Autopsy and Histologic Findings of Patients with New Coronavirus Pneumonia: The Pathologic Associations with Hypoxemia

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Background: Coronavirus 2 (SARS-CoV-2) was declared a pandemic by the World Health Organization (WHO) in March 2020. To further reveal the pathologic associations between coronavirus and hypoxemia, we report the findings of 4 complete systematic autopsies of severe acute respiratory syndrome coronavirus 2-positive individuals who died of multiple organ failure caused by severe hypoxemia.

Material/Methods: We examined the donated corpses of 4 deceased patients who had been diagnosed with severe acute respiratory syndrome coronavirus 2. A complete post-mortem examination was carried out on each corpse, and multiple organs were macroscopically examined.

Results: The 4 corpses were 2 males and 2 females, with an average age of 69 years. Bilateral lungs showed various degrees of atrophy and consolidation, with diffusely tough and solid texture in the sections. A thromboembolism was found in the main pulmonary artery extending into the atrium in 1 corpse, and significant atherosclerotic plaques tagged in the inner wall of the aortic arch were found in 2 corpses. Two corpses were found to have slightly atrophied bilateral renal parenchyma. Atrophic changes in the spleen were found in 2 corpses. Notably, there were significantly expanded alveolar septa and prominent fibroblastic proliferation.

Conclusions: The laboratory data of these corpses showed a progressive decrease in blood oxygen saturation, followed by refractory and irreversible hypoxemia. Clinical and laboratory information and autopsy and histologic presentations of multiple organs showed insufficient air exchange due to abnormalities in the respiratory system, and reduced erythropoiesis in bone marrow may play a role.

Keywords: Autopsy • Coronavirus • COVID-19

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Background

Coronavirus is a large family of viruses known to cause Middle East Respiratory Syndrome (MERS) and Severe Acute Respiratory Syndrome (SARS). The widespread of coronavirus 2 (SARS-CoV-2), a novel coronavirus named by the Coronavirus Study Group of the International Committee, has emerged as a global health emergency since December 2019 [1]. The coronavirus pneumonia induced by this virus has been officially named COVID-19 by the WHO. As of March 2020, it had caused more than 5,800,000 cases and 360,000 deaths globally. Most infections were non-severe, with common symptoms of upper-respiratory tract disease and pneumonia, including fever, cough, dyspnea, fatigue, and myalgia [2,3]. However, some patients have severe symptoms clinically characterized by hypoxemia, acute lung injury (ALI), acute respiratory distress syndrome (ARDS), septic shock, or acute renal injury [2].

Hypoxemia is defined as arterial oxygen tension (PaO2) below normal (normal PaO2=80-100 mmHg) [4]. Severe hypoxemia is also a characteristic of ARDS [5]. The hypoxia caused by hypoxemia and ensuing multiple organ failure is the main cause

Table 1. Clinical and laboratory features of 4 corpses with COVID-19.

| No. | Age (yr.) | Sex | Temperature (°C) | Duration (dy.) | History | Clinical presentation | Changes in red blood cell count and hemoglobin | Changes in white blood cell count, neutrophil and lymphocyte proportion | Imaging (CT) | Changes of PaO2/ PaCO2 (mmHg) | BPH | BB/BE (mmol/L) |
|-----|-----------|-----|-----------------|----------------|---------|----------------------|-----------------------------------------------|------------------------------------------------|-------------|------------------|-----|----------------|
| 1#  | 53        | F   | 38.9            | 7              | Diabetes for 10 yr. | Cough, fever, intermittent chest tightness, wheezing | 1.89-2.12 ×10^{12}/L; 58-65 g/L | 7.50-6.06 ×10^{9}/L; 80.4-95.2%; 15.1-2% | Bilateral thickened pleura, high density in both lungs | 99-96 /NA | NA | NA |
| 2#  | 62        | M   | 39.5            | 9              | None | Cough, asthma and intermittent fever for 13 dy. | 3.79-3.64 ×10^{12}/L; 127-121 g/L | 4.26-8.68 ×10^{9}/L; 80.8-88.9%; 14.0-5.0% | Right thickened pleura, bilateral pleural effusion, high density in both lungs | 92-64 /NA | NA | NA |
| 3#  | 73        | F   | 38.3            | 22             | Hypertension for 10 yr. | Cough, fever, asthma and intermittent fever for 12 dy. | 4.26-2.73 ×10^{12}/L; 129-83 g/L | 8.80-11.82 ×10^{9}/L; 91.4-90.8%; 6.7-5.5% | High density in both lungs | 94-62-51/52-28 | 7.46-6-7.52 | 52/28-31.8-32.8 |
| 4#  | 88        | M   | 38.4            | 15             | Back pain for 20 yr., itchy skin for 3 yr. | Fever, cough for 5 dy. | 4.74-3.69 ×10^{12}/L; 143-109 g/L | 4.52-13.64 ×10^{9}/L; 80.7-87.2%; 11.5-4.5% | Bilateral thickened pleura, high density in both lungs. A large renal cystic mass | 97-52/NA | NA | NA |
of disease progression and death for patients with coronavirus pneumonia [2]. Although there have been some publications describing the clinical, imaging, and treatment findings of patients with COVID-19, few histologic studies have been conducted and published, and most of them focused on the lungs [6-8]. Our team performed a systematic anatomy and detailed pathological analysis on the corpses of 4 COVID-19 patients who died of multiple organ failure caused by severe hypoxemia, aiming to assess the pathologic associations between COVID-19 and hypoxemia.

**Material and Methods**

**Patients and Clinical Data Collection**

This study was approved by the Ethics Committee of Jin Yintan Hospital and Ruijin Hospital, Shanghai Jiaotong University (KY-2020-15.01). All the patients’ families consented to using the patients’ personal information. The corpses of 4 patients with COVID-19 with a complete clinical information were assessed. Clinical and laboratory data were collected and recorded.

**Autopsy**

The consent for body donation and autopsy for scientific research was obtained from the bereaved families. Four autopsy pathologists participated from Department of Pathology, Ruijin Hospital. The research team assured that the corpses were treated with respect. Complete post-mortem external and internal examinations were performed on the 4 corpses at the Military Hospital in Wuhan within 12 h after death. The pathologists involved in the anatomy used strict positive-pressure protection, and the dissection was performed in a negative-pressure square cabin dedicated to autopsy.

The anatomy was assessed by dry dissection. The anatomical operation, collection, storage, and transfer of samples were strictly in accordance with the “Regulations on Autopsy of Patients with Infectious Diseases or Suspected Infectious Diseases” (Order of the Ministry of Health No. 43), and the General Office of the National Health and Health Commission on Regulating the Development of New Coronavirus Infection “Notice of Autopsy Examination of Pneumonia Death Cases” (National Health Office Medical Letter [2020] No. 105) was implemented. A complete post-mortem was carried out on each corpse, and organs were macroscopically examined, including

| No. | Thoracic cavity                                                                                                                                                                                                 | Lung, appearance                                                                 | Lung, section                                                                 | Trachea and primary bronchi                                                                 | Hilar lymph node                                                                 |
|-----|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------|--------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------|
| 1   | Moderate, yellow-green bilateral pleural effusion; extensive adhesion between lung and thoracic wall                                                                                                               | Bilateral atrophic, consolidated lungs                                           | Significant carnification, rubbery, solid feeling                                      | Little mucus                                                                             | No.=10; diameter, 1-3 cm; ash black color                                           |
| 2   | Moderate, faint yellow bilateral pleural effusion; extensive adhesion between lung and thoracic wall                                                                                                                                 | Bilateral atrophic, consolidated lungs                                           | Variegated solid areas with mucus feeling                                              | Little mucus                                                                             | No.=10; diameter, 1-3 cm; gray and black color                                     |
| 3   | Moderate, faint yellow bilateral pleural effusion; both right pulmonis, and upper and lower lobes adhere to thoracic wall                                                                                                   | Bilateral atrophic, consolidated lungs, particularly the right lung              | rubbery, solid feeling, carnification                                                  | Foamy mucus                                                                             | No.=10; diameter, 1-3 cm; ash black color                                           |
| 4   | Little, faint yellow pleural effusion in both sides of the chest, adherence between two lungs and the chest wall, particularly in the middle and lower lobes                                                                 | Bilateral atrophic, consolidated lungs                                           | Ashes red in color, solid and rubbery feeling                                          | Little mucus                                                                             | No.=10; diameter, 1-3 cm; ash black color                                           |
lung, trachea and primary bronchus, thoracic cavity, heart, aorta, liver and gall bladder, spleen, pancreas, intestine, genital organs, kidney, adrenal gland, and thyroid gland.

Histopathologic Evaluation

Representative tissues from organs were sampled, followed by fixed in 10% formalin and embedding in paraffin blocks. The slides were stained by hematoxylin and eosin (HE) staining and evaluated independently by 2 senior pathologists. Any morphologic changes were recorded. Immunohistochemical staining was also carried out using commercially available antibodies (all were prediluted, from Dako, Carpinteria, US, if not otherwise described) including SMA, ERG, AE1/AE3, TTF-1, CK7, CD68, Desmin, MPO, CD235a, and RP3-NP (1: 100; the Rp3-NP antibody was provided by Prof. Zheng-Li Shi, Wuhan Institute of Virology, Chinese Academy of Sciences). Alcian blue/periodic acid-Schiff (AB-PAS) staining and Masson staining were also carried out. A Dako automated immunohistochemistry system (Dako, Carpinteria, CA, USA) was used according to the manufacturer's protocol.

Table 3. Autopsy features in other organs.

| No. | Heart | Aorta | Liver/ gallbladder | Pancreas/ spleen | Intestines | Reproductive organs | kidney/ adrenal gland | Thyroid gland |
|-----|-------|-------|--------------------|------------------|------------|----------------------|----------------------|---------------|
| 1   | Slightly larger in size, slightly thicker in left wall | NEA | Mildly enlarged liver with a solid, dark-red cut resection and medium quality; obvious enlarged gallbladder, and filled with dark brown bile pigment deposits and stones lead to a spherical appearance with a thin wall | NEA/slightly atrophy | NEA | NEA | Bilateral atrophy/NEA | NEA |
| 2   | MI | NEA | NEA/NEA | NEA | NEA | NEA | NEA | NEA |
| 3   | Thromboembolism in the right ventricular outflow tract into the pulmonary trunk, with 15 cm in length, 1 cm in diameter | Extensive atherosclerotic plaques on the inner wall of the aorta; coronary atherosclerosis with grade II stenosis in the left anterior descending branch | NEA | NEA | NEA | NEA | NEA | NEA |
| 4   | NEA | Multiple atherosclerotic plaques on the wall of the aorta | NEA | NEA | NEA | NEA | Bilateral atrophy with multiple cysts/NEA | NEA |

NEA – no evidence of abnormalities; MI – myocardial infarction.
Results

Clinical Features

The detailed clinical features are summarized in Table 1. The 4 corpses were 2 males and 2 females, ages 53, 62, 73, and 88 years old, with an average age of 69 years. None of them had underlying lung disease and all 4 had experienced a similar symptom onset of cough, fever, chest tightness, and wheezing. The course from fever to death was 7, 9, 22, and 15 days (average 13 days, median 12 days). The patients had been admitted to hospital due to exacerbating pneumonia and were diagnosed as having COVID-19 by use of a coronavirus nucleic acid detection kit. All 4 patients had received a conventional antiviral treatment program, but none of them showed a significant remission and all eventually died. Their chest computed tomography (CT) scans typically presented with dense ground-glass opacity in both lungs, with thickened pleura, and bilateral pleural effusion could be seen in Case 2. Laboratory examination (Table 1) showed a gradually increasing proportion of neutrophils, decreased proportion of lymphocytes, and lower red blood cell count and hemoglobin. The partial pressure of oxygen (PaO2) in 3 of 4 patients was low, varying from 97 mmHg to 51 mmHg (normal, 80-100 mmHg), but Case 1 consistently maintained a normal level. More details of other blood gas data were available in Case 3: it showed a continuous increase of partial pressure of carbon dioxide in arteries (PaCO2, range 5.29 to 39 to 44 to 81, and to more than 115 mmHg; normal, 34-45 mmHg), elevated blood pH (alkalemia, 7.466-7.52; normal, 7.355-7.45), level of bicarbonate (BB, range, 28 to 31.8 to 32.8 mmol/L; normal, 22-26 mmol/L), and base excess (BE, range, 4.4 to 8.9 to 20.4 mmol/L; normal, -3-3 mmol/L).

Figure 1. (A) Lung consolidation. (B) Lung consolidation (SMA showed a hyperplasia of myofibroblasts). (C) Lung injury, pulmonary bullae. (D) Hyaline membrane (brown color highlighted by Masson’s stain). (E) Abundant serous exudation in the alveoli. (F) Cellulose exudation in the alveoli (brown color stained by Masson’s stain).
Autopsy Results

Macroscopic features of lungs and thoracic cavities of the 4 patients with COVID-19 are listed in Table 2. The thoracic cavity of the 4 corpses had low to medium volume of pale-yellow effusion, and varying degree of adhesion was found between the lungs and thoracic wall. Bilateral lungs showed various degrees of atrophy and consolidation, with diffusely tough and solid texture in the sections. Mucus exudate was seen in the pulmonary section in Case 2. In all 4 corpses, a small amount of mucus in trachea and enlarged hilar lymph nodes were also found. The sizes of the hearts of 4 corpses were normal, but 1 showed myocardial infarction (Case 2). A thromboembolism was found in the main pulmonary artery extending into the atrium in Case 3, and significant atherosclerotic plaques tagged in the inner wall of the aortic arch were found in 2 cases (Case 3, Case 4). None of the 4 had any obvious liver abnormalities. The gallbladder of Case 1 had a spherical enlargement with dark-brown bile pigment deposits and stones in its cyst. Two corpses (Case 1 and Case 4) had slightly atrophied bilateral renal parenchyma, and Case 4 had multiple serous cysts in both kidneys. Atrophic changes in the spleen were found in 2 corpses (Case 1 and Case 2). There were no obvious abnormalities in the pancreas, small intestine, large intestine, uterus, ovaries, fallopian tubes, or testes (Table 3).

Histologic Features

Microscopic examination of the lungs revealed that the significantly expanded alveolar septa had prominent fibroblastic proliferation. The hyperplastic fibrous tissue filled the alveolar cavity, forming solid interalveolar fibroblastic plugs, resembling organizing pneumonia (Figure 1A, 1B). Some areas showed the alveolar epithelial shedding and extensive alveolar injury; most showed the widening alveolar septa were irregular with...
rupture, leading to the formation of bullae (Figure 1C). The lining of the alveolar walls was extensively replaced by a thick, homogeneous, eosinophilic hyaline membrane (Figure 1D). Serous and fibrous exudates and hemorrhage could be seen in the alveolar spaces (Figure 1E, 1F). The mucous plugs were formed due to the exfoliated ciliated columnar epithelium intermingled with secreted mucous in the small bronchi, bronchioles, terminal bronchioles, and respiratory bronchioles, which may have blocked the airway. Residual mucus plugs were also seen in the focal alveolar ducts (Figure 2A, 2B). The interstitial capillaries showed loss of endothelial cells, formation of thrombosis, and recanalization (Figure 2C, 2D). Type I alveolar epithelial cells (AECs) were decreased or vanished, and instead there was a florid proliferation of type II AECs, usually with tufted or papillary growth with or without exfoliation (Figure 3A, 3D). Obvious aggregation of macrophages deposited in the alveolar spaces. Viral inclusion could be seen in the cytoplasm of both II alveolar epithelial cells and macrophages (Figure 4A, 4B). Immunohistochemically, the proliferated or exfoliated Type II AECs were further labeled by AE1/AE3, TTF1, and CK7 (Figure 3B, 3C, 3E); the 2019-nCoV-specific marker RN3-NP was also expressed in these cells (Figure 3F). The aggregated macrophages were stained by CD68 (Figure 4D) and RN3-NP (Figure 4E). RN3-NP was found to localize in type II alveolar epithelial cells and macrophages by immunofluorescence assay (Figure 4C, 4F).

In the cardiac tissues, vacuolar degeneration of myocardial cells was prominent, showing a focal infarct and hyaline degeneration with scattered or small aggregates of chronic inflammatory cell infiltration (Figure 5A-5C).

Bone marrow biopsy of the sternum demonstrated a decrease in hematopoietic red lines and a relatively increased number...
Figure 4. (A, B) Macrophage aggregation was found in the alveolar cavity, and type II alveolar epithelial cells were surrounded by cellulose exudates (type II alveolar epithelial cells labeled by AE1/AE3). (D) Macrophages were stained by CD68. (C, E, F) The 2019-nCoV-specific marker RN3-NP was expressed in hyperplastic macrophages.

Discussion

The laboratory data of these 4 corpses showed a progressive decline in their oxygen saturation of blood, followed by refractory and irreversible hypoxemia. Combining the clinical and laboratory information with autopsy and histologic presentations of multiple organs, the potential causes of hypoxemia, appears to lie in several causes described below.

Mechanical obstruction in the outflow tract leads to difficulty exchanging air with the outside. The pulmonary conducting portion is from trachea down to the level of the terminal bronchioles [9]. Under normal circumstances, the luminal surfaces of the bronchial tubes at all levels of the airway are lined with intact ciliated columnar epithelium, and as the cilia consistently swing toward the pharynx, the foreign bodies, including mucus, are pushed in the same direction to the pharynx and then coughed out; instead, the respiratory portion generally does not produce mucus due to absence of ciliated cells [10]. In our cases, some ciliary columnar epithelial cells in the small bronchi, bronchioles, terminal bronchioles, and respiratory bronchioles of the lungs fell off, and then mixed with the mucus to form a mucus plug, which severely hindered downstream air from entering the lung tissues, thus affecting the efficiency of ventilation. Moreover, the mucus plugs were found to exist in a varying extent in terminal respiratory sites such as alveolar ducts, alveolar sacs, and alveoli, interfering with gas exchange. These mucus plugs in the terminal location may have originated from the following: 1) mucus backflow and accumulation caused by prolonged bed rest; 2) the
Figure 5. (A) Myocardial cell degeneration and necrosis. (B) Inflammatory infiltrated between cardiac striated muscle bundles. (C) Atrophy of myocardial cells, interstitial looseness, and edema. (D, E) Bone marrow hematopoietic function slightly decreased, and erythroid hyperplasia was lower than normal (MPO showed myeloid cells, CD235a showed erythroid cells). (F) Spleen phagocytosis (arrow).

ventilator blows the mucus in the upstream bronchus into the downstream bronchus; 3) extensive shedding of the ciliated columnar epithelium from all levels of the conducting tract and the squamous metaplasia may result in a huge loss of ciliated cells, with ensuing significant decrease in the ability of the respiratory tract to clear mucus and diminished ventilation and gas exchange. Only 1 corpse showed a normal PaO2, partly because of consistent oxygen inhalation assisted by the mechanical ventilation. The other 3 patients underwent a decrease of PaO2, and alkalemia as well as high BE and BB, indicating the development of hypoxemia.

Histologically, the respiratory portion, containing respiratory bronchioles, alveolar ducts, alveolar sacs, and alveoli, is located at the end of the air-conducting portion, where gas-blood exchange is completed, allowing full oxygenation of the blood, and oxygen-laden erythrocytes are transported to all parts of the body to participate in the biochemical reaction, while carbon dioxide is removed [11]. The focal hemorrhage and mucus plugs and aggregated macrophages deposited in the alveolar cavities and occupying the spaces functioning in air exchanges decreased the amount of oxygen that can participate in air-blood exchange. The air-blood barrier consists primarily of a liquid layer on the alveolar surface, type I AECs, basement membrane, thin connective tissue, capillary basement membrane, and continuous capillary endothelial cells, which is an important structure involved in the air-blood exchange process [12]. Several changes during the process of COVID-19 may affect the air-blood barrier, causing impaired air exchange: the hyaline membrane fully covering the inner surface of involved alveoli prevent rapid diffusion of oxygen and carbon dioxide, and the deposited mucus retention further aggravate this pathologic
process; type I AECs, a component of the air-blood barrier, are substantially reduced due to damage and exfoliation, but instead, type II AECs compensatory hyperplasia featuring tufted or papillary growth may greatly reduce the effective areas of air exchange [6]; the distended alveolar septa due to organizing connective tissues may result in an increased air diffusion distance; the endothelial cells, as the innermost layer of air-blood barrier, are damaged and the secondary thrombogenesis may be responsible for the impairment of the complete histologic air-exchanged structure and the focally reduced blood flow, and hence could affect the air diffusion.

Conclusions

The lack of sufficient air exchange because of these abnormalities in the respiratory portion discussed above can directly lead to hypoxemia. In addition, reduced erythropoiesis in bone marrow may lead to a decrease in the production of red blood cells and therefore a diminished ability to transport enough oxygen far away.

Conflicts of Interest

None.

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