INTRODUCTION

Coronavirus (CoVs) is a virus of the coronavirus family, which has the largest genome of all known RNA viruses and is widely found in humans, mice, pigs, cats, dogs and other animals. Seven coronavirus species are known to cause human disease, of which four species (HCoV-NL63, HCoV-229E, HCoV-OC43 and HCoV-HKU1) cause respiratory infections in immunocompromised individuals, infants and the elderly. The other three are highly pathogenic human coronaviruses, including the severe acute respiratory syndrome coronavirus (SARS-CoV), the Middle East respiratory syndrome coronavirus (MERS-CoV) and the 2019 new coronavirus (SARS-CoV-2) (summarized in Table 1). These three viruses can cause respiratory, intestinal, hepatic and neuronal diseases, and may lead to acute respiratory distress syndrome (ARDS), multiple organ failure (MOF) and even death in severe cases. Studies have shown that patients infected with SARS-CoV, MERS-CoV and SARS-CoV-2 may develop different degrees of liver injury. In this review, the characteristics and mechanism of liver injury caused by SARS-CoV, MERS-CoV as well as SARS-CoV-2 infection were summarized, which may provide help for further studies on the liver injury of COVID-19.

KEYWORDS
COVID-19, liver injury, MERS, SARS, SARS-CoV-2

Abstract

The severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), the pathogen of 2019 novel coronavirus disease (COVID-19), has posed a serious threat to global public health. The WHO has declared the outbreak of SARS-CoV-2 infection an international public health emergency. Lung lesions have been considered as the major damage caused by SARS-CoV-2 infection. However, liver injury has also been reported to occur during the course of the disease in severe cases. Similarly, previous studies have shown that liver damage was common in the patients infected by the other two highly pathogenic coronavirus – severe acute respiratory syndrome coronavirus (SARS-CoV) and the Middle East respiratory syndrome coronavirus (MERS-CoV), and associated with the severity of diseases. In this review, the characteristics and mechanism of liver injury caused by SARS-CoV, MERS-CoV as well as SARS-CoV-2 infection were summarized, which may provide help for further studies on the liver injury of COVID-19.

1 | INTRODUCTION

Coronavirus (CoVs) is a virus of the coronavirus family, which has the largest genome of all known RNA viruses and is widely found in humans, mice, pigs, cats, dogs and other animals. Seven coronavirus species are known to cause human disease, of which four species (HCoV-NL63, HCoV-229E, HCoV-OC43 and HCoV-HKU1) cause respiratory infections in immunocompromised individuals, infants and the elderly. The other three are highly pathogenic human coronaviruses, including the severe acute respiratory syndrome coronavirus (SARS-CoV), the Middle East respiratory syndrome coronavirus (MERS-CoV) and the 2019 new coronavirus (SARS-CoV-2) (summarized in Table 1). These three viruses can cause respiratory, intestinal, hepatic and neuronal diseases, and may lead to acute respiratory distress syndrome (ARDS), multiple organ failure (MOF) and even death in severe cases. Studies have shown that patients infected with SARS-CoV, MERS-CoV and SARS-CoV-2 may develop different degrees of liver injury. In this review, the characteristics

Abbreviations: ACE2, angiotensin-converting enzyme II; AKP, alkaline phosphatase; ALB, albumin; ALT, alanine transaminase; ARDS, acute respiratory distress syndrome; AST, aspartate aminotransferase; COVID-19, 2019 novel coronavirus disease; CoVs, coronavirus; DPP-4, dipeptidyl peptidase-4; GGT, gamma-glutamyl transferase; HBV, hepatitis B virus; HCoV-229E, human coronavirus 229E; HCoV-HKU1, human coronavirus HKU1; HCoV-NL63, human coronavirus NL63; HCoV-OC43, human coronavirus OC43; HCV, hepatitis C virus; hDPP-4, human dipeptidyl peptidase-4; IFN-γ, interferon-γ; IL-1, interleukin-1; IL-10, interleukin-10; IL-15, interleukin-15; IL-17, interleukin-17; IL-6, interleukin-6; MERS, the Middle East respiratory syndrome; MERS-CoV, the Middle East respiratory syndrome coronavirus; MOF, multiple organ failure; RT-PCR, reverse transcription-polymerase chain reaction; SARS, severe acute respiratory syndrome; SARS-CoV, severe acute respiratory syndrome coronavirus; SARS-CoV-2, severe acute respiratory syndrome coronavirus 2; TB, total bilirubin; TNF-α, tumour necrosis factor α; WHO, the World Health Organization.

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2 | SARS-COV AND LIVER INJURY

Severe acute respiratory syndrome (SARS) is an acute infectious disease caused by SARS-CoV. It was first reported in Guangdong Province and Hong Kong of China in November 2002, and soon spread to 29 countries and regions around the world. Patients with SARS-CoV infection are characterized by persistent fever, headache, muscle pain and decreased white blood cell count. Severe cases may develop ARDS and MOF. A number of studies have shown that liver injury occurred in SARS patients, which was mainly manifested in the mild and moderate elevation of ALT and/or AST during the early stage of the disease. Some patients had decreased serum albumin and increased serum bilirubin levels. The severe cases were more likely to have severe liver injury compared to mild cases.

Studies have been performed to understand the mechanism of liver damage caused by SARS-CoV. Autopsy of SARS patients found large numbers of virus particles not only in the lungs but also in the parenchymal cells and vascular endothelium of other organs, including the liver. SARS-CoV genome was also detected in hepatocytes by RT-PCR. It is known that SARS-CoV uses angiotensin-converting enzyme 2 (ACE2) as the receptor for cell entry. ACE2 was found to be abundantly expressed on endothelial cells of the liver, which makes the liver a potential target for SARS-CoV. Liver biopsies in SARS patients showed a significant increase in mitotic cells, with eosinophilic bodies and balloon-like hepatocytes, suggesting that SARS-CoV may induce apoptosis of liver cells and thus cause liver injury. Other studies showed that SARS-CoV-specific protein 7a can induce apoptosis in cell lines of different organs (including the lung, kidney and liver) through the caspase-dependent pathway, further confirming the possibility that SARS-CoV directly attacks liver tissue and causes liver injury.

Abnormal serum levels of cytokines and chemokines were found at the early stage of SARS-CoV infection in patients. Duan et al reported that serum IL-1, IL-6 and IL-10 levels in patients with abnormal liver function were higher than those in patients with normal liver function, suggesting a possible correlation between liver damage and the inflammatory responses induced by SARS-CoV infection. Besides, SARS patients with HBV/HCV infection were more prone to develop liver damage and severe hepatitis, which is probably due to enhanced replication of hepatitis virus during SARS-CoV infection. It is particularly worth noting that antibiotics (macrolides, quinolones), antivirals (ribavirin), steroids and other drugs used for the treatment of SARS patients may also result in liver damage.

3 | MERS-COV AND LIVER INJURY

Most Middle East respiratory syndrome (MERS) cases, caused by MERS-CoV infection, were firstly occurred in Saudi Arabia in 2012. The virus has since spread to Europe, Asia, Africa and North America. MERS-CoV infection in patients is characterized by fever, cough and shortness of breath. Severe MERS patients quickly progressed to respiratory and kidney failure. Besides, a number of retrospective studies have shown that patients with MERS had elevated liver enzymes and bilirubin levels, as well as decreased albumin levels. It has also been shown by Saad et al that the low level of albumin was a predictor of disease severity. Similar to the

### TABLE 1 Characteristics of SARS-CoV, MERS-CoV and SARS-CoV-2

| Virus          | Disease | Genome sequence homology to SARS-CoV-2 | Receptor | Possible intermediate hosts | Route of transmission | Human susceptibility | Mortality (%) |
|---------------|---------|----------------------------------------|----------|----------------------------|------------------------|----------------------|---------------|
| SARS-CoV      | SARS    | 82%                                    | ACE2^22  | Palm civets^59             | Droplets, contact^60   | People are generally susceptible^60 | 9.6%^50       |
| MERS-CoV      | MERS    | 50%                                    | DPP4^35  | Camel^3                    | contact^61             | People are generally susceptible^61 | 34.4%^61      |
| SARS-CoV-2    | COVID-19| -                                      | ACE2^52  | Pangolin^62                | Droplets, contact^29   | People are generally susceptible^39 | 3.7%^39       |

Abbreviations: ACE2, angiotensin-converting enzyme II; COVID-19, 2019 novel coronavirus disease; DPP-4, dipeptidyl peptidase 4; MERS, the Middle East respiratory syndrome; MERS-CoV, the Middle East respiratory syndrome coronavirus; SARS, severe acute respiratory syndrome; SARS-CoV, severe acute respiratory syndrome coronavirus; SARS-CoV-2, severe acute respiratory syndrome coronavirus 2.

^Available from the website of WHO on March 6, 2020.
| Disease | Reference         | Numbers of analyzed cases | Proportions of pre-existing liver diseases | Manifestations                                                                 | Note                                                                                                                                 |
|---------|-------------------|---------------------------|-------------------------------------------|-------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------|
| SARS    | Chang et al⁶     | 346                       | 2 (0.57%)                                 | Mild to moderate elevation of ALT and AST                                     | Non-survivors had a significantly higher level of AST than survivors                                                            |
|         | Liu et al⁷       | 259                       | —                                         | Abnormal ALT 146 (56.3%)                                                     | —                                                                                                                                    |
|         | Lu et al⁸        | 250                       | NA                                        | Abnormal ALT 87%                                                             | —                                                                                                                                    |
|         | Tie et al⁹       | 222                       | —                                         | 136 (61.7%)                                                                 | The incidence of liver injury in severe patients (74.4%) was markedly higher than that in mild patients (43.0%)          |
|         | Zhao et al¹⁰     | 169                       | —                                         | Abnormal ALT 62.5%                                                           | Liver injury mainly appeared in the second and the third week after disease onset                                                   |
|         | Yang et al¹¹     | 168                       | 12 (7.1%)                                 | Abnormal ALT 52.5%                                                          | —                                                                                                                                    |
|         | Duan et al¹²     | 154                       | 4 (2.6%)                                  | 58 (37.7%)                                                                 | The incidence of liver injury in severe patients (48.4%) was markedly higher than that in mild patients (13.0%)          |
|         | Huang et al¹³     | 108                       | 62 (57.4%)                                | 38/38 (100%), in patients with HBV infection                                | —                                                                                                                                    |
|         |                   |                           |                                           | 33/46 (71.7%), in patients without pre-existing liver disease                | —                                                                                                                                    |
|         | Wang et al¹⁴     | 76                        | 6                                         | Abnormal ALT 59 (77.6%)                                                     | —                                                                                                                                    |
|         |                   |                           |                                           | Abnormal AST 66 (86.9%)                                                     | —                                                                                                                                    |
|         | Jiang et al¹⁵    | 60                        | NA                                        | Abnormal ALT 46 (76.6%)                                                     | —                                                                                                                                    |
|         |                   |                           |                                           | Abnormal AST 24 (40.0%)                                                     | —                                                                                                                                    |
|         |                   |                           |                                           | Abnormal TB 18 (30.0%)                                                       | —                                                                                                                                    |
|         |                   |                           |                                           | Abnormal ALB 27 (45%)                                                        | —                                                                                                                                    |
|         | Wu et al¹⁶       | 52                        | 9 (17.3%)                                 | Abnormal ALT and AST 53%                                                    | Liver injury mainly appeared in the second week after disease onset                                                              |
|         | Duan et al¹⁷     | 43                        | 3 (6.9%)                                  | Abnormal ALT 33 (76.74%)                                                    | Liver injury mainly appeared in the second and the third week after disease onset                                               |
| MERS    | Arabi³⁰          | 330                       | 21 (6.4%)                                 | Abnormal ALT 142/252 (56.3%)                                                | The incidence of liver injury in non-survivors (91.3%) was significantly higher than that of survivors (77.9%) in ICU patients |
|         | Sad et al²⁷      | 70                        | —                                         | Liver dysfunction 22 (31.4%)                                                 | —                                                                                                                                    |
|         | Assiri³²         | 47                        | NA                                        | Abnormal ALT 5 (11%)                                                        | Low albumin was suggested as a predictor of disease severity                                                                     |
|         |                   |                           |                                           | Abnormal AST 7 (15%)                                                        | —                                                                                                                                    |
| COVID-19| Guan et al⁴¹     | 1099                      | 23 (2.3%)                                 | Abnormal AST, 168/757 (22.2%)                                               | The proportion of abnormal AST in severe cases (39.4%) was markedly higher than mild cases (18.2%)                               |
|         | Cai et al⁴²      | 298                       | 8 (2.7%)                                  | 44 (14.8%)                                                                  | The incidence of liver injury in severe patients (36.2%) was markedly higher than that in mild patients (9.6%).                |
|         | Fan et al⁴³      | 148                       | —                                         | 75 (50.7%)                                                                  | A higher proportion of patients with liver injury (56.1%) received lopinavir/ritonavir treatment than those without liver injury (25%) |
|         | Wang et al⁴⁴     | 138                       | 4 (2.9%)                                  | Mild elevation of ALT and AST                                                | —                                                                                                                                    |
observation in SARS patients, the pathological manifestations of liver injury in MERS patients are mild portal tract and lobular lymphocytic inflammation, as well as mild cellular hydropic degeneration in hepatic parenchyma.\textsuperscript{33,34}

Different from SARS-CoV, MERS-CoV was found to utilize dipeptidyl peptidase-4 (DPP-4) as its functional receptor for establishing infection in cells.\textsuperscript{35} The expression level of DPP-4 in the liver is high,\textsuperscript{36} suggesting it is a potential target organ of MERS-CoV. Zhao et al.\textsuperscript{37} constructed a transgenic mouse model globally expressing codon-optimized human DPP-4 (hDPP-4) and found that MERS-CoV is able to infect the liver cells via DPP-4 on the cell surface and cause cell damage. Mild to moderate liver injury occurred on day 5 after MERS-CoV infection in the hDPP-4 transgenic mice, and the main findings were scattered necrosis of liver cells in the hepatic sinus, infiltration of large numbers of activated Kupffer cells and macrophages. Fatty changes in liver cells were observed on day 9 post-infection with less liver cell necrosis.\textsuperscript{37}

Significant pro-inflammatory cytokine responses were observed in the acute phase of MERS-CoV infection in patients, and the concentrations of serum IFN-γ, TNF-α, IL-15 and IL-17 were significantly increased.\textsuperscript{38} However, studies on the correlation between pro-inflammatory cytokine responses and liver injury are still lacking. It remains to be explored whether the liver injury observed during MERS-CoV infection is the consequence of direct viral infection, inflammation-mediated pathogenesis or applying liver-damaging drugs during the course of treatment.

4 | SARS-COV-2 AND LIVER INJURY

COVID-19 is a novel infectious disease caused by SARS-CoV-2. In December 2019, pneumonia cases of unknown origins were firstly identified in Wuhan City, Hubei Province, China, and then rapidly spread to the whole country, and up to date, more than 70 countries worldwide. Currently, the number of SARS-CoV-2-infected patients is still rapidly increasing on a global scale.\textsuperscript{39} Mild cases of COVID-19 showed symptoms of fever, fatigue, dry cough, vomiting and diarrhea. In severe cases, respiratory distress and/or hypoxemia occurred 1 week after the onset of the disease and then deteriorated into ARDS, septic shock, metabolic acidosis and even death.\textsuperscript{40}

Recent studies on COVID-19 have shown that the incidence of liver injury ranged from 14.8% to 53%, mainly indicated by abnormal ALT/AST levels accompanied by slightly elevated bilirubin levels.\textsuperscript{40-51} The albumin is decreased in severe cases and the level of albumin is around 26.3-30.9 g/L.\textsuperscript{46} The proportion of elevated AST levels of ICU patients (62%) was higher than non-ICU patients (25%). One study reported that serum ALT and AST levels increased up to 7590 U/L and 1445 U/L, respectively, in a severe COVID-19 patient.\textsuperscript{46} Our unpublished data showed very similar findings to other studies, except that we found that serum GGT increased in severe cases and serum AKP level was at normal range in both mild and severe cases. Currently, studies on the mechanisms of SARS-CoV-2-related liver injury are
limited. It has been shown that SARS-CoV-2 also uses ACE2 as its entry receptor as SARS-CoV does.\textsuperscript{52} Chai et al\textsuperscript{53} found that both liver cells and bile duct cells express ACE2. However, the ACE2 expression of bile duct cells is much higher than that of liver cells, but to a comparable level of alveolar type 2 cells in the lung. Bile duct epithelial cells are known to play important roles in liver regeneration and immune response.\textsuperscript{54} These results suggested that the liver injury occurred in COVID-19 patients may be due to the damage to bile duct cells, but not liver cells by the virus infection. Besides, the inflammatory cytokine storm was observed in severe COVID-19 cases,\textsuperscript{55} yet whether it results in liver damage in patients remains to be investigated. Postmortem biopsies were recently performed in a death COVID-19 patient, and the results showed moderate microvascular steatosis and mild lobular and portal activity, indicating the injury could have been caused by either SARS-CoV-2 infection or drug-induced liver injury.\textsuperscript{56} Similar to the situation in SARS, antibiotics, antivirals and steroids are widely used for the treatment of COVID-19.\textsuperscript{57} These drugs are all potential causes of liver injury during COVID-19, but not yet being evident.\textsuperscript{49} Actually, a recent study reported that the liver injury observed in COVID-19 patients might be caused by lopinavir/ritonavir, which is used as antivirals for the treatment of SARS-CoV-2 infection.\textsuperscript{43} So far, there is a lack of reports that liver failure occurs in COVID-19 patients with chronic liver diseases, such as chronic hepatitis B or C.

5 | CONCLUSION

In this review, we summarized the reports of liver injury caused by SARS-CoV, MERS-CoV and SARS-CoV-2 infection (Table 2). The mechanisms of liver injury that occurred during SARS-CoV-2 infection remain largely unclear. Our current understanding suggests that infection of highly pathogenic human coronavirus may result in liver injury by direct virus-induced cytopathic effects and/or immunopathology induced by overshooting inflammatory responses. Meanwhile, SARS-CoV may aggravate liver injury in patients with viral hepatitis, but there is no evidence for MERS-CoV and SARS-CoV-2. Importantly, drug-induced liver injury during the treatment of coronavirus infection should not be ignored and needs to be carefully investigated. From a clinical perspective, in addition to actively dealing with the primary disease caused by coronavirus infection, attention should also be paid to monitor the occurrence of liver injury, and to the application of drugs which may induce liver damage, such as antibiotics of macrolides or quinolone, and steroids, etc. Patients with liver damage are advised to be treated with drugs that could both protect liver functions and inhibit inflammatory responses, such as ammonium glycyrrhizinate,\textsuperscript{58} which may, in turn, accelerate the process of disease recovery.

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CONFLICT OF INTEREST

The authors disclose no conflicts of interest.

AUTHOR CONTRIBUTIONS

Xin Zheng designed and planned the work, and revised the manuscript. Ling Xu and Jia Liu performed the literature search and interpretation, and manuscript drafting. Mengji Lu and Dongliang Yang revised the manuscript.

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