Extension of Coronavirus Disease 2019 on Chest CT and Implications for Chest Radiographic Interpretation

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In December 2019, an outbreak of coronavirus pneumonia developed in the city of Wuhan, Hubei Province, China, with evidence of human-to-human transmission. Severe acute respiratory syndrome coronavirus 2 was identified as the causative agent (1) of coronavirus disease 2019 (COVID-19), which became a pandemic in January 2020, with evidence of human-to-human transmission. Severe acute respiratory syndrome coronavirus 2 was identified as the causative agent (1) of coronavirus disease 2019 (COVID-19), which became a pandemic in January 2020, with evidence of human-to-human transmission.
Chest radiography is the primary imaging modality for evaluating acute respiratory illness in immunocompetent patients (10). Although COVID-19 can present with evident abnormalities on chest radiographs (1), in approximately two-thirds of the patients, radiographs were normal (11). The primary utilization of CT scans instead of chest radiographs might be suggested for evaluating suspected cases of COVID-19 based on the presumed higher sensitivity of the former. Nevertheless, it is operationally more complex to perform CT scans of suspected cases than chest radiographs, considering the preventive measures necessary to prevent the spread of the infectious agent (eg, disinfection of imaging resources). Therefore, it is necessary to understand the diagnostic performance of chest radiographs in comparison with CT images in COVID-19. This study aimed to compare the detectability of pulmonary opacities on chest radiographs of patients with COVID-19, correlating these findings with quantitative measurements obtained with CT.

Materials and Methods

A part of the study population was included in another study that qualitatively analyzed the chest radiologic and CT findings of COVID-19 in Korea (nine of 14 patients) (12). The institutional review board of all participating institutions (Seoul National University Hospital, Seoul National University Bundang Hospital, Incheon Medical Center, Seoul Medical Center, and The First Hospital of Lanzhou University) approved this retrospective study, and the requirement for informed consent was waived.

Study Population

There were 17 patients (mean age, 45.0 years ± 16.5 [standard deviation]; male-to-female ratio, 10:7) from five hospitals in Korea and China (14 patients from Korea and three patients from China) with PCR-proven COVID-19, who underwent a diagnostic chest CT scan and had an available same-day chest radiograph. One patient eventually required mechanical ventilation support during hospitalization; otherwise, patients recovered uneventfully. Thirteen of the patients underwent CT once at baseline, and the other four patients underwent CT twice (at baseline and follow-up). After excluding one normal baseline CT scan, we analyzed 20 CT scans and the corresponding chest radiographs of the patients. To analyze the diagnostic accuracy of chest radiographs for lung opacification caused by COVID-19, we additionally collected 20 chest radiographs as controls from 20 patients at a single hospital who were under investigation for COVID-19 (mean age, 32.0 years ± 13.7; male-to-female ratio, 9:11) but who had both negative PCR results and chest radiographs.

Image Acquisition

All noncontrast CT scans were obtained in the supine position at full inspiration using a multidetector CT scanner with 16 or more detector channels (Emotion 16, Somatom Sensation 64, Somatom Definition, Somatom Definition AS+, and Somatom Force; Siemens Healthineers, Erlangen, Germany). The CT tube voltage and current were 120 kVp, and a standard-dose or low-dose setting with automatic exposure control was used according to institutional protocols. Axial CT images were reconstructed with a slice thickness of 1 mm (3 mm in a minority of the cases) and a sharp reconstruction kernel. Chest radiographs were obtained using the following devices: DRX-Revolution (Carmeda, Rochester, NY); Optima XR220 (GE Healthcare, Chicago, Ill); Fluorospot Compact FD (Siemens Healthcare, Erlangen, Germany); and CXDI (Canon, Tokyo, Japan). All chest radiographs consisted of single frontal view. Fourteen chest radiographs were taken at upright position with posteroanterior projection, and the remaining were taken with anteroposterior (AP) projection in supine position or sitting position.

Quantitative CT Analysis

After uploading CT images from each patient to commercially available segmentation software (MEDIPIP Pro v2.0.0.0; MEDICALIP, Seoul, Korea), a deep neural network (Deep Catch v1.0.0.0; MEDICALIP, Seoul, Korea) automatically generated a volumetric mask of the lungs, lobes, intrapulmonary vessels, and airways. An image technician made a tentative volumetric opacity mask by applying a variable density mask based on CT attenuation thresholds to contain the entire opacity. Then, the pulmonary and airway masks were subtracted from the tentative mask. The mask containing the entire opacity was separated by checking the connectivity across individual opacities, and the separated opacity masks were labeled in numerical order. A chest radiologist (S.H.Y., with 15 years of clinical experience in thoracic imaging) reviewed and confirmed the opacity masks. If any corrections were required, a manual adjustment was applied to the minimum extent necessary (Fig 1a). In addition, the radiologist recorded whether the individual opacities showed AP overlap with the heart or hilum, or if located below the diaphragmatic dome or above the top of the aortic arch on CT, as opacities in these locations often tend to be less visible on radiographs.
The mean attenuation values and three-dimensional (3D) volumes were extracted based on the opacity masks from the CT scans. The quantitative CT opacity mass (QCT$_{\text{max}}$) was defined as the density of lung opacities multiplied by 1.065 (g/mL) (13) and by the combined 3D volume (cm$^3$) of the individual opacities in the whole CT scan. As lung opacities typically had attenuation values below zero, the attenuation values were converted to the density of lung tissue by adding 1000 to the attenuation values of each voxel and dividing by 1000 (13). The attenuations in the range from air (−1024 HU) to water (0 HU) were approximately equal to the physical densities (14), and the density of the lung tissue was assumed to be 1.065 g/mL (13).

**Radiograph Interpretation**

Eight thoracic radiologists (H.C., J.H.H., H. Ko, E.J.H., C.H.L., K.H.K., H. Kim, and J.M.G., with 5 years to 23 years of clinical experience in thoracic imaging) reviewed 40 anonymized chest radiographs (20 radiographs of patients with COVID-19 and 20 control radiographs) in a random order. The readers independently rated the presence of opacities on the radiographs using a clinical picture archiving and communication system workstation, using a five-point Likert scale (1, definitely absent; 2, probable absent; 3, uncertain; 4, probably present; 5, definitely present). They also recorded the location and type of each opacity (consolidation or GGO) when assigning a rating higher than 3.
Comparisons between CT Images and Radiographs

The lung and opacity 3D masks (Fig 1b) on CT images were displayed in different color renderings and viewed as a single image in the AP projection, enabling the estimation of the two-dimensional (2D) area (cm²) on chest radiographs (Fig 1c). A opacity on a CT image was considered to be visible on a chest radiograph if at least three of the eight readers agreed that it was probably or definitely present, and if the recorded location of the opacity on the chest radiograph matched the location of the projected image. In cases where opacities were visible, a radiologist (H.C.) who was blinded to the CT images manually drew a free-hand region of interest on the chest radiographs. For two additional cases of radiograph and CT image comparison, see Figures E1 and E2 (supplement).

Statistical Analysis

The diagnostic performance of the readers on chest radiographs was evaluated through a receiver operating characteristic curve analysis, with a Likert score for pulmonary opacity of 4 or 5 as evidence for COVID-19. The relationship between opacity 3D volume and 2D area was assessed by calculating the Pearson correlation coefficient ($r$). The quantitative parameters

### Table 1: Quantitative CT Analysis of Segmented Opacities

| Case | No. of Opacities | Location | Total Lung Volume (cm³) | Total Opacity Volume (cm³) | Extent of Opacities (%) | Mean Attenuation (HU)* | QCTmass (g)† |
|------|-----------------|----------|-------------------------|---------------------------|-------------------------|------------------------|--------------|
| 1    | 12              | RUL (4), RLL (3), LUL (3), LLL (2) | 3716.9                  | 28.6                      | 0.8                     | -481.2 ± 151.6         | 38.1         |
| 2    | 6               | RLL (3), LUL (2), LLL (1)         | 7937.5                  | 26.6                      | 0.3                     | -352.0 ± 170.1         | 30.0         |
| 3    | 1               | LUL (1)                            | 4489.1                  | 7.4                       | 0.2                     | -196.0                 | 6.3          |
| 4    | 2               | RLL (1), LUL (1)                   | 2997.1                  | 1.4                       | 0.05                    | -497.0 ± 44.0          | 0.8          |
| 5    | 9               | RUL (3), RML (1), RLL (1), LUL (3), LLL (1) | 2936.7 | 581.6                    | 19.8                    | -309.8 ± 63.2          | 420.7        |
| 6    | 15              | RUL (1), RML (1), RLL (5), LUL (4), LLL (4) | 6296.7 | 823.1                    | 13.1                    | -714.5 ± 40.2          | 250.1        |
| 7    | 1               | RLL (1)                            | 5478.4                  | 2.7                       | 0.1                     | -777.0                 | 0.7          |
| 8    | 2               | RLL (1), LUL (1)                   | 4290.0                  | 21.2                      | 0.4                     | -537.5 ± 51.5          | 9.3          |
| 9    | 22              | RUL (4), RML (3), RLL (7), LUL (7), LLL (1) | 4484.0 | 87.                       | 1.9                     | 470.1 ± 111.2          | 62.3         |
| 10   | 1               | RUL (1)                            | 5096.9                  | 6.8                       | 0.1                     | -280.0                 | 5.2          |
| 11   | 4               | RML (2), RLL (2)                   | 7474.9                  | 84.8                      | 1.1                     | -666.8 ± 67.3          | 37.4         |
| 12   | 9               | RML (2), RLL (6), LUL (1)          | 3323.2                  | 69.5                      | 2.1                     | -309.4 ± 127.5         | 54.8         |
| 13   | 33              | RML (1) RLL (15), LUL (2), LLL (15) | 5026.5 | 20.1                    | 0.4                     | -642.2 ± 68.4          | 8.5          |
| 14   | 12              | LUL (12)                           | 5148.4                  | 106.6                     | 2.1                     | -488.9 ± 74.8          | 59.6         |
| 15   | 1               | LUL (1)                            | 3237.0                  | 5.8                       | 0.2                     | -127.0                 | 5.4          |
| 16   | 12              | RUL (5), RML (2), RLL (3), LUL (1), LLL (1) | 4930.3 | 60.8                    | 1.2                     | -398.8 ± 104.5         | 48.1         |
| 17   | 19              | RUL (4), RML (3), RLL (3), LUL (6), LLL (3) | 3890.5 | 675.5                    | 17.4                    | -561.7 ± 39.9          | 353.0        |
| 18†  | 13              | RUL (4), RLL (5), LUL (2), LLL (2) | 3751.6                  | 24.2                      | 0.7                     | -272.2 ± 120.3         | 20.9         |
| 19†  | 7               | LUL (7)                            | 4960.3                  | 17.1                      | 0.3                     | -314.4 ± 57.5          | 12.8         |
| 20†  | 6               | RML (2), RLL (2), LLL (2)          | 4932.0                  | 46.1                      | 0.9                     | -56.7 ± 70.9           | 23.4         |

Note.—Data in parentheses are the number of opacities. RUL = right upper lobe; RML = right middle lobe; RLL = right lower lobe; LUL = left upper lobe; LLL = left lower lobe; QCTmass = Quantitative CT opacity mass.

* Data are mean ± standard deviation.
† The QCTmass was calculated as (mean attenuation + 1000)/1000 × 1.065 × opacity volume (11).
‡ Cases 18–20 are follow-up images of cases 1, 3, and 8, respectively.
Results

CT Opacification in COVID-19

A total of 186 opacities were identified in 20 patients, with an average number of 9.4 ± 8.1 opacities per patient. Table 1 shows the results of the quantitative CT analysis in the 20 patients with COVID-19. The mean QCTmass per patient was 72.4 g ± 120.8 (range, 0.7 to 420.7 g). The mean relative 3D extent of opacities in the lung parenchyma per patient was 3.2% ± 5.8 of the total lung volume (range, 0.1%–19.8%). The mean CT attenuation of all opacities per patient was −448.2 HU ± 173.1 (range, −777.0 to −127.0 HU). The mean QCTmass per opacity was 7.3 g ± 19.5 (range, 0.005 to 111.9 g). The mean attenuation per opacity was −492.4 HU ± 168.8 (range, −816.0 to −126.0 HU). The mean 3D volume of the opacities was 13.2 cm³ ± 35.2 (range, 0.02 to 185.8 cm³).

Reader Performance for Detecting COVID-19-related Opacities on Chest Radiographs

The median sensitivity among readers was 25% (interquartile range [IQR], 20%–26.3%), and the median specificity was 90% (IQR, 88.8%–96.3%) with a median area under the curve of 0.575 (range, 0.525 to 0.725) (Fig 2). Four of the 20 chest radiographs with opacities on CT were correctly diagnosed by all readers, and nine chest radiographs with opacities

Figure 2: Receiver operating characteristic curve analysis of observer performance for detecting pneumonia.

Figure 3: Scatterplots comparing the two-dimensional opacity area (in cm²) and three-dimensional (3D) volume (in cm³) and quantitative opacity mass (in grams) at CT on a (a, b) per-patient and (c, d) per-opacity basis.
on CT were missed by all readers. The median number of positive calls on chest radiographs was four (IQR, 3 to 4.75).

**Lung Area and Relative Opacity Extent on AP Projection View**

On AP projections of the CT images, the average relative opacity extent per patient was 13.9% ± 18.0% (range, 0.5%–57.8%). In the 20 patients, the Pearson correlation coefficient between the 2D area on the AP projection view and the 3D volume on chest CT was 0.978 on a per-patient basis and 0.901 on a per-opacity basis (P < .001). The correlation coefficient between the 2D area on the AP projection view and the QCTmass was 0.878 on a per-patient basis and 0.847 on a per-opacity basis (all P < .001) (Fig 3).

**Comparison between Visible and Invisible Opacities on Chest Radiographs**

Nineteen of the 186 opacities were detected on chest radiographs. The median proportion between the identifiable opacity area on the chest radiograph to the projected opacity area based on CT was 55.8% (IQR, 49.9%–57.1%). On a per-patient basis, the visible opacities on chest radiographs showed a significantly greater opacity extent and QCTmax than did the invisible opacities (P < .033 and P < .025, respectively). Five of the six patients with COVID-19 (83.3%) with a CT extent larger than 2% or a QCTmax of greater than 55 g had visible opacities on radiographs (Table 2).

On a per-lung basis, there were significant differences in the number of involved lobes, the number of opacities, the opacity extent, and the QCTmax (P < .027, P < .020, P < .001, and P < .001, respectively). Visible opacities on chest radiographs were detected in 87.5% (seven of eight) with a QCTmax greater than 55 g, and in 100% (seven of seven) of the lungs with a relative volume extent exceeding 4%. There were no significant differences in the mean attenuation between the visible and invisible opacities on both a per-patient and a per-lung basis (P = .618 and P = .636, respectively) (Table 3).

**Predictive Factors of Opacity Visibility on Chest Radiographs**

Logistic regression analysis showed that the QCTmax (P < .001) and 3D opacity volume (P < .001) significantly affected the visibility of opacities on chest radiographs (Table 4), whereas no significant differences in opacity visibility were found according to the mean opacity attenuation value (P = .618) or if the opacity was located in a predetermined less visible region (P = .309).

**Discussion**

In the current study, we performed a quantitative CT analysis to assess the radiologic burden of COVID-19. The mean attenuation of pulmonary opacities was −492.4 HU ± 168.8, and the attenuation was in accordance with the qualitative CT findings reported in the literature, according to which...
COVID-19 typically manifests as predominant GGO (6,7). The QCTmass and 3D opacity extent on CT per patient ranged widely, from 0.7 g to 420.7 g and from 0.1% to 19.8%, respectively, which is in line with observations of a diverse spectrum of disease severity in COVID-19. The diverse radiologic burden in COVID-19 cases with similar radiologic findings indicates that a simple qualitative description of CT findings (ie, predominant GGO in the peripheral lung) may be insufficient for the proper patient management.

The prevention of transmission and quarantine of infected patients are vital components of the management of COVID-19. Chest CT was extensively used for diagnosis and monitoring of patients under investigation for COVID-19 in China. Nevertheless, utilizing chest CT as the primary imaging modality for all suspected cases of COVID-19 has logistical limitations, in that disease is thought to spread from person to person, leading to time-consuming disinfection procedures and undesirable downtime of CT facilities, potentially overwhelming the capacity of radiologic services. On the other hand, although chest radiography is a more flexible imaging modality, widely available globally, the assessment of its performance in a head-to-head comparison with CT in COVID-19 was lacking. We found in this study that chest radiographs were remarkably less sensitive for detecting COVID-19–related lung opacities, despite its high specificity. Depending on the probability of infection in suspected cases of COVID-19, the use of chest radiography and CT scans can be appropriately balanced in each institution, considering the available resources of health care personnel, medical facility, and disinfection procedures versus the lower diagnostic performance of the former imaging method.

Opacities were not only underdetected on chest radiographs, but also underestimated in size when compared with CT. Only about 56% of the opacities on the projected image were actually seen on radiographs. We found that the extension of disease was the main factor driving the visibility of lung opacities on chest radiographs. Therefore, clinicians and radiologists should keep in mind that a greater extent of disease can exist than that suggested by inspection of chest radiographs, and that chest radiographs may also have limitations for monitoring the disease extent.

Our study had several limitations. First, the study population was relatively small. Second, as aforementioned, we solely

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### Table 3: Comparison between Visible and Invisible Opacity on Chest Radiographs

| Parameter                  | Visible opacity (n = 5) | Invisible Opacity (n = 15) | P Value | Visible Opacity (n = 8) | Invisible Opacity (n = 32) | P Value |
|----------------------------|------------------------|---------------------------|---------|------------------------|---------------------------|---------|
| Bilaterality*              | 3                      | 10                        | .787    | N/A                    | N/A                        | N/A     |
| No. of involved lobes†     | 3.6 ± 1.7              | 2.7 ± 1.4                 | .306    | 2.1 ± 0.8              | 1.3 ± 8.4                  | .027    |
| No. of opacities†          | 11.2 ± 6.1             | 8.7 ± 8.9                 | .395    | 7.0 ± 7.5              | 3.8 ± 4.4                  | .020    |
| Mean attenuation (HU)†     | −454.2 ± 183.3         | −446.2 ± 175.4            | .933    | −481.2 ± 195.2         | −453.4 ± 156.1             | .636    |
| Extent of opacity (%)†     | 10.5 ± 8.0             | 0.7 ± 6.6                 | .033    | 13.2 ± 7.5             | 0.7 ± 9.0                  | <.001   |
| QCTmass (g)†               | 217.9 ± 180.5          | 23.2 ± 20.3               | .025    | 136.2 ± 76.4           | 10.9 ± 15.8                | <.001   |

Note.—Data are mean ± standard deviation. QCTmass = quantitative CT opacity mass.
* P values were calculated using the Fisher exact test.
† P values were calculated using the Mann-Whitney test.

### Table 4: Logistic Regression Analysis of Factors Affecting Opacity Visibility on Chest Radiographs

| Parameter                  | Odds Ratio | 95% CI | P Value* |
|----------------------------|------------|--------|----------|
| Mean attenuation (HU)      | 0.999      | 0.996, 1.002 | .618    |
| QCTmass (g)                | 1.092      | 1.054, 1.131 | <.001   |
| 3D volume (cm³)            | 1.000      | 1.000, 1.000 | <.001   |
| Less-visible opacity location† | 1.740      | 0.598, 5.061 | .309    |

Note.—Data are mean ± standard deviation. CI = confidence interval, QCTmass = quantitative CT opacity mass, 3D = three-dimensional.
* P values were calculated using logistic regression analysis.
† Less visible opacity locations include locations that showed anteroposterior overlap with the heart or hilum or were below the diaphragmatic dome or above the top of the aortic arch at CT.
evaluated the radiologic burden of COVID-19 and did not investigate correlations of radiologic findings with clinical manifestations or outcomes. Third, as cases were collected from multiple centers, the image quality and positioning of the chest radiographs were not consistent. Although such inconsistencies reflect real clinical practice, they may also have decreased the readers’ performance. Fourth, although we excluded pulmonary vessels within the opacity as much as possible, residual intraopacityal vessels after segmentation may have increased the CT attenuation of opacities, potentially affecting the calculated QCT\textsubscript{mass}.

In conclusion, chest radiographs had low sensitivity and high specificity for detecting COVID-19–related lung opacities. The QCT\textsubscript{mass} and 3D opacity volume at CT, which are quantitative surrogates of disease extension, were significant determinants of opacity visibility on radiographs. It is crucial to properly understand the diagnostic accuracy and limitations of chest radiographs in COVID-19 to improve the quality of patient management by ensuring an appropriate balance between the practicality of chest radiography versus better diagnostic performance of CT scans.

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This erratum serves to publicly disclose a conflict of interest for Sang Joon Park. Under the Disclosures of Conflicts of Interest section of the article, the entry under S.J.P. should read: S.J.P. founder and CEO of Medical IP, which provides quantitative CT analysis for this study.

The change was made online on December 14, 2020.