Coronavirus Pneumonia and Pulmonary Thromboembolism

Mingkang Yao¹, Phei Er Saw²,* and Shanping Jiang¹,*

Abstract
In 2019, a novel pneumonia, called coronavirus disease 2019 (COVID-19), spread rapidly throughout the world. This novel global pandemic severely threatened public respiratory health and medical services. To date, except for the common respiratory symptoms, coagulation disorders, especially pulmonary thromboembolism (PTE), have been proven as an important complication in severe COVID-19 patients, and the incidence of PTE causes poor clinical outcome and increased fatality. Therefore, it is important that healthcare providers, including respiratory physicians, emergency medicine specialists, hematologists, cardiologists, infectious disease specialists, and other specialists, recognize that patients with COVID-19 are at increased risk of PTE, and ensure that appropriate prophylaxis is administered to the appropriate patients, and that they effectively manage PTE when it does occur. The mechanism of PTE in patients with coronavirus pneumonia consists of endothelial injury, activated platelet, cytokine storm, and a suppressed fibrinolytic system. Early prophylaxis, antiviral therapy, anticoagulation, and supportive treatment are beneficial to COVID-19 patients. In this review, we summarize the harm that coronavirus pneumonia wreaks and highlight the clinical relationship between PTE and coronavirus infection. The potential mechanism and the prophylaxis and therapeutic measures are also discussed to call for more effort and research to investigate the strategies for PTE in COVID-19.

Keywords
Coronavirus pneumonia, COVID-19, pulmonary thromboembolism.

The background of coronavirus and pulmonary thromboembolism
Coronaviruses (CoVs) are a group of single-stranded positive-sense RNA viruses, which can infect humans and other species and which have had a great impact on global public health in the recent decades. CoVs can not only destroy the respiratory system of humans, but can also induce coagulation disorders and even pulmonary thromboembolism (PTE) [1]. PTE refers to a blood clot from the venous system or the right side of the heart that obstructs the pulmonary arteries and their branches and it has a poor clinical prognosis [2]. Patients with coronavirus disease 2019 (COVID-19) have an increased risk of thrombotic complications and the incidence of coagulation disorders or PTE can cause the deterioration of a patient’s condition and increases the mortality rate [3]. Therefore, this review will elaborate the mechanisms of the occurrence of coagulation disorders and PTE in patients with coronavirus pneumonia and introduces prophylactic and therapeutic measures.

The detrimental effect of coronaviruses and pulmonary thromboembolism
Coronaviruses belong to the Coronaviridea subfamily of the Coronaviridae family and they can be divided into four genera: alpha CoVs, beta CoVs, gamma CoVs, and delta CoVs. To date, a total of seven coronaviruses that can infect human have been found, including HCoV-229E, HCoV-OC43, HCoV-NL63, HCoV-HKU1, SARS-CoV, MERS-CoV, and SARS-CoV-2 (2019-nCOV) and these CoVs can lead to respiratory or digestive symptoms in humans. HCoV-229E and HCoV-NL63 are alpha CoVs while HCoV-OC43, HCoV-HKU1, SARS-CoV, MERS-CoV, and SARS-CoV-2 are the members of beta coronaviruses [4]. SARS-CoV, MERS-CoV, and SARS-CoV-2 can result in a life-threatening pneumonia and all of them have caused global pandemics in the 21st century. At the end of 2002, the first case of severe acute respiratory syndrome (SARS) was reported in Guangdong Province, China. The disease...
Coronavirus-associated pulmonary thromboembolism

SARS and PTE

There was an outbreak of SARS in Toronto, Canada between March and July, 2003 that resulted in 375 infected cases. Forty-four patients died of SARS; post-mortem examinations were performed on 20 of them in order to understand the progression of SARS. Researchers found, using Martius scarlet blue staining, that endothelial injury of pulmonary small vessels and intravascular fibrin deposition were evident in all the cases of those who died. Fibrin thrombi (85%, 17/20) and pulmonary infracts (60%, 12/20) were also commonly found in those who died [11]. Furthermore, Lee et al. reported SARS patients usually had some concomitant coagulation disorders, such as thrombocytopenia (44.8%), prolonged activated partial-thromboplastin time (42.8%), and elevated D-dimer (45.0%) [12] and a retrospective analysis demonstrated that the incidence rate of thrombotic events in severe SARS patients would be much higher [13].

MERS and PTE

Li et al. found that microthrombi in pulmonary vasculature could present in the histopathologic examination of transgenic mice expressing the human dipeptidyl peptidase 4 (hDPP4) with the infection of MERS-CoV [14]. Moreover, Assiri and his colleagues found that thrombocytopenia was a common clinical feature of MERS patients [15]. Hwang et al. also reported that MERS patients tend to have a relatively lower platelet count [16]. These studies indicate that the poor prognosis of MERS patients may be associated with coagulation disorders and PTE.

COVID-19 and PTE

A recent single institutional study performed by Zhang et al. showed that out of 143 patients hospitalized with COVID-19, 66 patients developed lower extremity DVTs (46.1%, 66/143) and 43 of the patients developed DVTs in their distal veins (65.2%, 43/66), while the other 23 patients developed DVTs in their proximal veins (34.8%, 23/66) [17]. Kaminetzky et al. found 23 patients (37.1%) had positive computed tomography pulmonary angiography (CTPA) results for PE in a cohort of 62 COVID-19 patients who underwent CTPA [18]. Klok et al. also studied 184 COVID-19 patients in ICUs and found that the incidence rate of thrombotic events was as high as 31%, of which 27% were diagnosed as VTE and 3.7% were found to be arterial thrombi in the body circulation and this research indicated that COVID-19 may result in coagulation disorders in both the venous and arterial systems [19]. Bilaloglu et al. found that 533 out of 3334 hospitalized COVID-19 patients (16.0%), most of whom received low-dose anticoagulation for prophylaxis, had thrombotic events (patients could have more than one thromboembolism) and venous thromboembolism occurred in 207 (6.2%), while arterial thromboembolism occurred in 365 (11.1%) [20]. In Germany, Wichmann and his colleagues performed autopsies for 12 COVID-19-positive deaths and the autopsies showed that seven of 12 patients (58%) had DVTs. These venous thromboembolism events were not detected by clinical doctors and PE was the direct lethal factor in four patients while the other three patients had fresh venous thrombosis in their lower extremities. Fresh thrombosis was also found in the prostatic venous plexus in six male patients. And the histopathologic results of lungs revealed diffuse alveolar damage, microvascular thromboemboli, capillary congestion, and protein-enriched interstitial edema were the main pathological manifestations [21]. Zhang et al. suggested that COVID-19 patients with DVT had a lower oxygenation index and higher values of
C-reactive protein and procalcitonin than those without DVT. Besides, COVID-19 patients with DVT had a higher possibility of being found to have pulmonary hypertension and larger right atrial and right ventricular diameters on echocardiograms compared with a non-DVT group. In the same study, researchers revealed that advanced age (>65 years), prolonged bedridden time (>72 h) and high PaO2/FiO2 score (>14) were the risk factors of DVT in COVID-19 patients and the patients with DVT had a worse prognosis and higher mortality [17]. Kaminetzky et al. also found evidence of right heart strain on either an echocardiogram or CTPA in 10 of 23 COVID patients (43.5%) with PEs [18].

Moreover, the increase of d-dimer is the most common abnormal laboratory examination for COVID-19 patients. D-dimer is the product of fibrin degradation and usually increases during the incidence in a thrombotic event so it is used as a reliable marker of fibrinolysis [2]. A large clinical study in China showed 260 of 560 COVID-19 cases (46.4%) had an elevated d-dimer while the proportion was even higher in ICU patients (59.6%) [22]. Another study performed by Goshua et al. also demonstrated that the level of d-dimer of COVID-19 ICU patients was much higher than those in a non-ICU group and among the standard reference range [23]. Kaminetzky et al. suggested that the mean level of d-dimer in COVID-19 patients with PEs was much higher than those without PEs (6432 ng/ml versus 1774 ng/ml, p < 0.001) and they identified a value of d-dimer (>1394 ng/ml), which could predict the incidence of PE with a sensitivity of 94.5% and a specificity of 71.4% [18]. A recent study also pointed out that there was a positive correlation between the level of d-dimer and the mortality of COVID-19 patients who did not receive heparin treatment [24] and Zhang and his colleagues found that the level of d-dimer (>2.0 mg/L) could predict the patients’ mortality with 92.3% sensitivity of and 83.3% specificity [25].

A meta-analysis by Lippi et al. revealed that thrombocytopenia was a common feature in critically ill COVID-19 patients [weighted mean difference −31 × 10⁹/L; 95% confidence interval (CI), from −35 to −29 × 10⁹/L] and the decrease of platelet count was associated with the increased risk of severe disease and deaths in COVID-19 patients [26]. In contrast, some studies have reported that no significant difference of platelet count existed between the severe COVID-19 patients and moderate patients [27–29]. Lastly, a study also showed that the platelet count in COVID-19 patients with DVT was not significantly different from those without DVT [17]. Moreover, Qu et al. found platelet peaks and platelet-to-lymphocyte (PLR) at the platelet peak were associated with the severity and duration of COVID-19 patients [30]. However, some cases reported an elevated platelet count in severe COVID-19 patients and this phenomenon was considered as the over-activation of platelets resulting from the over-production of proinflammatory factors and the formation of a cytokine storm [30, 31]. Therefore, the platelet count can vary with each individual and the specific relation between platelets and COVID-19 needs more research to reveal it.

The mechanism for coronavirus-associated PTE

The risk factors for the incidence of pulmonary thromboembolism consist of genetic factors and acquired factors. Genetic risk factors mean the genetic mutation varies from person to person. The acquired risk factors include age, pregnancy, malignancy, and postoperative status and they can be summarized as the Virchow triad: blood stasis, endothelial injury, and creating a thrombophilic state [2, 32]. With the progression of coronavirus pneumonia, patients are usually asked for rest in bed or receive invasive manipulation and therefore, the risk factors for PTE would gradually cumulative and result in the episode of PTE. Researchers have demonstrated that SARS-CoV-2 interacts with human angiotensin-converting enzyme 2 (hACE2) via the spike (S) glycoprotein for virus entry [33]. SARS-CoV-2 keep replication and proliferation in alveolar epithelial cells and destroy the alveoli, which will cause hypoxemia and the necrosis of pulmonary vessel endothelium [21]. Besides, the activation of adaptive immune response resulting from the infection of SARS-CoV-2 will increase systematic inflammatory activity in humans. The infiltration of neutrophils and monocytes in the pulmonary vessel wall appears and leads to the apoptosis of endothelial cells and the release of tissue factors into the blood. At the same time, the increased expression of various proinflammatory cytokines on immune cells, such as tumor necrosis factor-α, interferon-γ, interleukin (IL)-1β and IL-6, will form a cytokine storm and initiate the extrinsic coagulation pathway with the tissue factors and excessively activate the coagulation cascade [3]. The excessive activation of the coagulation cascade was also found in an in vitro human model with SARS infection [34] and it can be demonstrated using a mouse model infected with MERS-CoV [14]. These proinflammatory cytokines can activate plenty of platelets and make them aggregate at the damaged vessel endothelium, which will promote the coagulation cascade and produce microcirculatory dysfunction and thrombus formation in the body [3]. On the other hand, Gralinski et al. reported the expression of urokinase-type plasminogen activator was reduced in severe SARS patients while the over-expression of plasminogen activator inhibitor-1 has been shown [35], which suggested that the suppression of the fibrinolytic system may play a large role in the formation of PTE in coronavirus pneumonia patients. Recently, some literature indicated that the elevated antiphospholipid antibodies resulting from immune dysfunction in COVID-19 patients may be related to the high incidence of thrombotic events of COVID-19 patients [36, 37].

The prophylaxis of PTE in COVID-19 patients

Compared to COVID-19, SARS was controlled rapidly with the help of strong governmental and medical interventions and no human SARS cases have been found since
2004. Similarly, MERS had been brought under good control after its first appearance and there have been few confirmed human MERS cases in recent years [5]. However, COVID-19 has infected over ten million people and severely threaten global public health and it is very urgent for everyone that we find appropriate measures to deal with this novel coronavirus pneumonia. Therefore, this review focuses mainly on the measures of prophylaxis and treatment for PTE in COVID-19 patients to assist clinical doctors to overcome COVID-19 soon.

Due to the high incidence of coagulation disorders and thrombotic events in critically ill COVID-19 patients, the Chinese Medical Doctor Association (CMDA) recommended that clinical doctors should use the Pau da score to evaluate the risk of venous thromboembolism of all the hospitalized COVID-19 patients and prevent the incidence of VTE. The patients whose total score is no less than 4 are considered as a high-risk group with VTE while the patients who have low score (<4) are considered low-risk patients. Hence, the CMDA recommended using a standard prophylaxis dose of low molecular weight heparin (LMWH) or unfractionated heparin (UFH) for the pharmacological prophylaxis of VTE in severe or critically ill patients according to an initial risk assessment. Even though the severe patients have pharmacological contraindications for anticoagulant therapy, they should also receive mechanical prophylaxis measures, such as an intermittent air pressure pump and graded pressure stretch socks [38]. Besides, some Chinese doctors in a consensus statement, also proposed using intensified heparin for VTE prophylaxis in severely or critically ill COVID-19 patients [39]. However, in a recent study, 53 of 143 hospitalized COVID-19 patients were given DVT prophylaxis and researchers found no statistically significant difference between the DVT group and the non-DVT group (33.3%, 22/66 versus 40.6%, 31/77; p = 0.393). Nonetheless, the researchers did not clarify the specific prophylaxis measures for the COVID-19 patients and the sample size of this study was limited, therefore, the real effect of VTE prophylaxis requires further investigation [17].

The therapeutic measures of PTE in COVID-19 patients

Nowadays, research about COVID-19 mainly focuses on three aspects: epidemiology, medical therapeutics, and virology; and interdisciplinary integration would help scientists to summarize the most appropriate methods in pathogen identification, virus screening, vaccine development, and therapeutics. For example, the integration of data collection and medical resources can help governments to track and administer to COVID-19 patients. The use of artificial intelligence (AI) and omics technology provides a new way for screening for the virus. What is more, the integration of data science, clinical medicine, and molecular biology can achieve effective personalized medicine for COVID-19 patients [40]. PTE has been found to be a common but life-threatening coagulation disorder for COVID-19 patients in this article. However, because of the short period of time it has been around and the quick infectious speed of COVID-19, there is no specific medicine available so far for COVID-19. Therefore, a multiple disciplinary team (MDT) is essential to look after COVID-19 patients with coagulation dysfunction, which can remedy limitations in thinking, reduce misdiagnosis, and make an effective protocol [41].

Antiviral treatment

Antivirals are likely to be the most foundational and important treatment of the coronavirus pneumonia. Remdesivir, an adenosine analog, can stop normal virus replication by incorporating it into the nascent SARS-CoV-2 RNA chain and it has shown a strong inhibitory effect to SARS-CoV-2 in an in vitro setting [42]. Another study of a cohort of 61 severely ill COVID-19 patients showed that compassionate use of remdesivir effectively promoted the clinical symptoms and condition of patients [43]. Besides, Beigel et al. conducted a randomized placebo-controlled trial in a total of 1063 adult hospitalized COVID-19 patients with evidence of lower respiratory tract involvement and demonstrated that the patients receiving remdesivir had a shorter median time to the disappearance of clinical symptoms (11 days; 95% CI, 9–12) than those who received placebo (15 days; 95% CI, 13–19), and there was evidence of lower respiratory tract infection (rate ratio for recovery, 1.32; 95% CI, 1.12–1.55; p < 0.001), which suggests that remdesivir may improve the clinical status of COVID-19 patients [44].

On the other hand, chloroquine was found to inhibit the SARS-CoV-2 in an in vitro setting [42]. Chloroquine and its derivatives, such as hydroxychloroquine, have been used to treat COVID-19 patients. Huang et al. found that 10 of 22 COVID-19 patients treated with chloroquine achieved negative SARS-CoV-2 results in a quicker time when evaluated by real-time polymerase chain reaction (RT-PCR) compared with those receiving lopinavir/ritonavir. Besides, the chloroquine group had shorter hospital stays and it took less time for them to achieve lung clearance based on CT imaging [45]. A multicenter prospective observational study by Huang et al. also indicated that chloroquine treatment in COVID-19 patients would shorten the time in achieving an undetectable viral RNA and no severe adverse events were observed during treatment with chloroquine [46]. Another clinical trial performed by Gautret et al. revealed that hydroxychloroquine can effectively clear the viral carriage in COVID-19 patients with the reinforcement of azithromycin [47]. In addition to the direct antiviral effect, chloroquine functions in anticoagulation, antithrombosis and reducing the damage of inflammatory response by inhibiting the release of inflammatory factors and the appearance of a cytokine storm [48], which suggests that chloroquine and hydroxychloroquine may improve the clinical outcome of COVID-19 patients with PTE. However, a randomized controlled trial by Tang et al. suggested that there was no significant difference of the probability
of negative conversion by 28 days between the standard care plus hydroxychloroquine group and the standard care alone group in hospitalized COVID-19 patients (85.4%, 53/70 versus 81.3%, 56/80). In the same study, Tang et al. also found that patients receiving hydroxychloroquine had more adverse events than hydroxychloroquine non-recipients (30%, 21/70 versus 9%, 7/80) [49]. Similarly, another multicenter study by Cavalcanti et al. with a cohort of 667 hospitalized patients with mild-to-moderate COVID-19 indicated that the use of hydroxychloroquine, alone or with azithromycin, had no improvement in clinical status at 15 days as compared with standard care but the prolongation of QT interval and elevation of liver-enzyme levels were more common in hydroxychloroquine recipients [50]. Therefore, the administration of hydroxychloroquine for COVID-19 patients is still being debated and more research is needed to explore its curative effect and safety.

**Anti-coagulant therapy**

Anticoagulant treatment is essential for all patients with PTE, which can effectively prevent the thrombosis from forming and relapsing and activating the human fibrinolytic system. Tang et al. reported that the use of heparin, mainly LMWH, achieved good clinical outcomes and notably decreased the 28-day mortality in severe COVID-19 patients with coagulation disorders compared with those not receiving heparin treatment (40.0% versus 64.2%, p = 0.029) [24]. Moreover, heparin can inhibit the inflammatory response in body and protect the endothelium of the microvessels [51], which suggests that heparin plays an important role in treating COVID-19 patients with PTE in various ways. However, the concrete dose of heparin should be carefully administered by clinical doctors on the basis of specific conditions and the risks of anticoagulation treatment, especially the threat of uncontrolled massive hemorrhage, should be weighed and considered in detail [2].

**Symptomatic and supportive treatment**

Due to the lack of a specific drug for COVID-19, symptomatic and supportive treatment has become the main and basic therapeutic mode for treating COVID-19 patients. The recent study by Zhang et al. revealed that COVID-19 patients with DVT need more high-flow oxygen (68.2% versus 42.9%, p = 0.002) and invasive mechanical ventilation (28.8% versus 5.2%, p < 0.001) while they had a higher portion of cardiac or pulmonary dysfunction compared with those without DVT [17]. Therefore, the monitoring of vital signs, electrocardiograms and arterial blood gasses should be provided for all the COVID-19 patients with high risk of or confirmed PTE and the supplemental oxygen and fluid resuscitation may be beneficial to these patients [2]. For patients who present a massive PE based on CTPA and echocardiogram, thrombolytic agents, such as alteplase (tPA), urokinase, and streptokinase, can be used for therapy after obtaining the fully informed consent of patients and the ruling out of related contraindications of thrombolysis, which can decrease the resistance of pulmonary vessels, recover the pulmonary perfusion, and improve the function of the side of the right heart. But the risk of massive hemorrhage or intracranial hemorrhage after thrombolytic therapy requires that doctors take more time to care about the clinical condition of their patients [2, 38].

**Conclusion**

In conclusion, the infection of CoVs, especially SARS-CoV-2, can frequently induce coagulation disorders and PTE, which will cause the deterioration of the patient, organ failure, and mortality in those with coronavirus pneumonia. The mechanism of PTE in coronavirus pneumonia patients, including pulmonary thromboembolism and the formation of primary thrombosis in pulmonary vessels, consist of four aspects: the damage of the pulmonary vessel endothelium, the production of excessive proinflammatory factors and a cytokine storm, the aggregation and adhesion of platelets, and the suppression of the human fibrinolytic system. Advanced assessment and prophylaxis, including both pharmacological and mechanical prophylaxis, may be beneficial to decrease the occurrence of PTE. For coronavirus pneumonia patients with PTE, antiviral treatment, anticoagulation treatment, and symptomatic and supportive treatment can effectively promote the clinical outcome and reduce the fatality rate. To date, the interdisciplinary communication and integration among academia, industry, government organizations and clinical medicine have been applied in the outbreak of COVID-19 to realize the appropriate methods for diagnosis and therapeutics. With the help of multidisciplinary cooperation and research, scientists can find better strategies for diagnosis, prophylaxis, and therapy for PTE in patients with coronavirus pneumonia.

**Conflicts of Interest**

The authors declare no conflict of interest.

**Acknowledgments**

This work was supported by the Emergency Program for Major Public Health Event of the Ministry of Science and Technology, Department of Science and Technology of Guangdong Province of China (2020B11113001, 2020B11105001), the Emergency Program for Guangzhou Regenerative Medicine and Health Guangdong Laboratory of China (2020GZR110106003), the Emergency Program for Guangzhou Municipal Science and Technology Bureau (202008040003) and Tencent Charity Foundation of China.
References

[1] Giannis D, Ziqas IA, Giannasi PC. Coagulopathy disorders in coronavirus infected patients: COVID-19, SARS-CoV-1, MERS-CoV and lessons from the past. J Clin Virol 2020;127:104362. [PMID: 32305883 DOI: 10.1016/j.jcv.2020.104362]

[2] Essien EO, Rali P, Mathai SC. Pulmonary embolism. Med Clin North Am 2019;103:549-64. [PMID: 30955521 DOI: 10.1016/j.mcna.2018.12.013]

[3] Iba T, Levy JH, Levi M, Connors JM, Thachil J. Coagulopathy of coronavirus disease 2019. Crit Care Med 2020;48:1358-64. [PMID: 32421381 DOI: 10.1016/j.ccm.2020.03.038]

[4] Al-Omari A, Rabaan AA, Salih S, Al-Tawfiq JA, Memish ZA. MERS coronavirus outbreak: implications for emerging viral infections. Diagn Microbiol Infect DIS 2019;93:265-85. [PMID: 30413355 DOI: 10.1016/j.diagmicrobio.2018.10.011]

[5] De Wit E, Van Doremalen N, Falzarano D, Munster VJ. SARS coronavirus disease 2019. Crit Care Med 2020;48:1358-64. [PMID: 32421381 DOI: 10.1016/j.ccm.2020.03.038]

[6] Meignan M, Rosso J, Gauthier H, Brunengo F, Claudel S, et al. Meniscal tears and venous thromboembolism in hospitalized patients with COVID-19 in Wuhan, China: prevalence, risk factors, and outcome [published correction appears in Circulation. 2020; Jul;142(2):e33]. Circulation 2020;142:114-28. [PMID: 32421381 DOI: 10.1161/CIRCULATIONAHA.120.046702]

[7] Klok FA, Kruip MJHA, van der Meer NJM, Arbous MS, Gommers DAMJ, et al. Incidence of thrombotic complications in critically ill ICU patient with COVID-19. Thoromb Res 2020;191:145-7. [PMID: 32291094 DOI: 10.1016/j.thromres.2020.04.013]

[8] Kaminetzky M, Zhang J, Wang B, Zhu X, Wang Q, et al. Autopsy findings and venous thromboembolism in patients with COVID-19: A prospective cohort study. Ann Intern Med 2020;173:268-77. [PMID: 32374815 DOI: 10.7326/M20-2003]

[9] Eastin C, Travis Eastin M. Clinical characteristics of coronavirus disease 2019 in China. Emerg Med 2020;58:711-2. [DOI: 10.1016/j.jemermed.2020.04.004]

[10] Goshua G, Pine AB, Meizlish ML, Chang CH, Zhang H, et al. Endotheliopathy in COVID-19-associated coagulopathy: evidence from a single-centre, cross-sectional study. Lancet Haematol 2020;7:E575-82. [PMID: 32619411 DOI: 10.1016/s2352-3026(20)30216-7]

[11] Heit JA, Crusan DJ, Ashrani AA, Pettersson TM, Bailey KR. Effect of a near-universal hospitalization-based prophylaxis regimen on annual number of venous thromboembolism events in the United States: findings from the nationwide inpatient sample. Chest 2009;136:983-90. [PMID: 19525357 DOI: 10.1378/chest.08-2258]

[12] Heit JA, Spencer FA, White RH. The epidemiology of venous thromboembolism. J Thromb Thrombolysis 2016;41:3-14. [PMID: 26780736 DOI: 10.1007/s11739-015-1116-1]

[13] Hwang DM, Chamberlain DW, Poutanen SM, Low DE, Asa SL, et al. Induction of a pro-inflammatory state associated with severe coronavirus disease 2019 in Toronto. Modern Pathol 2020;33:1358-62. [PMID: 32467444 DOI: 10.1097/CPM.0000000000000435]

[14] Li K, Wohlford-Lenane C, Perlman S, Zhao J, Jewell AK, et al. Mid- and long-term neurological manifestations in patients with severe coronavirus disease-19. J Med Virol 2020;92:1533-41. [PMID: 32181903 DOI: 10.1002/jmv.25767]

[15] Assiri A, Al-Tawfiq JA, Al-Rabeeah AA, Al-Rabiah FA, Al-Hajjar S, et al. Epidemiological, demographic, and clinical characteristics of 47 cases of Middle East respiratory syndrome coronavirus disease from Saudi Arabia: a descriptive study. Lancet Infect Dis 2013;13:752-61. [PMID: 23891402 DOI: 10.1016/S1473-3099(13)70204-4]

[16] Eastin C, Travis Eastin M. Clinical characteristics of coronavirus disease 2019 in Toronto. Modern Pathol 2020;33:1358-62. [PMID: 32467444 DOI: 10.1097/CPM.0000000000000435]

[17] Li K, Wohlford-Lenane C, Perlman S, Zhao J, Jewell AK, et al. Middle East respiratory syndrome coronavirus causes multiple organ damage and lethal disease in mice transgenic for human dipeptidyl peptidase 4. J Infect Dis 2016;213:712-22. [PMID: 26486634 DOI: 10.1093/infdis/jiv049]

[18] Assiri A, Al-Tawfiq JA, Al-Rabieh AA, Al-Rabiah FA, Al-Hajjar S, et al. Epidemiological, demographic, and clinical characteristics of 47 cases of Middle East respiratory syndrome coronavirus disease from Saudi Arabia: a descriptive study. Lancet Infect Dis 2013;13:752-61. [PMID: 23891402 DOI: 10.1016/S1473-3099(13)70204-4]

[19] Wang Q, Zhang Y, Wu L, Niu S, Song C, et al. Structural and functional basis of SARS-CoV-2 entry by using human ACE2. Cell 2020;181:894-904. [PMID: 32275855 DOI: 10.1016/j.cell.2020.03.045]

[20] Hwang SM, Na BJ, Jung Y, Lim HS, Seo JE, et al. Clinical and laboratory findings of Middle East respiratory syndrome coronavirus infection. Jpn J Infect Dis 2019;72:160-7. [PMID: 30584196 DOI: 10.7883/okyon.JJID.2018.187]

[21] Zhang L, Feng X, Zhang D, Jiang C, Mei H, et al. Deep vein thrombosis in hospitalized patients with COVID-19 in Wuhan, China: prevalence, risk factors, and outcome [published online ahead of print, 2020 Jul 14;142(2):e33]. Circulation 2020;142:114-28. [PMID: 32421381 DOI: 10.1161/CIRCULATIONAHA.120.046702]
[34] Ng LF, Hibberd ML, Ooi EE, Tang KF, Neo SY, et al. A human in vitro model system for investigating genome-wide host responses to SARS coronavirus infection. BMC Infect Dis 2004;4:34. [PMID: 15357874 DOI: 10.1186/1471-2334-4-34]

[35] Gralinski LE, Bankhead A, Jeng S, Menachery VD, Proll S, et al. Mechanisms of severe acute respiratory syndrome coronavirus-induced acute lung injury. mBio 2013;4.e00271-13. [PMID: 23919993 DOI: 10.1128/mBio.00271-13]

[36] Zhang H, Zhou P, Wei Y, Yue H, Wang Y, et al. Histopathologic changes and SARS-CoV-2 immunostaining in the lung of a patient with COVID-19. Ann Intern Med 2020;172:629-32. [PMID: 32163542 DOI: 10.7326/M20-0533]

[37] Zhang Y, Xiao M, Zhang S, Xia P, Cao W, et al. Coagulopathy and antiphospholipid antibodies in patients with Covid-19. N Engl J Med 2020;382:e38. [PMID: 32268022 DOI: 10.1056/NEJMc2007575]

[38] Pulmonary embolism and pulmonary vascular disease group, respiratory branch, Chinese Medical Association, Pulmonary embolism and pulmonary vascular disease working committee of respiratory branch of Chinese Medical Doctor Association, National Collaborative Group on prevention and treatment of pulmonary embolism and pulmonary vascular disease, et al. Prevention and treatment of new coronavirus pneumonia associated venous thromboembolism, a consensus statement (Preliminary Protocol)[J]. National Medical Journal of China. 2020;100:E007.

[39] Zhai Z, Li C, Chen Y, Gerotziafas G, Zhang Z, et al. Prevention and treatment of venous thromboembolism associated with coronavirus disease 2019 infection: a consensus statement before guidelines. Thromb Haemost 2020;120:937-48. [PMID: 32316065 DOI: 10.1055/s-0040-1710019]

[40] Er Saw P, Jiang S. The significance of interdisciplinary integration in academic research and application. BIO Integration 2020;1:2-5. [DOI: 10.15212/bioi-2020-0005]

[41] Zhao Z, He Z, Huang H, Chen J, He S, et al. Drug-induced interstitial lung disease in breast cancer patients: a lesson we should learn from multi-disciplinary integration. BIO Integration 2020;1:82-91. [DOI: 10.15212/bioi-2020-0009]

[42] Wang M, Cao R, Zhang L, Yang X, Liu J, et al. Remdesivir and chloroquine effectively inhibit the recently emerged novel coronavirus (2019-nCoV) in vitro. Cell Res 2020;30:269-71. [PMID: 32020029 DOI: 10.1038/s41422-020-0282-0]

[43] Grein J, Ohmagari N, Shin D, Diaz G, Asperges E, et al. Compassionate use of remdesivir for patients with severe Covid-19. N Engl J Med 2020;382:2327-36. [PMID: 32275812 DOI: 10.1056/NEJMoa2007016]

[44] Beigel JH, Tomashek KM, Dodd LE, Mehta AK, Zingman BS, et al. Remdesivir for the treatment of Covid-19—Preliminary Report. N Engl J Med 2020;22:NEJMoa2007764. [PMID: 32445440 DOI: 10.1056/NEJMoa2007764]

[45] Huang M, Tang T, Pang P, Li M, Ma R, et al. Treating COVID-19 with Chloroquine. J Mol Cell Biol 2020;12:322-5. [PMID: 32236562 DOI: 10.1093/jmcb/mjaa014]

[46] Huang M, Li M, Xiao F, Pang P, Liang J, et al. Preliminary evidence from a multicenter prospective observational study of the safety and efficacy of chloroquine for the treatment of COVID-19. National Science Review 2020;7:1428-36. [DOI: 10.1093/nsr/nwaa113]

[47] Gautret P, Lagier JC, Parola P, Hoang VT, Meddeb L, et al. Hydroxychloroquine and azithromycin as a treatment of COVID-19: results of an open-label non-randomized clinical trial. Int J Antimicrob Agents. 2020;56:105949. [PMID: 32205204 DOI: 10.1016/j.ijantimicag.2020.105949]

[48] Wei ZX, Tang TT, Jiang SP. The antiviral mechanisms, effects, safety and adverse effects of chloroquine. Eur Rev Med Pharmacol Sci 2020;24:7164-72. [PMID: 32633413 DOI: 10.26355/eurrev_202006_21712]

[49] Tang W, Cao Z, Han M, Wang Z, Chen J, et al. Hydroxychloroquine in patients with mainly mild to moderate coronavirus disease 2019: open label, randomised controlled trial. Br Med J 2020;369:m1849. Published 2020 May 14. [PMID: 32409561 DOI: 10.1136/bmj.m1849]

[50] Cavalcanti AB, Zampieri FG, Rosa RG, Azevedo LCP, Veiga VC, et al. Hydroxychloroquine with or without azithromycin in mild-to-moderate Covid-19. N Engl J Med 2020;23:NEJ-Moa2019014. [PMID: 32706953 DOI: 10.1056/NEJMoa2019014]

[51] Thachil J. The versatile heparin in COVID-19. J Thromb Haemost 2020;18:1020-2. [PMID: 32239799 DOI: 10.1111/jth.14821]