CT Features of Coronavirus Disease (COVID-19) in 30 Pediatric Patients

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OBJECTIVE. The purpose of this study is to characterize the CT findings of 30 children from mainland China who had laboratory-confirmed coronavirus disease (COVID-19). Although recent American College of Radiology recommendations assert that CT should not be used as a screening or diagnostic tool for patients with suspected COVID-19, radiologists should be familiar with the imaging appearance of this disease to identify its presence in patients undergoing CT for other reasons.

MATERIALS AND METHODS. We retrospectively reviewed the CT findings and clinical symptoms of 30 pediatric patients with laboratory-confirmed COVID-19 who were seen at six centers in China from January 23, 2020, to February 8, 2020. Patient age ranged from 10 months to 18 years. Patients older than 18 years of age or those without chest CT examinations were excluded. Two cardiothoracic radiologists and a cardiothoracic imaging fellow characterized and scored the extent of lung involvement. Cohen kappa coefficient was used to calculate interobserver agreement between the readers.

RESULTS. Among children, CT findings were often negative (77%). Positive CT findings seen in children included ground-glass opacities with a peripheral lung distribution, a crazy paving pattern, and the halo and reverse halo signs. There was a correlation between increasing age and increasing severity of findings, consistent with reported symptomatology in children. Eleven of 30 patients (37%) underwent follow-up chest CT, with 10 of 11 examinations (91%) showing no change, raising questions about the utility of CT in the diagnosis and management of COVID-19 in children.

CONCLUSION. The present study describes the chest CT findings encountered in children with COVID-19 and questions the utility of CT in the diagnosis and management of pediatric patients.

In December 2019, a pneumonia associated with coronavirus disease (COVID-19) emerged in Wuhan, the capital city in the Hubei province of China [1]. Cases have since spread worldwide, with significant numbers of cases occurring throughout Asia, Europe, and North America [2, 3]. Initially, cases outside China developed in patients who had traveled to China or had contact with travelers from China. However, reports of local community spread are increasing, including in the United States [4]. As of April 27, 2020, a total of 2,878,196 confirmed cases of COVID-19 have been reported worldwide in more than 100 countries, including 931,698 cases in the United States, and 198,668 deaths have been reported globally [4].

The median age of affected patients is 47 years [5], with older men with comorbidities disproportionately more severely affected [6]. Pediatric patients account for approximately

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2% of reported cases [7, 8], and 0.9% of all affected patients are younger than 15 years of age [5]. Early investigators described the clinical and imaging features of COVID-19 in adults [9–12], but CT findings in children have been described in small cohorts only [13–15]. In comparison with adult patients, children present with milder symptoms and have lower hospitalization rates [8, 13–17], making prompt diagnosis challenging. Rapid and accurate diagnosis in the pediatric population is especially important because there have been cases of severe symptoms and reported deaths among such patients [8]. In addition, the social and psychologic implications of quarantining children and the economic impact on their caregivers must be considered. In the present study, we characterize the CT findings of 30 children from mainland China with laboratory-confirmed COVID-19. Although recent recommendations from the American College of Radiology assert that CT should not be used as a screening or diagnostic tool for patients with suspected COVID-19, radiologists should be familiar with the imaging appearance of the disease to identify its presence in patients undergoing scanning for other reasons.

Materials and Methods

The institutional review board at Icahn School of Medicine at Mount Sinai waived written informed consent for this retrospective case series evaluating deidentified data. Each of the six hospital centers also received institutional review board approval for this study.

From January 23, 2020, to February 8, 2020, a total of 30 pediatric patients with COVID-19 underwent chest CT at six hospital centers throughout mainland China. Eleven patients had follow-up chest CT performed during the study period. All patients had findings positive for COVID-19 via quantitative real-time reverse transcription–polymerase chain reaction (rRT-PCR) testing of respiratory secretions obtained by use of a nasopharyngeal or oropharyngeal swab. Patients older than 18 years of age or those without chest CT scans were excluded. We did not review chest radiographs.

Ten patients were from Hangzhou (Zhejiang province). Of these patients, nine underwent imaging performed using an Aquilion ONE CT scanner (Toshiba Medical Systems) and a slice thickness of 1 mm, tube voltage of 120 kVp, tube current modulation of 350–440 mA, and spiral pitch factor of 1.4, and the remaining patient underwent imaging performed using a Revolution ACT CT scanner (GE Healthcare) and a slice thickness of 5 mm, tube voltage of 120 kVp, tube current modulation of 41 mA, and spiral pitch factor of 1.8. Eight patients were from Bozhou (in Anhui province) and underwent CT performed using a Somatom go.Now scanner (Siemens Healthineers) and a slice thickness of 5 mm, tube voltage of 130 kVp, tube current modulation of 18–220 mA, and spiral pitch factor of 1.5. Six patients were from Ruian (in Zhejiang province). Of these six patients, two underwent imaging performed using a UCT 550 CT scanner (United Imaging) and a slice thickness of 1 mm, tube voltage of 100 kVp, tube current modulation of 40–350 mA, and spiral pitch factor of 1.2; three underwent CT performed using a Somatom Perspective scanner (Siemens Healthineers) and a slice thickness of 1.5 mm, a tube voltage of 110 kVp, tube current modulation of 100–300 mA, and spiral pitch factor of 0.9; and one patient was imaged using a Somatom Definition AS CT scanner (Siemens Healthineers) and a slice thickness of 1.5 mm, a tube voltage of 120 kvP, tube current modulation of 320 mA, and spiral pitch factor of 1.5. Two patients were from Guilin (in Guangxi province) and were imaged using a Brilliance Big Bore scanner (Philips Healthcare) and a slice thickness of 1 mm thick, tube voltage of 120 kVp, tube current modulation of 170–280 mA, and spiral pitch factor of 0.9–1. One patient was from Chengdu (in Sichuan province) and underwent imaging performed using an Ingenuity CT scanner (Philips Healthcare) and a slice thickness of 1 mm, tube voltage of 120 kVp, tube current modulation of 100 mA, and spiral pitch factor of 1. Three patients were from Zhuhai (in Guangdong province) and were imaged using a uMI 780 scanner (United Imaging) and a slice thickness of 2 mm, tube voltage of 80–100 kVp, tube current modulation of 40–50 mA, and spiral pitch factor of 1.1.

All scanning was performed with the patient in the supine position. For all patients who were able to comply with breathing instructions (23 of 30 patients), scans were acquired in end-inspiration. No IV or oral contrast medium was administered. No dedicated protocol was used because this was a retrospective study. Imaging data were reconstructed with a slice thickness of 1–5 mm. Patient characteristics were obtained from a retrospective review of the medical records and included age, sex, exposure history, and clinical presentation (Tables 1 and 2), which included fever, cough, diarrhea, vomiting, dyspnea, sore throat, and lethargy.

CT Image Review

CT studies were deidentified, and the original DICOM images were transferred to a remote server. Images were viewed on a PACS workstation. CT scans were reviewed on both standard mediastinal and lung windows in the axial plane. Multiplanar reformations were not performed at the time of the examination because it was not part of the clinical protocol at each of the six institutions. All CT scans were reviewed independently by a fellowship-trained cardiothoracic radiologist with 5 years of experience and a cardiothoracic radiology fellow. The kappa coefficient was used to compare the consistency of the two readers in evaluating each lung segment. In cases of disagreement between the two primary radiologic interpretations, another fellowship-trained cardiothoracic radiologist with 5 years of experience adjudicated a final decision.

The reviewers had concordant readings for all CT examinations with negative findings. Discrepancies between the two initial reviewers occurred in the assessment of the seven examinations with positive findings. The two initial reviewers independently identified all seven examinations as having findings positive for COVID-19 and correctly identified all affected lobes; however, there were disagreements regarding the severity of findings in the per-lobe assessment of three of the lobes (with each lobe belonging to a separate patient). This discrepancy led to differing total CT severity scores for these three patients. The third reviewer was blinded to the results of the initial reviewers and independently scored these three lobes. The final score for these three lobes and the final total CT severity scores for the three patients were agreed on by this two-thirds consensus reading. The radiologists were not blinded to the diagnosis; however, they were blinded to all clinical information associated with each patient. No negative controls were used in the image dataset.

Chest CT scans of each of the 30 patients were evaluated for ground-glass opacities and consolidation, which are characteristics that have been associated with COVID-19 in adult patients [9–11, 18], and for findings that are most frequently absent in adult patients, including pulmonary nodules, pleural effusions, lymphadenopathy (defined as a lymph node size > 10 mm in short-axis dimension), bronchiectasis, and linear atelectasis or fibrosis. Ground-glass opacities were evaluated for associated interlobular septal thickening (i.e., crazy paving pattern), a surrounding ring of consolidation (i.e., a reverse halo sign), and central consolidation (i.e., a halo sign). The number of lobes affected and the degree of lobe involvement were assessed. Disease severity was calculated on the basis of the overall extent of disease in each lung. The degree of involvement was classified according to the grading system introduced by Chung et al. [9, 11].. Each of the five lung lobes was assessed for degree of involvement, which was classified as none (0%), minimal (1–25%), mild (26–50%), moderate (51–75%), or severe (76–100%). No involvement corresponded to a lobe score of 0; min-

TABLE 1: Characteristics of 30 Study Patients

Characteristic	Value
Age (y), median (IQR)	10 (6–15)
Sex	
Male	15 (50)
Female	15 (50)
Exposure history	
Exposure to infected patient	26 (87)
Recent travel to Wuhan, China	3 (10)
Unknown exposure	1 (3)
Symptoms at hospital admission	
Fever	16 (53)
No obvious symptoms	9 (30)
Cough	8 (27)
Lethargy	2 (7)
Diarrhea	1 (3)
Dyspnea	1 (3)
Sore throat	1 (3)
Vomiting	0 (0)
Abnormal laboratory findings	
Lymphocytic leukocytosis	4 (13)
Nonlymphocytic leukocytosis	0 (0)
Leukopenia	3 (10)
Lymphopenia	6 (20)
WBC count (× 10^9 cells/L), median (IQR)	6.6 (4.1–9.1)
Neutrophil count (× 10^9 cells/L), median (IQR)	3 (1.5–4.3)
Lymphocyte count (× 10^9 cells/L), median (IQR)	2.7 (1.8–4.4)

Note—Except where otherwise indicated, data are number (%) of patients. IQR = interquartile range.

imal involvement, a lobe score of 1; mild involvement, a lobe score of 2; moderate involvement, a lobe score of 3; and severe involvement, a lobe score of 4. A total CT severity score was reached by summing the five lobe scores (range of possible scores, 0–20). All imaging characteristics were defined according to the Fleischner Society's glossary of terms for thoracic imaging.

Eleven patients had follow-up chest CT scans obtained during the study period, and all such scans were assessed for degree of involvement.

Statistical Analysis

Numeric variables were reported as means and SDs. Categoric variables were reported as medians and interquartile ranges. The Cohen kappa coefficient was used to calculate the interobserver agreement between the readers.

Results

Patient Information

Thirty pediatric patients with COVID-19 had CT scans obtained during the study period and met the study inclusion criteria. Patient age ranged from 10 months to 18 years old, with a median age of 10 years (interquartile range, 6–15 years) and a ratio of female patients to male patients of 1:1.

Nine of 30 patients had no symptoms at the time of diagnosis based on rRT-PCR results, and all nine patients had negative CT findings.

CT Findings

Presence of abnormalities—Twenty-three of 30 patients (77%) had normal CT findings without ground-glass opacities or consolidation. Seven of 30 patients (23%) had positive chest CT findings (Table 3), with ground-glass opacities, consolidation, or both findings observed in at least one lobe.

Types of abnormalities—Of the seven patients with positive CT findings, six (86%) had ground-glass opacities only (with no consolidation), no patients had consolidation in the absence of ground-glass opacities, and one (14%) had both ground-glass opacification and consolidation. A crazy paving pattern was identified in two patients (29%), and a reverse halo sign was identified in two patients (29%) (Figs. 1 and 2). A halo sign was also identified in two patients (29%) (Figs. 2 and 3A). These signs were seen in patients older than 14 years old who underwent CT at least 6 days after symptom onset, with no sex predilection noted. Six patients (86%) had findings with a peripheral lung distribution.

Findings that were absent in all patients included lymphadenopathy, pleural effusions, pulmonary nodularity, and fibrosis.

TABLE 2: Characteristics of Seven Patients With CT Findings Positive for Coronavirus Disease

Patient	Age (y)	Sex	Exposure History	Symptoms at Hospital Admission	Symptom Duration Before CT (d)	CT Severity Score	Abnormal WBC Count at Hospital Admission (× 10^9 cells/L)	Interval Between Initial and Follow-Up CT (d)
1	3	M	Exposure to infected patient	Fever and cough	3	1	WNL	6
2	8	M	Exposure to infected patient	Fever and sore throat	7	2	WNL	NA
3	14	M	Exposure to infected patient	Fever and cough	9	1	< 4.5	4
4	18	M	Exposure to infected patient	Fever and cough	13	4	WNL	NA
5	15	M	Exposure to infected patient	Fever and cough	2	7	> 20	6
6	18	M	Exposure to infected patient	Fever and dyspnea	2	4	WNL	NA
7	14	F	Exposure to infected patient	Fever and cough	6	2	< 4.5	3

Note—M = male, WNL = within normal limits, NA = not applicable, F = female.

TABLE 3: Findings at Initial Chest CT Examination for Seven Patients With Positive Findings

Finding	No. (%) of Patients
No. of lobes affected	
1	2 (29)
2	3 (43)
3	1 (14)
4	1 (14)
5	0 (0)
Opacities	
Ground-glass opacities and consolidation	1 (14)
Ground-glass opacities only	6 (86)
Consolidation only	0 (0)
More than two lobes affected	5 (71)
Bilateral lung disease	5 (71)
Frequency of lobe involvement	
Right upper lobe	1 (14)
Right middle lobe	1 (14)
Right lower lobe	5 (71)
Left upper lobe	3 (43)
Left lower lobe	5 (71)
Total CT severity score, mean (range)[a]	3 (1–7)
Opacification distribution and pattern	
Rounded shape	3 (43)
Linear opacities	1 (14)
Crazy paving pattern	2 (29)
Reverse halo sign	1 (14)
Halo sign	2 (29)
Peripheral distribution	6 (86)
Cavitation	0 (0)
Other findings	
Discrete pulmonary nodules	0 (0)
Pleural effusion(s)	0 (0)
Lymphadenopathy	0 (0)
Pulmonary fibrosis	0 (0)

[a]The mean total CT severity score (range) for all 30 patients evaluated was 0.7 (0–7).

Extent of abnormalities—Two patients (29%) had opacities in one lobe, three (43%) had opacities in two lobes, one (14%) had opacities in three lobes, one (14%) had opacities in four lobes, and no patients had disease affecting all five lobes.

The lower lobes were most commonly involved and were affected in six of seven patients (86%). Of note, the crazy paving pattern, halo sign, and reverse halo sign were seen exclusively in the lower lobes. The right upper lobe was involved in one patient (14%), the right middle lobe was involved in one patient (14%), the right lower lobe was involved in five patients (71%), the left upper lobe was involved in three patients (43%), and the left lower lobe was involved in five patients (71%). Two patients had unilateral disease (one had right lung involvement only, and the other had left lung involvement only), and five patients (71%) had bilateral disease. The total CT severity score ranged from 0 (for the 23 CT examinations with normal findings) to a maximum of 7, with a mean severity score of 0.7.

Interobserver agreement—The interobserver agreement for lobe involvement was excellent for each of the five lobes ($\kappa = 1.00$). The interobserver agreement for the per-lobe severity assessment was very good ($\kappa = 0.76–1.00$). There was excellent interobserver agreement for the right upper and middle lobes, ($\kappa = 1$) and very good agreement for the right lower lobe ($\kappa = 0.79$), the left upper lobe ($\kappa = 0.76$), and the left lower lobe ($\kappa = 0.81$). Agreement for the total CT severity score per patient was moderate ($\kappa = 0.49$). The mean CT severity score for patients with positive CT examinations was 3. Within this cohort with positive findings, there was a correlation between increasing age and increasing CT severity score (mean CT severity score, 1.5 for patients younger than 14 years and 3.6 for patients 14 years or older). The median age of patients without symptoms was less than that of patients with symptoms (10 and 14 years, respectively), and five of seven patients (71%) with positive CT findings were 14 years of age or older. The ratio of affected female patients to affected male patients was 1:1, and of the seven patients with positive findings, six were male and one was female.

The date of symptom onset was documented for all 21 patients who had symptoms. In this cohort, the mean interval between initial onset of symptoms and the initial chest CT examination was 3.8 days. For the seven patients with positive findings, the mean time between initial onset of symptoms and the initial chest CT examination was 6 days. Eleven of 30 patients (37%) underwent follow-up chest CT during the study. The mean time between the initial and follow-up chest CT examinations was 5.9 days. Ten of these 11 patients (91%) had no change in findings on the follow-up CT of 11 patients (64%) had negative findings on initial CT scans, and all follow-up scans in this cohort showed no abnormality. Of the four patients whose initial scans had positive findings, three had unchanged findings on follow-up scans (Fig. 3), and one 15-year-old patient had changes compatible with organization and reticulation on a scan obtained 6 days after the initial scan (Fig. 4).

Clinical information—All patients were immunocompetent and had no comorbidities. Nine of 30 patients (30%) had no clinical symptoms. Fourteen of 23 patients (61%) with normal CT findings had at least one clinical symptom. All seven patients with positive CT findings had at least one clinical symptom. The most frequent clinical presentations were

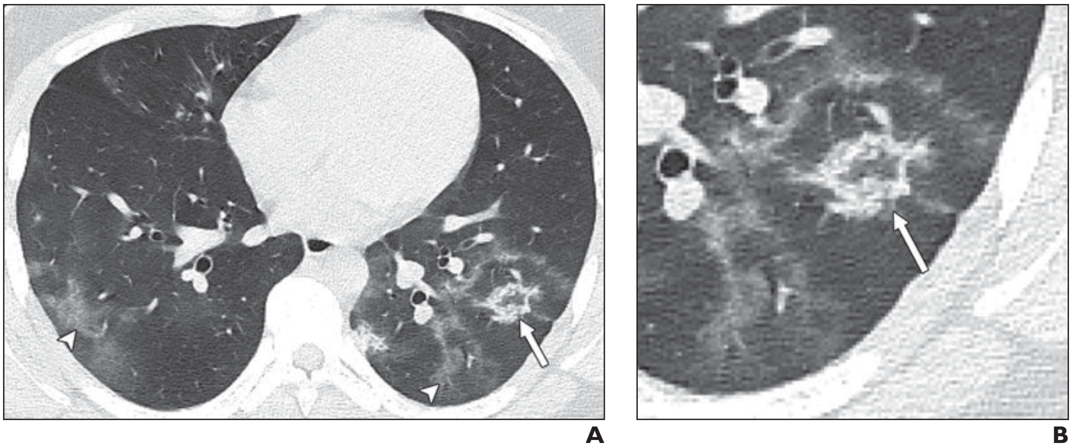

Fig. 1—18-year-old boy with coronavirus disease with multilobe involvement.
A, Unenhanced chest CT scan shows predominant peripheral and basilar distribution of ground-glass opacities (*arrowheads*) and area of ground-glass opacity in left upper lobe with peripheral consolidation (*arrow*), latter of which is known as reverse halo sign. CT findings were assigned CT severity score of 4.
B, Magnified view of unenhanced chest CT scan in **A** provides clearer view of reverse halo sign (*arrow*) in left lower lobe.

fever (body temperature, > 38°C) (53%), and cough (27%) (Table 1). Additional symptoms included lethargy (7% of patients), dyspnea (3%), and diarrhea (3%). WBC abnormalities were identified in 10 of 30 patients (33%), with lymphopenia seen in six of 30 patients (20%). The condition of all patients remained stable throughout hospitalization. No patients required supplemental oxygen, intubation, or ICU admission.

Discussion

The CT findings for children with COVID-19 may be normal, as seen in 23 of 30 patients (77%) in our study. Patients with positive CT findings in our study had characteristic findings, including airspace disease, which can present as ground-glass opacities or consolidation and may involve one or more lobes. Ground-glass opacities were more often encountered in our study cohort, and when consolidative opacities were identified, they were always accompanied by a ground-glass opacity. Of note, pleural effusions and lymphadenopathy were absent in all patients. Furthermore, patients who underwent scanning after a longer interval after symptom onset had a higher percentage of positive CT findings and showed findings including a crazy paving pattern and a reverse halo sign. The distribution of abnormalities in our cohort suggests a predominant pattern of disease. Five patients (71%) had bilateral lung involvement, six patients had findings in the lung periphery (86%), and six of seven patients (86%) showed involvement most commonly in the lower lobes.

These imaging findings suggest that COVID-19 may appear predominantly as ground-glass opacities in a bilateral, peripheral, and lower-lobe distribution in the pediatric population.

To our knowledge, this case series is the largest series to date that describes the imaging findings of pediatric patients with COVID-19. Our imaging findings and their distribution are consistent with findings published in the literature on COVID-19 in both pediatric and adult populations [9–14, 19]. Of note, two of seven patients (29%) with positive CT findings in our study had a halo sign (Figs. 2 and 3A), which has been described as a typical finding in children with COVID-19 [14].

Our rate of negative CT findings (77%) is significantly higher than that in previous reports of COVID-19 in the adult population (8–14%) [9, 10, 13]. These findings are consistent with those of Chen et al. [13], who found that compared with findings in the adult population, CT findings in the pediatric population are more often negative and, when positive, show less extensive disease. All of our patients with positive CT findings had clinical symptoms, whereas only 61% of patients with negative findings had clinical symptoms (Tables 1 and 2). The CT findings in our pediatric cohort are less extensive (Fig. 5), with fewer lobes affected (mean number of affected lobes, 0.5 vs 2.7–3.3 in adults) [9, 11] and a lower mean CT severity score (0.7 vs 9.9 in adults) [9]. Of the pediatric patients with positive CT findings, five of seven (71%) had bilateral disease; however, bilateral lung disease occurred less often in our total pediatric population (20%) compared with what has been noted in the adult population (76–82%) [9, 10]. Furthermore, in our pediatric cohort, there was a correlation between increasing age and an increasing CT severity score. However, the association between imaging severity and clinical symptoms has not been definitively established.

In addition, our clinical findings are consistent with the reported presentations of COVID-19 in adult and pediatric subgroups. Children have clinical symptoms develop that are similar to those reported in the adult population, including fever and cough [8–11, 13]. The reported pediatric presentation and clini-

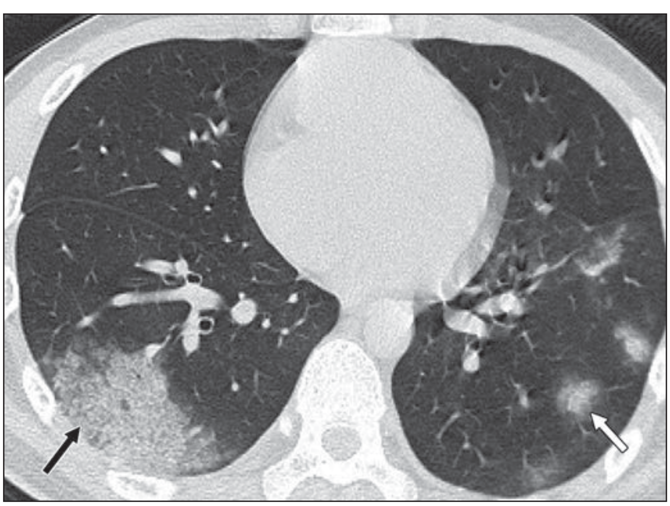

Fig. 2—18-year-old boy with coronavirus disease. Unenhanced chest CT scan shows round focal ground-glass opacity with septal thickening (crazy paving pattern) in right lower lobe (*black arrow*). Smaller amount of ground-glass opacity and multiple nodular opacities with peripheral ground-glass opacity (with halo sign) are seen in left lower lobe (*white arrow*). CT findings were assigned CT severity score of 4.

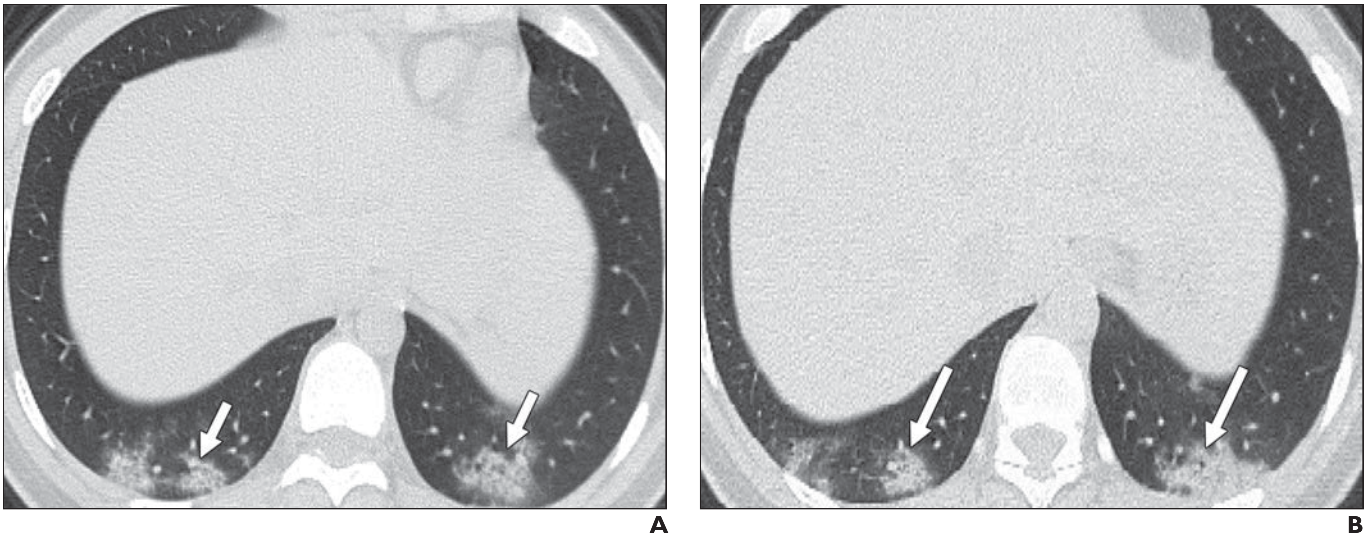

Fig. 3—14-year-old girl with coronavirus disease.
A, Initial unenhanced chest CT scan shows bilateral and peripheral distribution of predominantly rounded ground-glass opacities (*arrows*) with halo sign in left lower lobe. Upper lobes and right middle lobe show no abnormality, and CT findings were assigned CT severity score of 2.
B, Follow-up CT scan obtained 3 days after scan in A shows no significant change in opacities (*arrows*). CT severity score of 2 was unchanged.

cal course of disease are milder than those seen in adults [7, 8, 13, 20]. Nine of our 30 patients (30%) had no symptoms at the time of diagnosis, in comparison with 2–10% of patients in prior studies of adults [9, 10]. This makes early recognition, prompt isolation, and institution of infection control measures extremely challenging. Of note, this trend of milder symptoms developing in children was described in similar outbreaks of coronavirus infection, such as severe acute respiratory syndrome and Middle East respiratory syndrome [21, 22].

In our pediatric study population, female and male patients were infected with equal frequency; however, there was an increased prevalence among male patients (86%) when patients with positive CT findings were considered, similar to the reported predominance of infection among male patients noted in the literature on adult and pediatric populations [5, 8]. In addition, six of 30 patients (20%) had lymphopenia, a finding that has been reported in both pediatric and adult patient populations with COVID-19 [5, 14].

Recognizing the common CT pattern and distribution of findings of COVID-19 in children is crucial for prompt isolation and disease containment. Although children have milder symptoms overall, severe cases do occur in the pediatric population, and deaths have been reported [8]. These characteristic CT features are consistent with the typical findings published in the Radiological Society of North America's expert consensus statement on reporting chest CT findings in adults with COVID-19, including peripheral

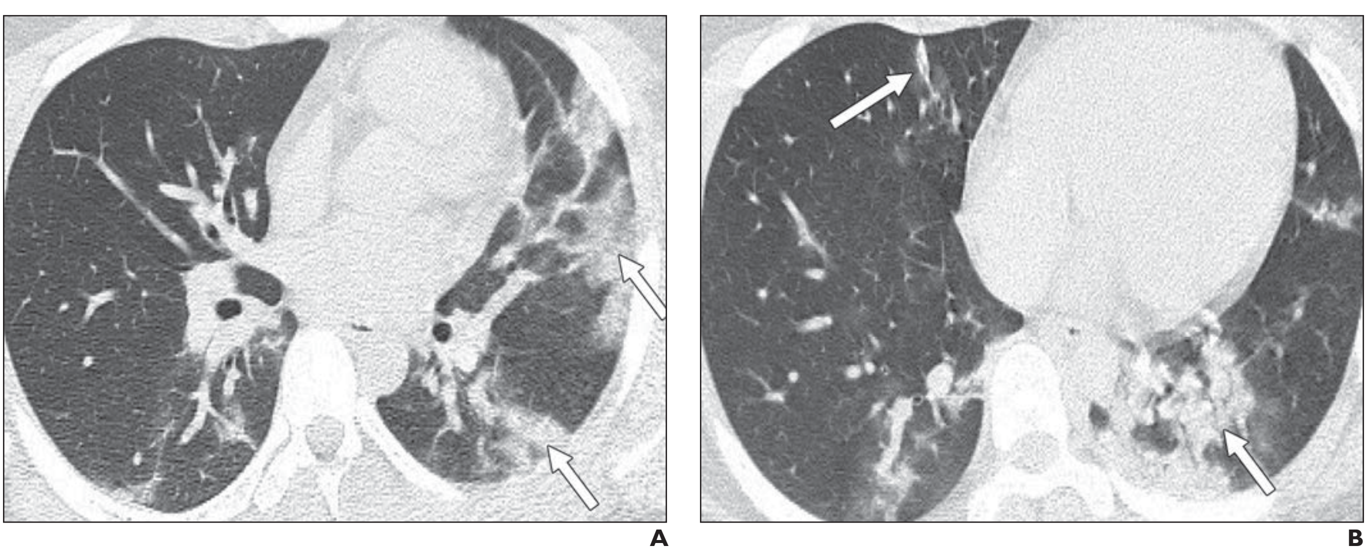

Fig. 4—15-year-old boy with coronavirus disease.
A and B, Initial unenhanced chest CT scans show bilateral ground-glass opacities and consolidation in peripheral and basilar predominant pattern (*arrows*), which is pattern that can be seen in acute organizing lung injury. CT findings from initial scans were assigned CT severity score of 7.

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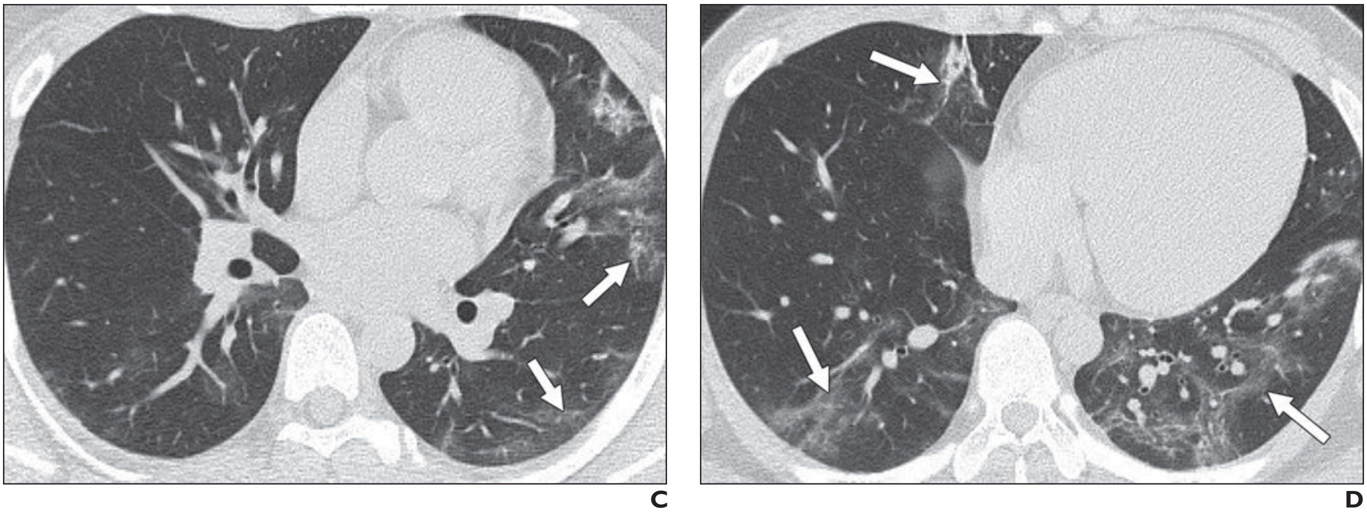

Fig. 4 (continued)—15-year-old boy with coronavirus disease.
C and **D,** Follow-up chest CT scans obtained 6 days after scans shown in **A** and **B** reveal increasing organization with reticular and linear opacities (*arrows*) and mild perilobular pattern of residual opacities, which can be seen in organizing pneumonia.

and bilateral ground-glass opacities, a crazy paving pattern, and a reverse halo sign [18]. Identifying these patterns and signs can help radiologists to distinguish COVID-19 pneumonia from other diseases such as a lobar pneumonia, which is more likely to present as consolidation rather than ground-glass opacity and is likely contained to a single lobe. It is important to note that these CT features, including the crazy paving pattern, halo sign, and reverse halo sign, are not specific to COVID-19 and can be seen in association with other atypical viral pneumonias or drug reactions. As shown in the present study, even negative CT findings cannot exclude COVID-19. For children with suspected infection but without suspicion of complication, in light of the low sensitivity of CT, its benefits may not outweigh the potential harm of radiation exposure. However, when these findings are encountered in a pediatric patient who has a suspicious clinical history or lives in an area with a high prevalence of COVID-19, they should alert the radiologist to consider a diagnosis of COVID-19.

With reported shortages in the availability of laboratory test kits in the United States and elsewhere, and with rRT-PCR having a reported sensitivity of 60–89% compared with 98% for chest CT [23–25], many have proposed chest CT as an important component of the diagnostic algorithm for adults with suspected COVID-19, especially in settings where disease prevalence is high and the availability of PCR testing is low [10]. However, the potential limitations of CT include its low positive predictive value in areas where the prevalence of COVID-19 is low and the lack of specificity of some CT findings that can be seen in association with other infections as well as other inflammatory diseases [25]. The low incidence of CT examinations with positive findings and the low severity of disease on CT in pediatric patients in our study can be considered when weighing the benefits and limitations of CT in the evaluation of COVID-19 in the pediatric population. Of note, the use of CT may be warranted in assessing suspected complications of COVID-19, such as other superimposed infections, pulmonary emboli,

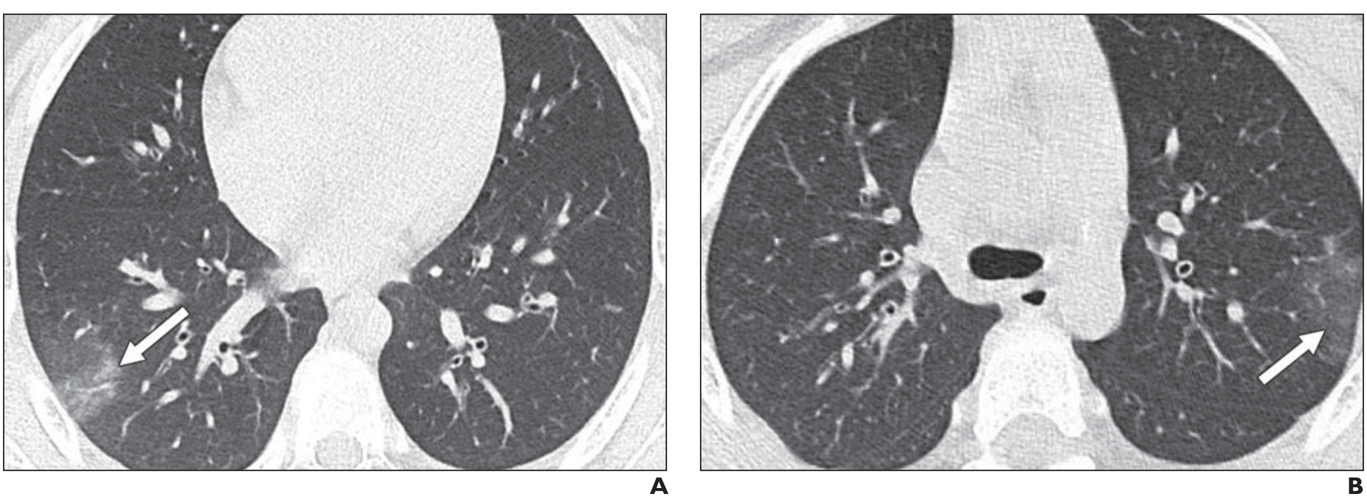

Fig. 5—8-year-old boy with coronavirus disease.
A and **B,** Unenhanced chest CT scans show minimal ground-glass opacities (in right lower and left upper lobes) (*arrows*) and no consolidation. Only two lobes were affected, and CT findings were assigned CT severity score of 2.

or cases in which the relative contributions of COVID-19 infection and preexisting disease may need to be clarified.

If chest CT is deemed necessary, additional workflow complexities must be addressed. Clinicians, CT technologists, and chaperones for young pediatric patients need to use appropriate precautions during patient contact, including hand hygiene, airborne measures (N95 respirator masks), and contact precautions as described by the Centers for Disease Control and Prevention [26]. Cleaning of all imaging equipment and rooms is an important and limiting factor, and appropriate use of infection control measures is necessary to prevent transmission to health care workers. Of importance, when these findings are encountered on pediatric CT, the radiologist must notify the referring physician as well as CT technologists and nursing staff. This will ensure initiation of the proper sanitization protocols in the CT suite and patient areas, notification of staff who may have been exposed, and prompt isolation of the patient.

More research is needed to fully characterize the clinical symptoms and imaging findings of COVID-19 among all age groups; however, our early study investigating pediatric patients with known infection raises questions about the widespread utilization of chest CT in children. Our findings show the limited sensitivity and poor negative predictive value of chest CT for the detection of suspected COVID-19 in children and highlight that normal chest CT findings do not exclude disease [9, 11]. In addition, when imaging results are positive, they are often nonspecific, as has been seen in association with multiple other infectious and inflammatory conditions.

There are several limitations of the present study. The primary limitation is that the threshold for performing chest CT for children in a location where the prevalence of disease is high, even children with mild or no symptoms, was significantly lower in China in comparison with other affected areas. Therefore, practice patterns will significantly differ in other areas, including the United States. In addition, the reasons why follow-up CT was performed for 11 of our patients were not well documented; earlier in the course of the pandemic, uncertainty about the persistence and prognostic significance of baseline CT findings may have been a factor. There was no correlation between worsening symptoms and the performance of follow-up CT, which also suggests a low threshold for follow-up CT. Our cohort includes all pediatric chest CT examinations performed for children with COVID-19 at six hospital centers during our study period. However, the total numbers of children with COVID-19 who were admitted to three of the hospitals are unknown. Our cohort includes all pediatric patients with COVID-19 admitted to three of the hospitals (those in Ruian, Bozhou, and Hangzhou); however, the total numbers of pediatric patients admitted in the remaining three hospitals (those in Guilin, Chengdu, Zhuhai) who did not undergo chest CT are unknown. Furthermore, in our study design, the radiologists were not blinded to the diagnosis of COVID-19. We acknowledge that in clinical practice, other conditions, including infectious diseases or adverse drug reactions, can have imaging findings similar to the CT findings described in this study. Also, only a small percentage of our patients (23%) had abnormal CT findings. With this small number of positive cases, generalization of CT findings for pediatric COVID-19 pneumonia can be somewhat challenging. Follow-up studies are needed to assess the link between severity of imaging findings in children and their clinical course, as well as evaluate the effects of the long-term sequelae associated with these imaging findings on the respiratory health of children.

Conclusion

Our investigation reveals a high frequency of negative chest CT findings among pediatric patients with COVID-19 and also suggests that bilateral, lower lobe–predominant ground-glass opacities are common in the subset of patients with positive CT findings. The clinical and CT findings for children may be less severe than those noted in previously reported adult populations, and further studies are needed to assess the appropriateness of CT in the diagnostic workup of pediatric patients.

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References

1. Chen N, Zhou M, Dong X, et al. Epidemiological and clinical characteristics of 99 cases of 2019 novel coronavirus pneumonia in Wuhan, China: a descriptive study. *Lancet* 2020; 395:507–513
2. European Centre for Disease Prevention and Control (ECDC). Geographical distribution of COVID-19 cases. ECDC website. www.ecdc.europa.eu/en/geographical-distribution-2019-ncov-cases. Accessed March 11, 2020
3. Centers for Disease Control and Prevention (CDC). Coronavirus disease (2019) (COVID-19): cases in the US. CDC website. www.cdc.gov/coronavirus/2019-ncov/cases-in-us.html. Accessed March 18, 2020
4. World Health Organization (WHO). Coronavirus disease 2019 (COVID-19): situation report – 98. WHO website. www.who.int/docs/default-source/coronaviruse/situation-reports/20200427-sitrep-98-covid-19.pdf?sfvrsn=90323472_4. Published April 27, 2020. Accessed April 27, 2020
5. Guan WJ, Ni ZY, Hu Y, et al.; China Medical Treatment Expert Group for COVID-19. Clinical characteristics of coronavirus disease 2019 in China. *N Engl J Med* 2020; 382:1708–1720
6. Del Rio C, Malani PN. 2019 Novel coronavirus: important information for clinicians. *JAMA* 2020 Feb 5 [Epub ahead of print]
7. Wu Z, McGoogan JM. Characteristics of and important lessons from the coronavirus disease 2019 (COVID-19) outbreak in China: summary of a report of 72 314 cases from the Chinese Center for Disease Control and Prevention. *JAMA* 2020 Feb 24 [Epub ahead of print]
8. CDC COVID-19 Response Team. Coronavirus disease 2019 in children: United States, February 12-April 2, 2020. *MMWR Morb Mortal Wkly Rep* 2020; 69:422–426
9. Chung M, Bernheim A, Mei X, et al. CT imaging features of 2019 novel coronavirus (2019-nCoV). *Radiology* 2020; 295:202–207
10. Zhao W, Zhong Z, Xie X, Yu Q, Liu J. Relation between chest CT findings and clinical conditions of coronavirus disease (COVID-19) pneumonia: a multicenter study. *AJR* 2020; 214:1072–1077
11. Bernheim A, Mei X, Huang M, et al. Chest CT findings in coronavirus disease-19 (COVID-19): relationship to duration of infection. *Radiology* 2020 Feb 20 [Epub ahead of print]
12. Salehi S, Abedi A, Balakrishnan S, Gholamrezanezhad A. Coronavirus disease 2019 (COVID-19): a systematic review of imaging findings in 919 patients. *AJR* 2020 Mar 14 [Epub ahead of print]
13. Chen A, Huang J, Liao Y, et al. Differences in clinical and imaging presentation of pediatric patients with COVID-19 in comparison with adults. *Radiol Cardiothorac Imaging* 2020; 2:e200117
14. Xia W, Shao J, Guo Y, Peng X, Li Z, Hu D. Clinical and CT features in pediatric patients with COVID-19 infection: different points from adults.

Pediatr Pulmonol 2020; 55:1169–1174

15. Cai J, Xu J, Lin D, et al. A case series of children with 2019 novel coronavirus infection: clinical and epidemiological features. *Clin Infect Dis* 2020 Feb 28 [Epub ahead of print]
16. Shen KL, Yang YH. Diagnosis and treatment of 2019 novel coronavirus infection in children: a pressing issue. *World J Pediatr* 2020 Feb 5 [Epub ahead of print]
17. Dong Y, Mo X, Hu Y, et al. Epidemiological characteristics of 2143 pediatric patients with 2019 coronavirus disease in China. *Pediatrics* 2020 (in press)
18. Simpson S, Kay FU, Abbara S, et al.; Radiological Society of North America expert consensus statement on reporting chest CT findings related to COVID-19: endorsed by the Society of Thoracic Radiology, the American College of Radiology, and RSNA. *J Thorac Imaging* 2020 Apr 28 [Epub ahead of print]
19. Li W, Cui H, Li K, Fang Y, Li S. Chest computed tomography in children with COVID-19 respiratory infection. *Pediatr Radiol* 2020; 2020:1–4
20. Garg S, Kim L, Whitaker M, et al. Hospitalization rates and characteristics of patients hospitalized with laboratory-confirmed coronavirus disease 2019: COVID-NET, 14 states, March 1–30, 2020. *MMWR Morb Mortal Wkly Rep* 2020; 69:458–464
21. Memish ZA, Al-Tawfiq JA, Assiri A, et al. Middle East respiratory syndrome coronavirus disease in children. *Pediatr Infect Dis J* 2014; 33:904–906
22. Babyn PS, Chu WC, Tsou IY, et al. Severe acute respiratory syndrome (SARS): chest radiographic features in children. *Pediatr Radiol* 2004; 34:47–58
23. Fang Y, Zhang H, Xie J, et al. Sensitivity of chest CT for COVID-19: comparison to RT-PCR. *Radiology* 2020 Feb 19 [Epub ahead of print]
24. Ai T, Yang Z, Hou H, et al. Correlation of chest CT and RT-PCR testing in coronavirus disease 2019 (COVID-19) in China: a report of 1014 cases. *Radiology* 2020 Feb 26 [Epub ahead of print]
25. Kim H, Hong H, Yoon SH. Diagnostic performance of CT and reverse transcriptase-polymerase chain reaction for coronavirus disease 2019: a meta-analysis. *Radiology* 2020 Apr 17 [Epub ahead of print]
26. Centers for Disease Control and Prevention (CDC). Interim infection prevention and control recommendations for patients with suspected or confirmed coronavirus disease. 2019 (COVID-19) in healthcare settings. CDC website. www.cdc.gov/coronavirus/2019-ncov/infection-control/control-recommendations.html. Published February 21, 2020. Accessed March 10, 2020