT interval monitoring is mandatory with their use. When hypoxia or acute respiratory distress syndrome arises, oxygen therapy is required, basically administered through a nasal cannula, face mask or noninvasive CPAP. If an adequate arterial O2 level is not reached (SatO2 < 93%), invasive mechanical ventilation via intubation is necessary. Advanced techniques such as prone positioning should be considered[20], as should extracorporeal membrane oxygenation. The national multicenter clinical trial in Italy based on the use of tocilizumab, a monoclonal antibody against IL-6R, was prematurely interrupted[21] because no improvement in patients was shown. However, other possible therapeutic options represented by specific anti-inflammatory molecules and multiple monoclonal antibodies/immunostimulants are under investigation. Some options include anti-IL-17, interferon and mesenchymal stromal cells able to reduce inflammation and stimulate regeneration of tissues[22], amplification of anti-2019nCoV specific T lymphocytes[23], the use of anti-Th1-mediated inflammatory cascades such as canakinumab (anti-IL-1B)[24] and roflumilast (inhibitor of enzyme phosphodiesterase-4 already used to control neutrophilic inflammation in patients with COPD)[25]. Gurwitz et al[26] suggested that sartanics (angiotensin receptor 1 blockers) may be considered for their ability to inhibit binding between the spike S protein of the virus and ACE2, though other studies hypothesized that sartanics may predispose patients toward COVID-19 by targeting ACE receptors in pulmonary tissue. Another interesting option is based on the use of molecules able to target structural genes encoding the S, envelope or membrane protein along with small interfering RNAs[27]. Moreover, some broad-spectrum antiviral agents (e.g., dsRNA-activated caspase oligomerizers) can cause selective apoptosis of host cells containing the virus, which should be exploited in fighting COVID-19; however, combination with other therapies (such as thiopurine compounds, naphthalene and protease inhibitors, zinc or mercury) is necessary because antivirals alone cannot block the virus from entering the cell or disrupt viral nucleic acid[28]. COVID-19-related bradykinin-dependent local lung angioedema can be treated with bradykinin receptor B1 and B2 antagonists and anti-inflammatory agents or neutralizing strategies for anti-S antibody-induced effects[29]. In addition, the use of passive immunotherapy with plasma derived from convalescent patients is still debated[30]. Vaccination may constitute a solution, but vaccine development is ongoing. All drugs currently employed or suggested for the treatment of COVID-19 are summarized in Table 1.

The aim of this review is to evaluate the possible role of nucleotide analogs in the treatment of this dangerous pandemic, given that no drugs currently available for the treatment of SARS-CoV-2 infections seem to be effective.
### Table 1 Current ongoing treatment for coronavirus disease 2019

| Rationale of use                                                                 | Notes                                                                 |
|--------------------------------------------------------------------------------|----------------------------------------------------------------------|
| Steroids                                                                      | Prevent and treat acute lung injury and respiratory distress due to host inflammatory response secondary to SARS-CoV-2 infection | May determine Hyper-glicemia, arterial hypertension                     |
| Anticoagulation therapy                                                       | Prevent and/or treat the over-activation of the coagulation cascade, responsible for ischaemic events and disseminated intravascular coagulation | May determines Hemorrhagic risk                                           |
| Antiviral agents                                                              | Protease inhibitors (lopinavir), nucleotide analogue (remdesivir)      | May determine Drug/drug interactions, allergic reactions, acquired resistance |
| Chloroquine/hydroxychloroquine                                                | Increasing in endosomal pH, avoiding the fusion between the virus and the host cell, but also the interference with the ACE2 cell receptor targeted by the virus. immunomodulatory activity | May determine common side effects (nausea, vomiting, diarrhea, abdominal pain, extrapyramidal disorders), and arrhythmogenic cardiotoxicity (thus monitor QT interval) |
| Oxygen therapy                                                                | Treatment of hypoxia basically administered through a nasal cannula, face mask or noninvasive CPAP. If an adequate arterial O2 level is not reached (SatO2 < 95%), invasive mechanical ventilation or intubation is necessary. Advanced technique such as prone positioning should be considered as well as extracorporeal membrane oxygenation |
| Antinflammatory molecules – multiple monoclonal antibodies/immunostimulants (anti IL-17, interferon and mesenchymal stromal cells) | Able to reduce inflammation and stimulate regeneration of tissues as well, the amplification of anti-2019nCoV specific T lymphocytes, the employment of anti-Th1-mediated inflammatory cascade such as canakinumab (anti IL-1B) and roflumilast (inhibitor of enzyme phosphodiesterase-4 already used to control neutrophilic inflammation in patients with COPD) |
| Sartanics (angiotensin receptor 1 blockers)                                   | Could be considered for their ability to inhibit the link between the spike S protein of the virus and ACE2 | According to other studies could predispose to COVID targeting ACE receptors on pulmonary tissue |
| Some broad spectrum antiviral agents (dsRNA-activated caspase oligomerizer)    | Cause selective apoptosis of host cells containing virus, this skill could be exploited in fighting COVID-19 |
| Bradykinin receptors B1 and B2 antagonists                                     | COVID related bradykinin-dependent local lung angioedema               |
| Plasma                                                                        | Passive immunotherapy                                                  |

COVID-19: Coronavirus disease 2019; SARS-CoV-2: Severe acute respiratory syndrome coronavirus 2; ACE2: Angiotensin receptor 2; RNA: Ribonucleic acid.

**NUCLEOTIDE ANALOGS IN THE TREATMENT OF CORONAVIRUS DISEASE 2019: WHERE ARE WE NOW?**

A novel therapeutic approach for COVID-19 is based on the use of nucleotide analogs. One such analog is Sofosbuvir, a powerful anti-hepatitis C virus direct-acting agent that targets HCV polymerase NS5B, approved by national and international agencies. It has a demonstrated ability to suppress other positive-strand RNA viruses, such as members of Flaviviridae and Togaviridae, in addition to Coronaviridae. Although not currently listed as a potential option for SARS-CoV-2 therapy, sofosbuvir may represent a key step in the control of the COVID-19 pandemic, as stated by Jácome et al. Nevertheless, the winning strategy may instead be based on a multitargeted approach of different drugs targeting many viral proteins. Sofosbuvir binds to the active site of HCV and is thus incorporated in the nascent strand, preventing the addition of the next nucleotide. The replication mechanisms of coronaviruses, flaviviruses and togaviruses require an RNA-dependent RNA polymerase that is targeted by sofosbuvir, ribavirin and AZT. This has been demonstrated by Elfiky et al. in a recent in silico study based on homology modeling: the docking scores that emerged from the study suggested the possible use of these antiviral drugs in the treatment of disease caused by SARS-CoV-2.

The RdRp enzyme of coronaviruses tightly embody biologically activated triphosphate forms of “four nucleotide/nucleoside analog” antiviral drugs (sofosbuvir, tenofovir alafenamide, alovudine and AZT), without further...
incorporation thereafter, as clearly reported by Chien et al\(^{(31)}\). Therefore, all these compounds may be considered permanent terminators for SARS-CoV-2 RdRp\(^{(30,32)}\) and are of curative significance for COVID-19, though the authors did not suggest the best RdRp inhibitor.

**Sofosbuvir: An antiviral drug**

The antiviral effect of sofosbuvir and its potent, fast action\(^{(31)}\), even against liver cirrhosis, is well known, even in the setting of a lack of response to other medications, such as interferon and ribavirin\(^{(31)}\). Pivotal trials of this pangenotypic DAA\(^{(35)}\) (Fission, Positron, Fusion and Photon 1)\(^{(36-38)}\) report its high rate of success, significant efficacy, low rate of side effects and tolerability. Moreover, this antiviral compound does not interfere with the cytochrome P450 system or other major drug-metabolizing enzymes and has low drug-drug interactions. With a good pharmacokinetic profile, sofosbuvir can be prescribed as a single oral daily dose. The antiviral activity of the active form of sofosbuvir is related to the intracellular production of its active triphosphate metabolite by intracellular nucleoside diphosphate kinase (NDK), an enzyme encoded by National Military Establishment that is present in all cells, including the alveolar epithelial type II cells targeted/infected by SARS-CoV-2. The main role of NDK is to maintain an equilibrium between the concentrations of several nucleoside/nucleotide triphosphates, which are thus the source of RNA and deoxyribonucleic acid precursors such as CTP, UTP and GTP\(^{(31)}\). The presence of NDK-A and NDK-B in airway epithelial membranes has been suggested by Muimo et al\(^{(39)}\) using isoform-specific antibodies, whereby local COVID-19-mediated lung inflammation enhanced sofosbuvir endothelial permeability and improved epithelial uptake during SARS-CoV-2 infection. The extremely high intracellular stability of sofosbuvir and its triphosphate metabolite is a main feature of this antiviral drug and explains its significant and persistent HCV effect in inhibiting HCV-NS5B polymerase\(^{(31)}\). Moreover, intracellular levels of its triphosphate metabolite in alveolar epithelial type II cells may inhibit SARS-CoV-2 RdRp (in accordance with its EC50).

Notably, it must be emphasized that use of the currently employed nucleoside analog remdesivir has recently been reduced. In fact, the living WHO guidelines on drugs for COVID-19\(^{(18)}\) released on September 4 and then updated in November 2020 strongly suggest no remdesivir use for patients with COVID-19 at any severity; this was based on results of a systematic review and network meta-analysis including data for 4 randomized trials with 7333 adult patients hospitalized for COVID-19. No effect on mortality, need for mechanical ventilation, or time to clinical improvement was found among COVID-19 patients treated with remdesivir. The conclusion is that remdesivir does not improve important patient outcomes. Jockusch et al\(^{(40)}\) reported in Nature that RNA terminated by sofosbuvir is more resistant to SARS-CoV-2 proofreading than RNA terminated by remdesivir.

Several randomized and nonrandomized clinical trials have been performed comparing DAA-based regimens and standard of care (SOC) in hospitalized COVID-19 patients\(^{(30)}\). Trials eligible for inclusion were identified by reviewing clinicaltrials government, WHO International Clinical Trials Registry Platform and Cochrane Central Register of Controlled Trials. Three\(^{(34,35)}\) of eight studies reviewed were considered by Simmons et al\(^{(40)}\) because they met the inclusion criteria (completed trials about the comparison of predetermined DAA-based regimens and SOC for the treatment of COVID-19). The primary outcomes highlighted were clinical recovery in 14 d and all-cause mortality from enrollment to the end of the follow-up; the findings along with secondary outcomes are summarized in Table 2. An individual patient data meta-analysis was produced, and treatment effects were reported as risk ratios and mean differences for binary and continuous outcomes, respectively. Cox proportional hazards models were used to estimate the cause-specific hazard ratios for recovery, and the Fine and Gray competing risk model was employed to account for death as a competing risk. A sensitivity analysis for the primary outcomes involved excluding nonrandomized trials because of the potential risk of bias. A second analysis for primary binary outcomes was performed, including the worst outcomes not yet considered in the Intention to treat analysis of all the studies included in the meta-analysis.

The effects of nonrandomized treatment assignment were studied in a final sensitivity analysis in which the effect of sofosbuvir/daclatasvir on clinical recovery and death was estimated using the inverse probability weighting estimator adjusted for age, sex and comorbidities (hypertension, chronic pulmonary illness, diabetes mellitus). Data were analyzed using STATA vers 14.2 and Rstudio vers 3.5.3.

Three Iranian studies of the eight available were conducted among 176 hospitalized patients, with equal reported baseline characteristics among the intervention and
control groups. Two of the three studies were randomized\(^{[44,45]}\) and included patients affected by severe disease. A combination of DAA + SOC at the time of trial (hydroxychloroquine + lopinavir/ritonavir) was administered to the intervention arm of each trial; the control groups received only SOC (hydroxychloroquine plus lopinavir/ritonavir, hydroxychloroquine plus lopinavir/ritonavir and ribavirin, hydroxychloroquine plus lopinavir/ritonavir plus or without ribavirin), as reported in Table 3. Ninety-three percent of patients in the intervention arm and 68% in the control arms achieved clinical recovery after 14 d of randomization. Five percent in the intervention arms and 20% in the control arms died during the trial: a higher frequency of comorbidities, though not significant, was detected in the control arm. Significant differences in secondary outcomes (duration of hospitalization and intensive care unit admission or intermittent mandatory ventilation requirement) in favor of the DAA treatment-based group were found. Although limited by the small number of studies included and lack of full blinding and uniform reported primary outcomes, the cited meta-analysis revealed significant differences in clinical recovery and all-cause mortality in favor of sofosbuvir/daclatasvir regimens for the treatment of COVID-19. In conclusion, considering that managing a placebo-controlled trial during a pandemic is difficult, it is important to underline that the Iranian authors of those clinical trials took up a tough challenge, raising awareness of the whole scientific community about the use of sofosbuvir for the treatment of COVID-19 and encouraging larger randomized trials to establish the potential utility of nucleotide inhibitors for this disease. Moreover, given that sofosbuvir has been used for treating early stages of COVID-19, further studies are needed to evaluate whether this nucleotide analog may even be used to prevent SARS-CoV-2 contagion suddenly after the first exposure to this specific antigen.

**CONCLUSION**

The addition of Sofosbuvir to standard care significantly reduced the duration of hospital stay compared with standard care alone in clinical trials examined. If efficacy of these repurposed, cheap and easily available drug against SARS-CoV-2 is further demonstrated, it could be essential to refine the treatment of COVID-19.

### Table 2 Primary and secondary outcomes of studies included in simmons’ meta-analysis

| Outcomes                  | Intervention arm (92 patients) | Control arm (84 patients) |
|---------------------------|-------------------------------|---------------------------|
| Primary                   |                               |                           |
| Clinical recovery in 14 d | 86 (93%)                      | 57 (68%)                  |
| All cause mortality       | 5 (5%)                        | 17 (20%)                  |
| Secondary                 |                               |                           |
| Duration of hospitalization | 6 (IQR: 5-7)             | 8 (IQR: 6-11)            |
| ICU admission/imv needed  | 9 (10%)                       | 24 (29%)                  |

ICU: Intensive care unit.
Table 3 Therapeutic schedule of clinical trials considered in meta-analysis

| Disease stage | Treatment arm                                                      | Control arm                                                      | Duration |
|---------------|-------------------------------------------------------------------|-----------------------------------------------------------------|----------|
| Esfandi        | 35 patients: SOC (lopinavir/ritonavir + hydroxychloroquine) + Sof/dac started 24-48 h later (after PCR and TC confirmation of COVID-19) | 27 patients: SOC (lopinavir/ritonavir + hydroxychloroquine) + ribavirin | 14 d     |
| Kasgari        | 24 patients: Sof/dac + ribavirin                                  | 24 patients: Lopinavir/ritonavir + hydroxychloroquine + Ribavirin | 6 d?     |
| Sadeghi        | 33 patients: Sof/dac + lopinavir/ritonavir                        | 33 patients: Lopinavir/ritonavir                                 | 14 d     |

SOC: Standard of care; COVID-19: Coronavirus disease 2019.

REFERENCES

1. Richman DD, Whitley RJ, Hayden FG. Clinical Virology, 4th ed. Washington: ASM Press; 2016. Available from: https://www.wiley.com/en-us/Clinical-Virology%3A+4th+Edition-p-9781683673163

2. World Health Organization, WHO Director-General’s Remarks at the Media Briefing on 2019-nCoV on 11 February 2020 (cited February 23, 2021). Available from: https://www.who.int/dg/speeches/detail/who-director-general-s-remarks-at-the-media-briefing-on-2019-ncov-on-11-february-2020

3. Zhou P, Yang XL, Wang YX, Hu B, Zhang L, Zhang W, Si HR, Zhi Y, Li B, Huang CL, Chen HD, Chen J, Luo Y, Guo H, Jiang RD, Liu MQ, Chen Y, Shen XR, Wang X, Zheng XS, Zhao K, Chen QJ, Deng F, Liu LL, Yan B, Zhan FX, Wang YY, Xiao GF, Shi ZL. A pneumonia outbreak associated with a new coronavirus of probable bat origin. Nature 2020; 579: 270-273 [PMID: 32015507 DOI: 10.1038/s41586-020-2012-7]

4. Chan-Yeung M, Xu RH. SARS: epidemiology. Respiratory 2003; 8 Suppl: S9-14 [PMID: 15018127 DOI: 10.1046/j.1440-1843.2003.00518.x]

5. Singhal T. A Review of Coronavirus Disease-2019 (COVID-19). Indian J Pediatr 2020; 87: 281-286 [PMID: 32166607 DOI: 10.1007/s12098-020-03263-6]

6. Zou L, Ruan F, Huang M, Liang L, Huang H, Hong Z, Yu J, Kang M, Song Y, Xia J, Guo Q, Song T, He J, Yen HL, Peiris M, Wu J. SARS-CoV-2 Viral Load in Upper Respiratory Specimens of Infected Patients. N Engl J Med 2020; 382: 1177-1179 [PMID: 32074444 DOI: 10.1056/NEJMoa2001777]

7. Cheng ZJ, Shan J. 2019 Novel coronavirus: where we are and what we know. Infection 2020; 48: 155-163 [PMID: 32072560 DOI: 10.1007/s12098-020-04104-y]

8. Li YC, Bai WZ, Hashikawa T. The neuroinvasive potential of SARS-CoV-2 may play a role in the respiratory failure of COVID-19 patients. J Med Virol 2020; 92: 552-555 [PMID: 32104915 DOI: 10.1002/jmv.25728]

9. Russell CD, Millar JE, Baille JK. Clinical evidence does not support corticosteroid treatment for 2019-nCoV lung injury. Lancet 2020; 395: 473-475 [PMID: 32043983 DOI: 10.1016/S0140-6736(20)30317-2]

10. Zhou W, Liu Y, Tian D, Wang C, Wang S, Cheng J, Hu M, Fang M, Gao Y. Potential benefits of precise corticosteroids therapy for severe 2019-nCoV pneumonia. Signal Transduct Target Ther 2020; 5: 18 [PMID: 32296012 DOI: 10.1038/s41392-020-0127-9]

11. Lin L, Lu L, Cao W, Li T. Hypothesis for potential pathogenesis of SARS-CoV-2 infection—a review of immune changes in patients with viral pneumonia. Emerg Microbes Infect 2020; 9: 727-732 [PMID: 32196410 DOI: 10.1002/emm.12773]

12. Chu CM, Cheng VC, Hung IF, Wong MM, Chan KH, Chan KS, Kao RY, Poon LL, Wong CL, Guan Y, Peiris JS, Yuen KY. HKU/UCH SARS Study Group. Role of lopinavir/ritonavir in the treatment of SARS: initial virological and clinical findings. Thorax 2004; 59: 252-256 [PMID: 14985565 DOI: 10.1136/thorax.2004.012658]

13. Lim J, Jeon S, Shin HY, Kim MJ, Seong YM, Lee WJ, Choe KW, Kang YM, Lee B, Park SJ. Case of the Index Patient Who Caused Tertiary Transmission of COVID-19 Infection in Korea: the Application of Lopinavir/Ritonavir for the Treatment of COVID-19 Infected Patients Monitored by Quantitative RT-PCR. J Korean Med Sci 2020; 35: e79 [PMID: 32056407 DOI: 10.3346/jkms.2020.35.e79]

14. Yao TT, Qian JD, Zhu WY, Wang Y, Wang GQ. A systematic review of lopinavir therapy for SARS coronavirus and MERS coronavirus-A possible reference for coronavirus disease-19 treatment option. J Med Virol 2020; 92: 556-563 [PMID: 32149047 DOI: 10.1002/jmv.25729]

15. Al-Tawfiq JA, Al-Homoud AH, Memish ZA. Remdesivir as a possible therapeutic option for the COVID-19. Travel Med Infect Dis 2020; 34: 101615 [PMID: 32145386 DOI: 10.1016/j.tmaid.2020.101615]

16. Siemieniuk R, Rochwerg B, Agoritsas T, Lamontagne F, Leo YS, Macdonald H, Agarwal A, Zeng L, Lytvyn L, Appiah JA, Amin W, Arabi Y, Blumberg L, Burhan E, Bausch DJ, Caffee CS, Cao B, Cecconi M, Chanda D, Cooke G, Du B, Dunning J, Geduld H, Ge P, Hashimi M, Hui DS, Kabra S, Kanda S, Kawano-Dourado L, Kim YJ, Kissoon N, Kwizera A, Laake JH, Machado FR, Mahak J,
Mani H, Mino G, Nsetedu E, Pshenichnaya N, Qadir N, Sabzwari S, Sarin R, Sharland M, Shen Y, Sri Ranganathan S, Souza J, Ugarte S, Venkatapuran S, Quoc Dat V, Vuyiseka D, Stiegmann M, Wijewickrama A, Maguire B, Zenzhukar D, Bartoszko J, Ge L, Brigandrello-Petersen R, Owen A, Guyat G, Diaz J, Jacobs M, Vandvik PO. A living WHO guideline on drugs for covid-19. BMJ 2020; 370: m3379 [PMID: 3288769] DOI: 10.1136/bmj.m3379

Savarino A, Di Trani L, Donatelli I, Cauda R, Cassone A. New insights into the antiviral effects of chloroquine. Lancet Infect Dis 2006; 6: 67-69 [PMID: 16439323 DOI: 10.1016/S1473-3099(06)70361-9]

Munshi L, Del Sorbo L, Adhikari NKJ, Hodgson CL, Wunsch H, Meade MO, Uldery E, Mancebo J, Pesenti A, Ranieri VM, Fan E. Prone Position for Acute Respiratory Distress Syndrome. A Systematic Review and Meta-Analysis. Ann Am Thorac Soc 2017; 14: S280-S288 [PMID: 29068269 DOI: 10.1513/AnnalsATS.201704-343OT]

Agenzia Italiana del Farmaco. COVID 19: Studio randomizzato italiano, nessun beneficio dal tocilizumab, 2020 (cited February 23, 2021). Available from: https://www.aifa.gov.it/web/guest/-/covid-19-studio-randomizzato-italiano-nessun-beneficio-dal-tocilizumab

Horie S, Gonzalez HE, Laffey JG, Masterson CH. Cell therapy in acute respiratory distress syndrome. J Thorac Dis 2018; 10: 5607-5620 [PMID: 30416812 DOI: 10.21037/jtd.2018.08.28]

Zamula A, Hui DS, Azhar EI, Memish ZA, Maquer M. Reducing mortality from 2019-nCoV: host-directed therapies should be an option. Lancet 2020, 395: e35-e36 [PMID: 32030181 DOI: 10.1016/S0140-6736(20)30305-6]

Chakraborty A, Tannenbaum S, Rordorf C, Lowe PJ, Floch D, Gram H, Roy S. Pharmacokinetic and pharmacodynamic properties of canakinumab, a human anti-interleukin-1β monoclonal antibody. J Allergy Clin Immunol 2012; 51: e1-e18 [PMID: 22550964 DOI: 10.2166/jaci.2012.00750]

Wedzicha JA, Calverley PM, Rabe KF. Roflumilast: a review of its use in the treatment of COPD. Int J Chron Obstruct Pulmon Dis 2016; 11: 81-90 [PMID: 26792988 DOI: 10.2147/COPD.S89849]

Gurwitz D. Angiotensin receptor blockers as tentative SARS-CoV-2 therapeutics. Drug Dev Res 2020; 81: 537-540 [PMID: 32129518 DOI: 10.1002/ddr.21656]

Khan S, Siddique R, Shereen MA, Ali A, Liu J, Bai Q, Bashir N, Xue M. Emergence of a Novel Coronavirus, Severe Acute Respiratory Syndrome Coronavirus 2: Biology and Therapeutic Approaches. J Clin Microbiol 2020; 58: 10.1128/JCM.01187-20

van de Veerdonk F, Netea MG, van Deuren M, van der Meer JW, de Mast Q, Bruggemann RJ, van der Hoeven H. Kinins and Cytokines in COVID-19: A Comprehensive Pathophysiological Approach. 2020 Preprint [DOI: 10.20944/preprints202004.0023.v1]

Zhang L, Liu Y. Potential interventions for novel coronavirus in China: A systematic review. J Med Virol 2020; 92: 479-490 [PMID: 32052466 DOI: 10.1002/jmv.25707]

Sayad B, Sobhani M, Khodarahmi R. Sofosbuvir as Repurposed Antiviral Drug Against COVID-19: Why Were We Convinced to Evaluate the Drug in a Registered/Approved Clinical Trial?. Arch Med Res 2020; 51: 577-581 [PMID: 32387040 DOI: 10.1016/j.arcmed.2020.04.018]

Jácome R, Campillo-Balders JA, Ponce de León S, Becerra A, Lázcano A. Sofosbuvir as a potential alternative to treat the SARS-CoV-2 epidemic. Sci Rep 2020; 10: 9294 [PMID: 32518317 DOI: 10.1038/s41598-020-66440-9]

Elfiky AA. Anti-HCV, nucleotide inhibitors, repurposing against COVID-19. Life Sci 2020; 248: 117477 [PMID: 32119961 DOI: 10.1016/j.lfs.2020.117477]

Chien M, Anderson TK, Juckusch S, Tao C, Li X, Kumar S, Russo JJ, Kirchdoerfer RN, Ju J. Nucleotide Analogues as Inhibitors of SARS-CoV-2 Polymerase, a Key Drug Target for COVID-19. J Proteome Res 2020; 19: 4690-4697 [PMID: 32692185 DOI: 10.1021/acs.jproteome.0c00392]

Chien M, Anderson TK, Juckusch S, Tao C, Kumar S, Li X, Russo JJ, Kirchdoerfer RN. J. Nucleotide Analogues as Inhibitors of SARS-CoV-2 Polymerase. bioRxiv 2020 [PMID: 32511320 DOI: 10.1101/2020.03.18.997585]

Guedj J, Pang PS, Denning J, Rodríguez-Torres M, Lawitz E, Symonds W, Perelson AS. Analysis of hepatitis C viral kinetics during administration of two nucleotide analogues: sofosbuvir (GS-7977) and GS-9038. Antivir Ther 2014; 19: 211-220 [PMID: 2446551 DOI: 10.3851/IMP2733]

Gentile I, Maroalo AE, Buonomo AR, Zappulo E, Borgia G. The discovery of sofosbuvir: a revolution for therapy of chronic hepatitis C. Expert Opin Drug Discov 2015; 10: 1363-1377 [PMID: 26563720 DOI: 10.1517/17464404.2015.1049051]

Hebner C, Lee Y-J, Han B, Chiu S, Tian Y, Pagratís N, Miller M, Mo H. In vitro pan-genotypic and combination activity of sofosbuvir (GS-7977) in stable replicon cell lines. Hepatology 2012; 56: 1066A

Lawitz E, Mangia A, Wyles D, Rodriguez-Torres M, Hassanein T, Gordon SC, Schultz M, Davis MN, Kayali Z, Reddy KR, Jacobson IM, Kowdley KV, Nyberg L, Subramanian GM, Hyland RH, Arterburn S, Jiang D, McNally J, Brainard D, Symonds WT, Jecichinsowki FG, Sheikh AM, Yousoufi Z, Gane EJ. Sofosbuvir for previously untreated chronic hepatitis C infection. N Engl J Med 2013; 368: 1878-1887 [PMID: 23607594 DOI: 10.1056/NEJMoa1214853]

Jacobson IM, Gordon SC, Kowdley KV, Yoshida EM, Rodriguez-Torres M, Sulkowski MS, Shiffman ML, Lawitz E, Everson G, Bennett M, Schiff E, Al-Assi MT, Subramanian GM, An D, Lin M, McNally J, Brainard D, Symonds WT, McHutchison JG, Patel K, Feld J, Pianko S, Nelson DR; POSITRON Study; FUSION Study. Sofosbuvir for hepatitis C genotype 2 or 3 in patients without treatment options. N Engl J Med 2013; 368: 1867-1877 [PMID: 23607593 DOI: 10.1056/NEJMoa1214854]
Spera AM. Sofosbuvir: An antiviral drug for a viral infection

38 Sulkowski M, Rodriguez-Torres M, Lalezari J, Fessel W, Mounzer K, Shuhart M, Lucetkemeyer A, Asmuth D, Gaggar A, Ni L, Svarovskaia E, Symonds B, McHutchison J, Naggie S, Dieterich D. All-oral therapy with sofosbuvir plus ribavirin for the treatment of HCV genotype 1, 2, and 3 infection in patients coinfected with HIV (PHOTON-1). 64th Annual Meeting of the American Association for the Study of Liver Diseases (AASLD); Washington, DC. November 1-5, 2013. Available from: https://www.natap.org/2013/AASLD/AASLD_34.htm

39 Boissan M, Schlattner U, Lacombe ML. The NDPK/NME superfamily: state of the art. Lab Invest 2018; 98: 164-174 [PMID: 29451272 DOI: 10.1038/labinvest.2017.137]

40 Muino R, Crawford RM, Mehta A. Nucleoside diphosphate kinase A as a controller of AMP-kinase in airway epithelia. J Biol Chem 2006; 38: 181-187 [PMID: 17039396 DOI: 10.1007/s10863-006-9033-2]

41 Meier C. Nucleoside diphosphate and triphosphate prodrugs - An unsolvable task? Antivir Chem Chemother 2017; 25: 69-82 [PMID: 29096525 DOI: 10.1177/2040206617738856]

42 Jockusch S, Tao C, Li X, Chien M, Kumar S, Morozova I, Kalachikov S, Russo JJ, Ju J. Sofosbuvir terminated RNA is more resistant to SARS-CoV-2 proofreader than RNA terminated by Remdesivir. Sci Rep 2020; 10: 16577 [PMID: 33024223 DOI: 10.1038/s41598-020-73641-9]

43 Simmons B, Wentzel H, Mobarak S, Eslami G, Sadeghi A, Ali Asgari A, Abbaspour Kasgari H, Tirgar Fakheri H, Merat S, Hill A. Sofosbuvir/daclatasvir regimens for the treatment of COVID-19: an individual patient data meta-analysis. J Antimicrob Chemother 2021; 76: 286-291 [PMID: 33063117 DOI: 10.1093/jac/dkaa318]

44 Abbaspour Kasgari H, Moradi S, Shabani AM, Bahamahmoodi F, Davoudi Badabi AR, Davoudi L, Alikhani A, Hedayatizadeh Omran A, Saeedi M, Merat S, Wentzel H, Garratt A, Levi J, Simmons B, Hill A, Tirgar Fakheri H. Evaluation of the efficacy of sofosbuvir plus daclatasvir in combination with ribavirin for hospitalized COVID-19 patients with moderate disease compared with standard care: a single-centre, randomized controlled trial. J Antimicrob Chemother 2020; 75: 3373-3378 [PMID: 32812025 DOI: 10.1093/jac/dkaa332]

45 Sadeghi A, Ali Asgari A, Norouzi A, Kheiri Z, Anushirvani A, Montazeri M, Hosamirud sai H, Afsahi S, Akbarpour E, Aliannejad R, Radmard AR, Davaranah AH, Levi J, Wentzel H, Qavi A, Garratt A, Simmons B, Hill A, Merat S. Sofosbuvir and daclatasvir compared with standard of care in the treatment of patients admitted to hospital with moderate or severe coronavirus infection (COVID-19): a randomized controlled trial. J Antimicrob Chemother 2020; 75: 3379-3385 [PMID: 32812039 DOI: 10.1093/jac/dkaa334]

46 Eslami G, Moussaviasl S, Radmanesh E, Jelvay S, Bitaraf S, Simmons B, Wentzel H, Hill A, Sadeghi A, Freeman J, Salmanzadeh S, Esmaeili H, Mobarak M, Tabibi R, Safari Kashi AH, Lotfi Z, Talebzadeh SM, Wickramatilleke A, Momtazan M, Hajjizadeh Farsani M, Marjani S, Mobarak S. The impact of sofosbuvir/daclatasvir or ribavirin in patients with severe COVID-19. J Antimicrob Chemother 2020; 75: 3366-3372 [PMID: 32812051 DOI: 10.1093/jac/dkaa331]
