



## Simple quantitative chest CT for pulmonary edema

Maria Barile<sup>a,b,\*</sup>, Tomoyuki Hida<sup>a,c</sup>, Mark Hammer<sup>c</sup>, Hiroto Hatabu<sup>a</sup>

<sup>a</sup> Departments of Radiology, Brigham and Women's Hospital, Boston, MA, United States

<sup>b</sup> Department of Radiology at University of Massachusetts Memorial Medical Center, Worcester, MA, United States

<sup>c</sup> Department of Radiology, Kyushu University Hospital, Japan

### HIGHLIGHTS

- Quantitative CT is a highly accurate but underutilized method for identifying pulmonary edema on CT.
- There is a moderately strong correlation between CT HUs and CXR pulmonary edema grade in every lobe with correlation coefficients ranging from 0.585–0.685.
- CT Hounsfield unit measurement yields excellent accuracy in differentiating no edema from mild to severe edema, with AUCs up to 0.995 in the LUL.
- Qualitative CT with a sensitivity of 84% and specificity of 95% versus 78% Qualitative CT with a HU cut-off of -825 in the LUL is more sensitive (100% vs 84%) and specific (95% vs 78%) than qualitative CT.

### ARTICLE INFO

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### ABSTRACT

**Purpose:** To determine the accuracy of quantitative CT to diagnose pulmonary edema compared to qualitative CT and CXR and to determine a threshold Hounsfield unit (HU) measurement for pulmonary edema on CT examinations.

**Method:** Electronic medical records were searched for patients with a billing diagnosis of heart failure and a Chest CT and CXR performed within three hours between 1/1/2016 to 10/1/2016, yielding 100 patients. CXR and CT examinations were scored for the presence and severity of edema, using a 0–5 scale, and CT HU measurements were obtained in each lobe. Polyserial correlation coefficients evaluated the association between CT HUs and CXR scores, and receiver operating characteristic (ROC) curve analysis determined a cutoff CT HU value for identification of pulmonary edema.

**Results:** Correlation between CT HU and CXR score was moderately strong ( $r = 0.585–0.685$ ) with CT HU measurements demonstrating good to excellent accuracy in differentiating between no edema (grade 0) and mild to severe edema (grades 1–5) in every lobe, with AUCs ranging between 0.869 and 0.995. The left upper lobe demonstrated the highest accuracy, using a cutoff value of -825 HU (AUC of 0.995, sensitivity = 100% and specificity = 95.1%). Additionally, qualitative CT evaluation was less sensitive (84%) than portable CXR in identifying pulmonary edema. However, quantitative CT evaluation was as sensitive as portable CXR (100%) and highly specific (95%).

**Conclusions:** Quantitative CT enables the identification of pulmonary edema with high accuracy and demonstrates a greater sensitivity than qualitative CT in assessment of pulmonary edema.

### 1. Introduction

Pulmonary edema is one of the most common entities that is encountered on routine chest imaging in both the inpatient and outpatient settings. Cardiogenic pulmonary edema is commonly caused by

acute decompensated heart failure. The chest x-ray (CXR) is one of the most frequently utilized noninvasive diagnostic tests ordered to confirm or rule out pulmonary edema. CXR assessment of pulmonary edema has been shown to correlate with volume status, total blood volume [1–3], and other indicators of heart failure [4]. Snashall, et al. demonstrated

**Abbreviations:** CXR, chest X-ray; CT, computed tomography; HU, hounsfield unit; ROI, region of interest; ROC, receiver operating characteristic; R, correlation coefficient; AUC, area under the curve.

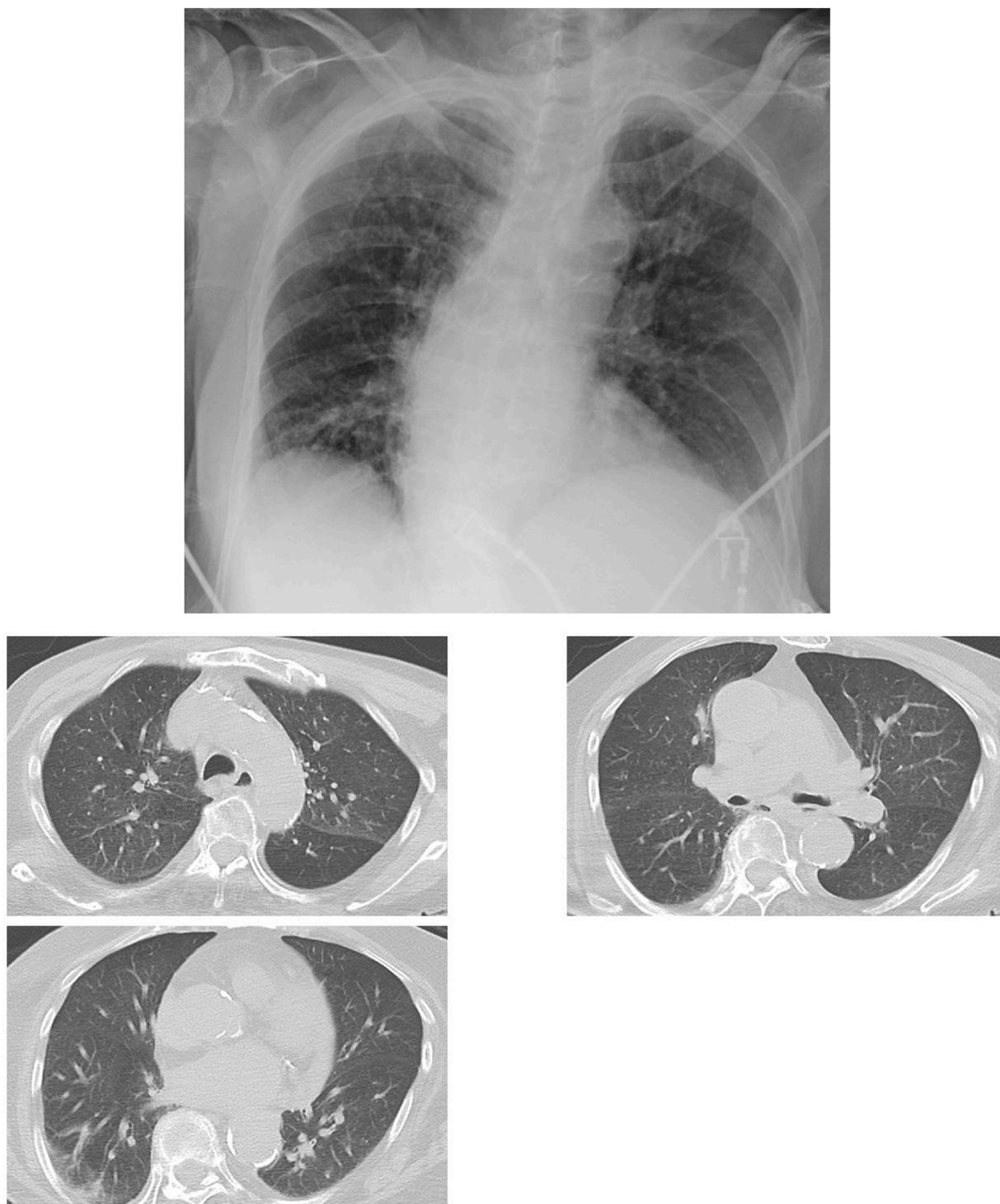
\* Corresponding author at: Department of Radiology at University of Massachusetts Memorial Medical Center, Worcester, MA, United States.

E-mail address: [maria.barile@umassmemorial.org](mailto:maria.barile@umassmemorial.org) (M. Barile).

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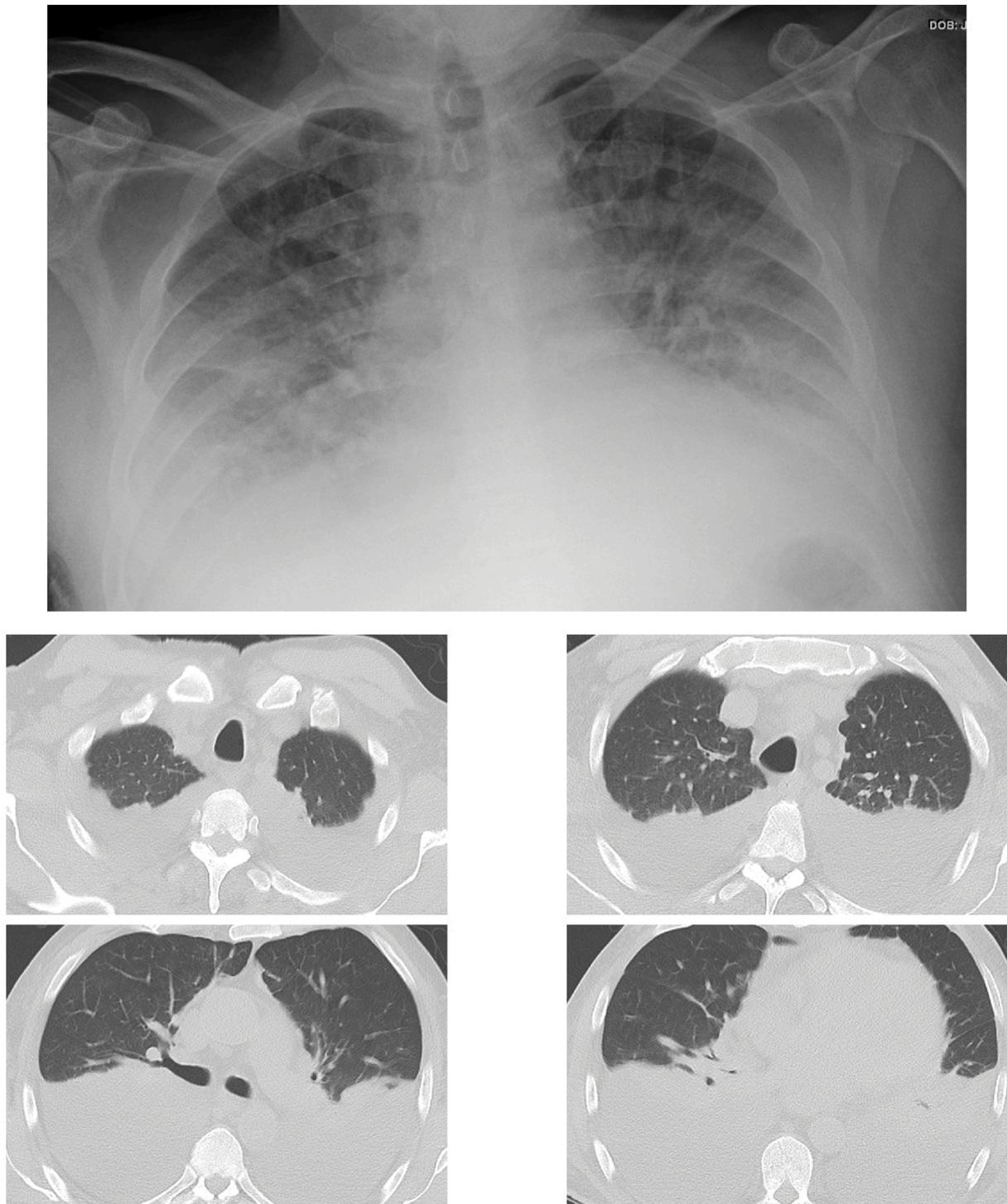
**Fig. 1.** 87 y.o. female status post a fall with mild to moderate pulmonary edema on portable CXR (CXR score 2) and no pulmonary edema on CT (CT score 0), RUL -705 HU and LUL -763 HU.

that changes in water lung volume in animal models as low as 35 % can be detected on CXR [5].

Chest computed tomography (CT) has also been used in the noninvasive evaluation of pulmonary edema and offers the added value of allowing for the quantitative assessment of lung density as a proxy for alterations in lung water content. Several different methods of quantifying lung density have been described, including the sector method [6], in which the density of a peripheral area of lung parenchyma is measured, and the whole lung method [7] in which the mean HU (Hounsfield unit) measurement of the lung parenchyma and central

vascular structures is quantified. CT lung density measurements have been shown to increase with worsening pulmonary edema, as defined by severity of pulmonary edema on CXR, and also to correlate with increasing pulmonary artery wedge pressures [8].

CT is believed to have a greater sensitivity for the detection of many pulmonary disease conditions when compared to conventional chest radiography. However, the authors have noted that mild pulmonary edema is often identified on CXR but not on concurrent CT examinations. To our knowledge, no studies have evaluated the sensitivity of CT versus CXR in the detection of pulmonary edema. We hypothesize that



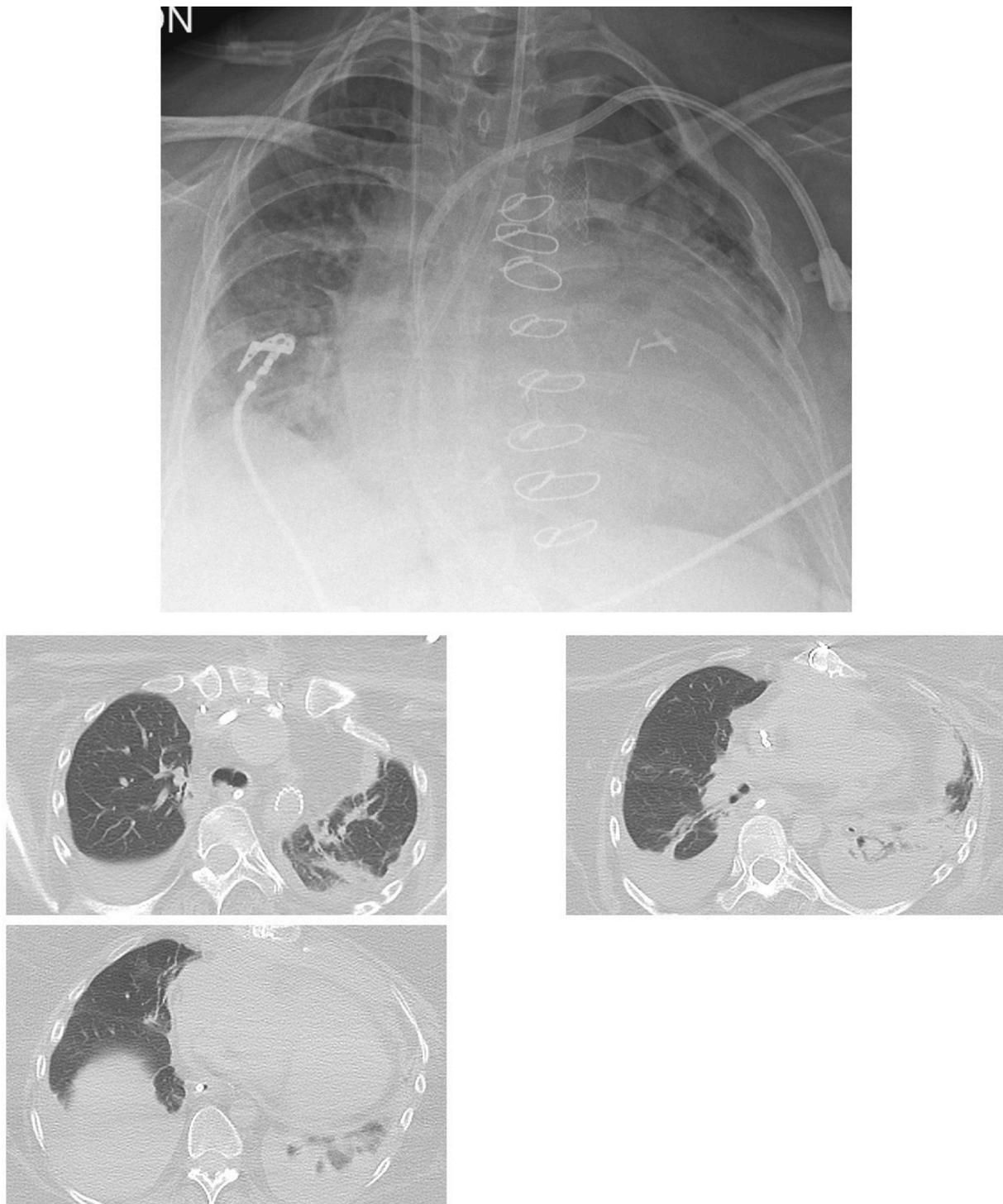
**Fig. 2.** 64 y.o. neutropenic male with tachypnea and moderate to severe pulmonary edema on portable CXR (CXR score 4) and mild pulmonary edema (CT score 1), RUL -747 HU, LUL -800 HU.

CXR evaluation for pulmonary edema is more sensitive than qualitative (visual) CT evaluation in the absence of lung density measurements on CT. Our results imply the necessity to establish the Hounsfield unit (HU) threshold to distinguish between patients with and without pulmonary edema for the routine chest CT examinations.

## 2. Materials and methods

### 2.1. Patient selection

IRB approval was obtained, and informed consent was waived for our HIPAA-compliant retrospective study. The electronic medical records were searched for patients with a billing diagnosis of heart failure who had a CXR and Chest CT performed on the same day between 1/1/2016 to 10/1/2016. Patients with contrast enhanced CTs and those with CXR and CT performed greater than three hours apart were excluded



**Fig. 3.** 38 y.o. female with congenital heart disease and hypotension with moderate pulmonary edema on portable CXR (CXR score 3) and with mild pulmonary edema on CT (CT score of 1), RUL -815 HU, and LUL -774 HU.

from analysis. The electronic medical record was also reviewed for demographic information including age and sex.

## 2.2. Imaging acquisition and interpretation

Portable supine AP and upright PA and lateral CXRs (2-view) were included for analysis. Two thoracic subspecialty trained radiologists (HH, 20+ years of experience and MH, 2 years of experience) analyzed the CXRs *in consensus*. The severity of pulmonary edema was graded on CXRs using a scale of 0–5 (0: no edema, 1: mild, 2: mild to moderate, 3:

moderate, 4: moderate to severe, 5: severe). Additionally, the presence of emphysema, pleural effusions, parenchymal consolidations, and intubation status were recorded.

CT examinations were performed using a tube voltage of 100–120 kVp. The data was then reconstructed using a lung kernel and 3.0 mm thick slices. One radiologist (MB, a thoracic radiologist with 3-year experience) manually drew ROIs (Region of Interest) on axial images in the right and left upper lobes, right and left lower lobes, lingula, and right middle lobe using the sector method. The central vasculature, including the main and lobar pulmonary arteries, pulmonary veins and

**Table 1**  
Demographics, CXR scores, and CT HU measurements of the study population.

	All	Portable CXR	Two views CXR
n	100	64	36
Age	21–101	22–101	21–89
Sex, male/female	65/35	77/23	88/12
<b>CXR</b>			
Score0	15	9	6
1	33	13	20
2	22	16	6
3	19	15	4
4	10	10	0
5	1	1	0
Intubation	25	21	4
Effusion	29	20	9
Emphysema	8	2	6
Consolidation	22	13	9
<b>CT HU measurements median HU, (n)</b>			
RUL	-753.0 (79)	-725.5 (50)	-793.0 (29)
RML	-795.0 (77)	-786.0 (48)	-811.0 (29)
RLL	-746.0 (69)	-732.0 (42)	-776.0 (27)
LUL	-768.0 (79)	-755.0 (49)	-790.0 (30)
Lingula	-766.0 (71)	-760.5 (44)	-798.0 (27)
LLL	-745.5 (64)	-737.0 (37)	-770.0 (27)

CT, computed tomography; CXR, chest X-ray radiograph; HU, Hounsfield unit; LLL, left lower lobe, LUL, left upper lobe; RML, right middle lobe; RLL, right lower lobe; RUL, right upper lobe.

airways were excluded from the ROI. The average CT density within the ROI in HU was recorded. ROIs were not calculated in lobes which contained emphysema, lobar atelectasis, or pneumonia.

CT examinations corresponding to patients with portable CXR were visually evaluated by HH and MH *in consensus* for the presence and severity of pulmonary edema, using a 0–5 scale (0: no edema, 1: mild, 2: mild to moderate, 3: moderate, 4: moderate to severe, 5: severe) (Figs. 1–3). As the same two readers analyzed both CXR and CT images, the analysis of CT examinations was performed after greater than a 3 month wash out period. All CTs were viewed on a PACS system with a window width and level of 1500 HU and -700 HU, respectively. Additionally, the presence or absence of the following was recorded: ground-

glass opacity, pleural effusions, and interlobular septal thickening. The radiologists were blinded to the CXR pulmonary edema scores and the Hounsfield unit measurements of each lobe.

**2.3. Statistical analysis**

Polyserial correlation coefficients were used for evaluating the association between continuous values of CT HU measurements in each lobe and categorical values of the CXR scores for pulmonary edema. Receiver operating characteristic (ROC) curve analysis was performed to determine the cutoff value of CT HU measurements for differentiation between CXR score 0 (no evidence of pulmonary edema) and CXR scores 1–5 (mild to severe edema). All statistical analyses were performed using R version 3.5.2 software (R Foundation for Statistical Computing, Vienna, Austria).

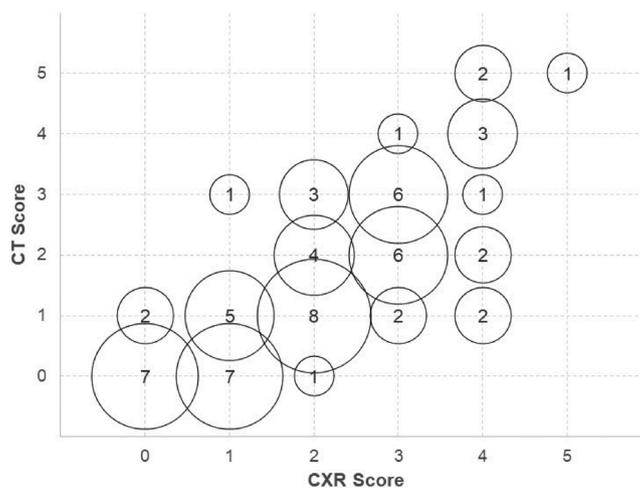
**3. Results**

**3.1. Patient demographics and CXR scores**

Patient demographics and CXR pulmonary edema scores are summarized in Table 1. Of the 100 chest radiographs, 64 CXRs were obtained in the supine position using AP portable technique and the remaining 36 cases were obtained in the upright position using a 2-view technique. Of the 100 cases, 15, 33, 22, 19, 10 and 1 cases were classified as CXR scores 0–5, respectively. Twenty-five cases had an endotracheal tube or tracheostomy tube in place. Pleural effusions and emphysema were seen in 29 and 8 CXRs, respectively.

**3.2. Qualitative (visual) CT assessment for pulmonary edema**

CT images for patients with portable CXRs were qualitatively scored for the presence of pulmonary edema (0 = no edema, 1 = mild edema through 5 = severe edema), blinded to the CT attenuation HU measurements, corresponding CXR images and scores. Fig. 4a shows how these scores compared to the portable CXR scores for each patient. The sensitivity of qualitative (visual) CT assessment for pulmonary edema (score ≥ 1) compared to portable CXR (score ≥ 1) was 84 %, with a specificity of 78 %. Of note, this sensitivity and specificity is less than that of quantitative CT, which yielded a sensitivity of 100 % and specificity of 95 % using a HU threshold of -825 in the LUL.



**Fig. 4.** a. Bubble plot showing qualitative CT score for pulmonary edema based on visual assessment (score 0-5) versus portable CXR score (score 0-5) of pulmonary edema. The number inside each circle corresponds to the number of patients with that combination of CXR and CT scores. b. Beeswarm boxplots demonstrating the relationship between CT HU versus CXR scores for pulmonary edema (portable and 2-view combined).

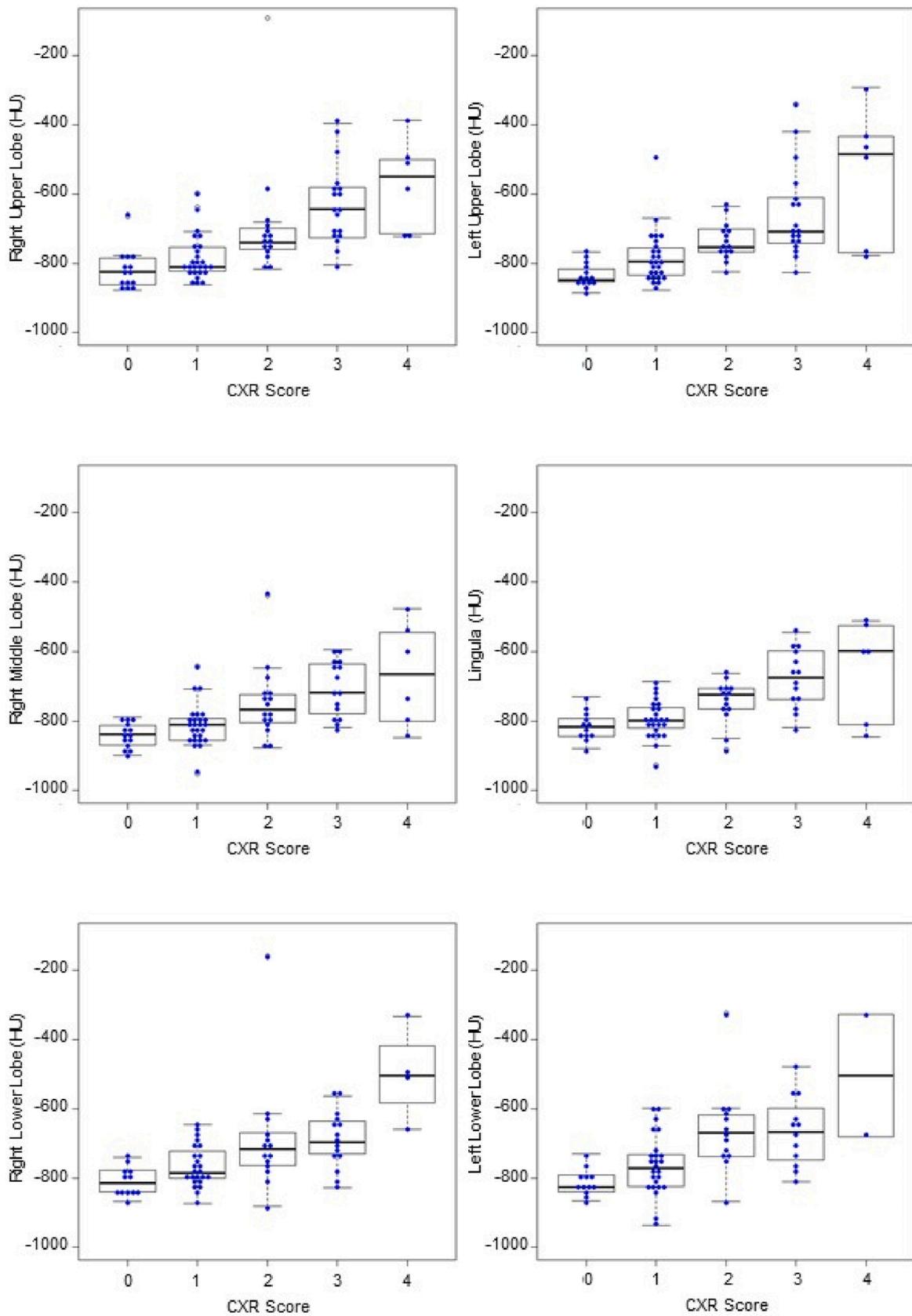


Fig. 4. (continued).

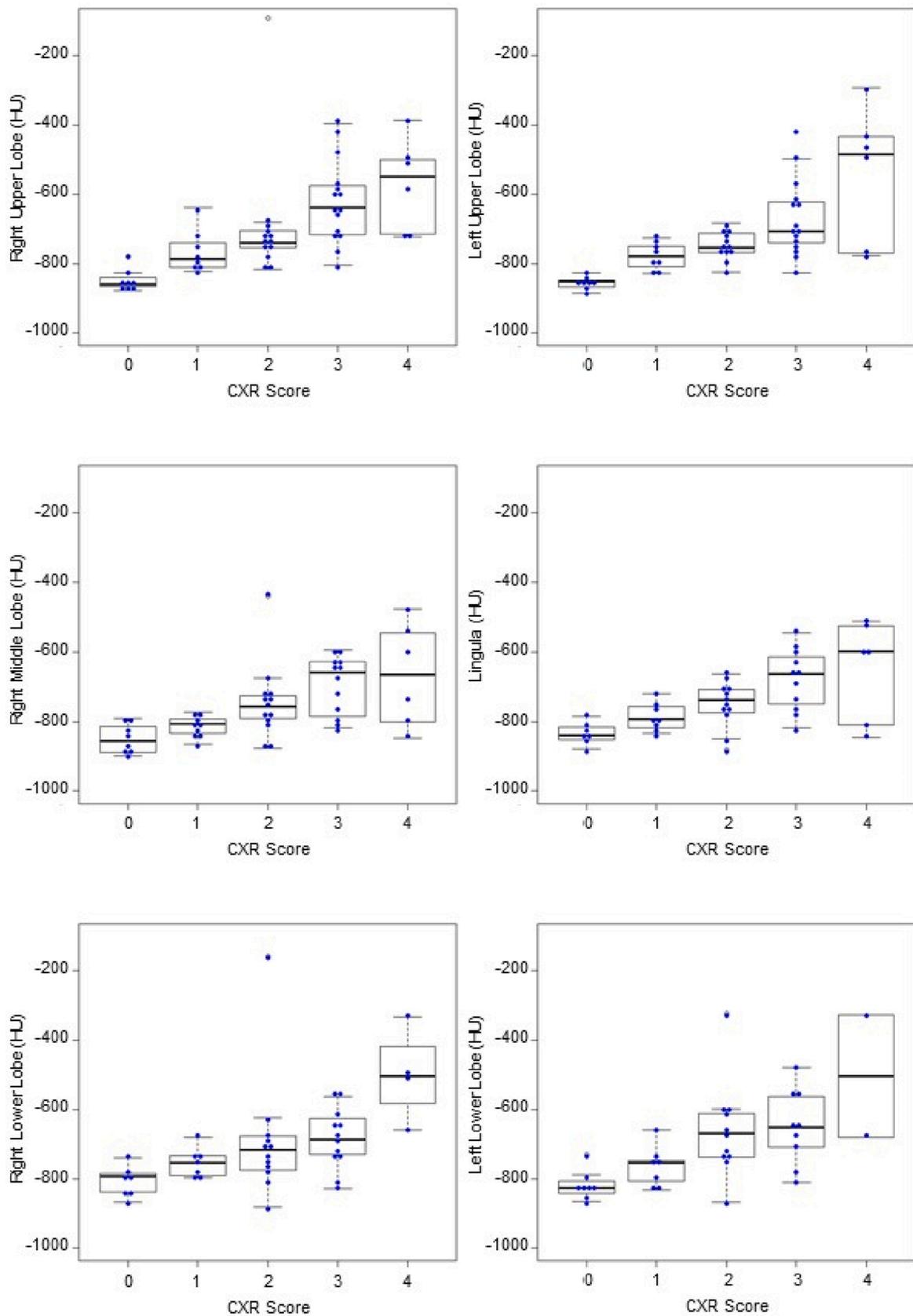


Fig. 5. a. Beeswarm boxplots demonstrating the relationship between CT HU versus CXR scores for pulmonary edema based on portable CXR. b. Beeswarm boxplots demonstrating the relationship between CT HU versus CXR scores for pulmonary edema based on 2-view CXR.

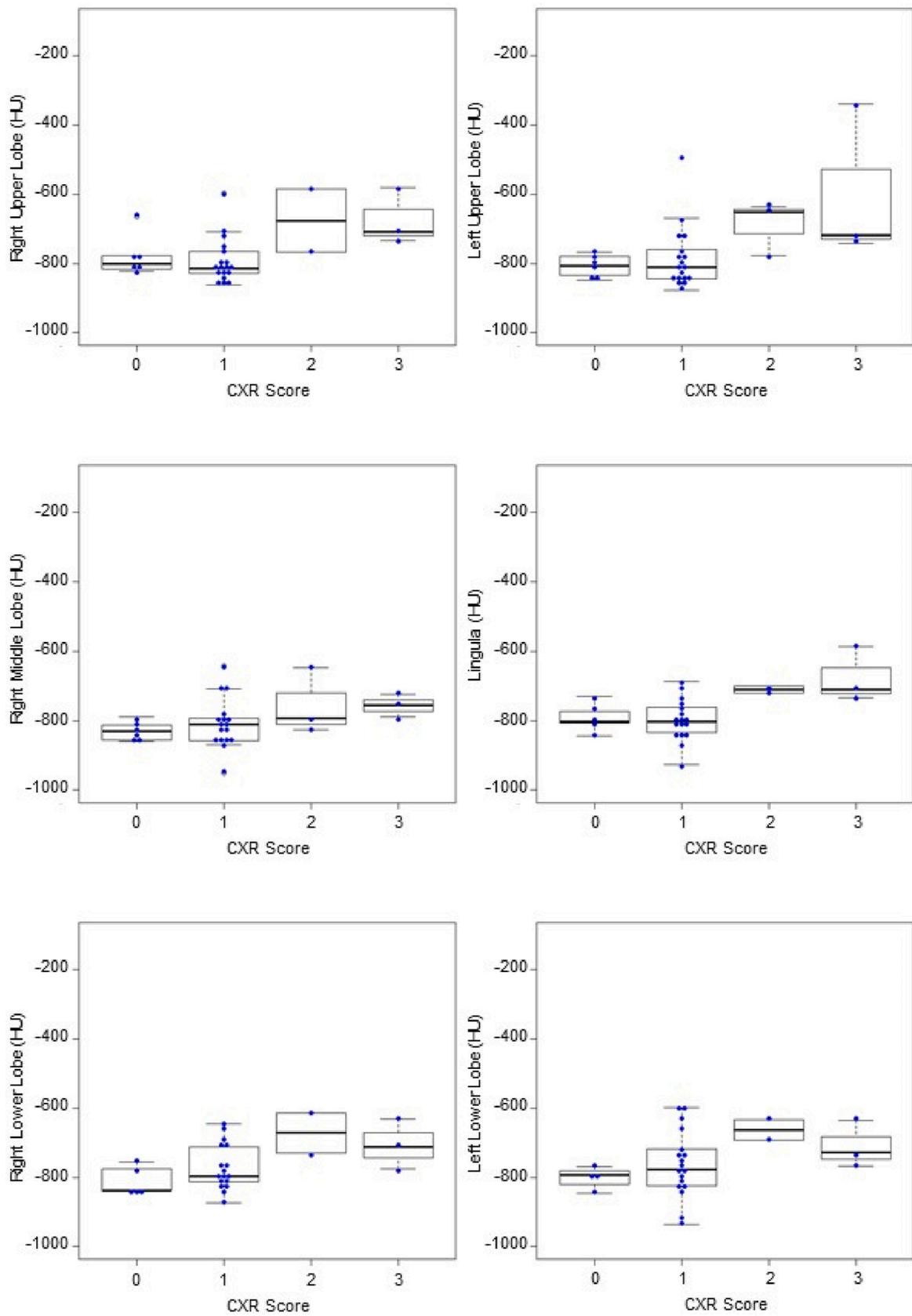
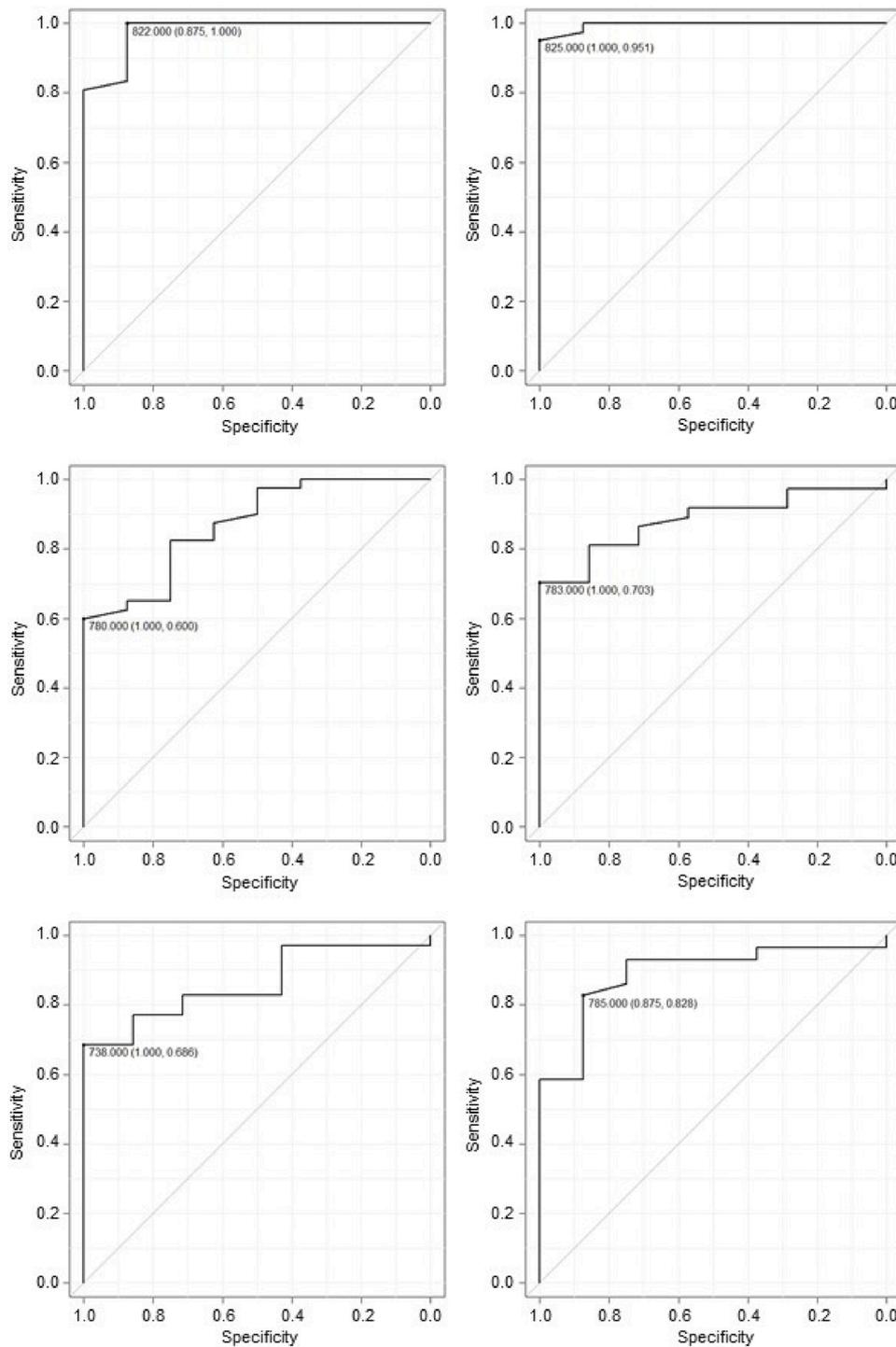


Fig. 5. (continued).



**Fig. 6.** a. Receiver operator characteristic (ROC) analysis results of CT HU measurements for diagnosis of pulmonary edema based on portable CXR. b. Receiver operator characteristic (ROC) analysis results of CT HU measurements for diagnosis of pulmonary edema based on 2-view CXR.

**3.3. Quantitative CT assessment of pulmonary edema using CT Hounsfield unit measurements**

CT HU measurements of the right upper lobe (RUL), the right middle lobe (RML), the right lower lobe (RLL), the left upper lobe (LUL), the lingula (Lingula), and the left lower lobe (LLL) were measurable in 79, 77, 69, 79, 71, and 64 cases, respectively. Beeswarm boxplots of CT HU versus CXR scores (portable and 2-view combined) are shown in Fig. 4b. The polyserial correlation analysis demonstrated moderate to strong

correlations between CT HU measurements in each lobe and CXR score with portable and 2-view data combined (correlation coefficients: RUL 0.642, RML 0.616, RLL 0.585, LUL 0.685, Lingula 0.671, and LLL 0.599).

To evaluate for differences in detection of pulmonary edema between portable and 2-view techniques, Beeswarm boxplots of CT HU versus CXR scores for both techniques were created and are shown in Fig. 5a and b. There were moderate to strong correlations between CT HU measurements in each lobe and portable CXR score (correlation

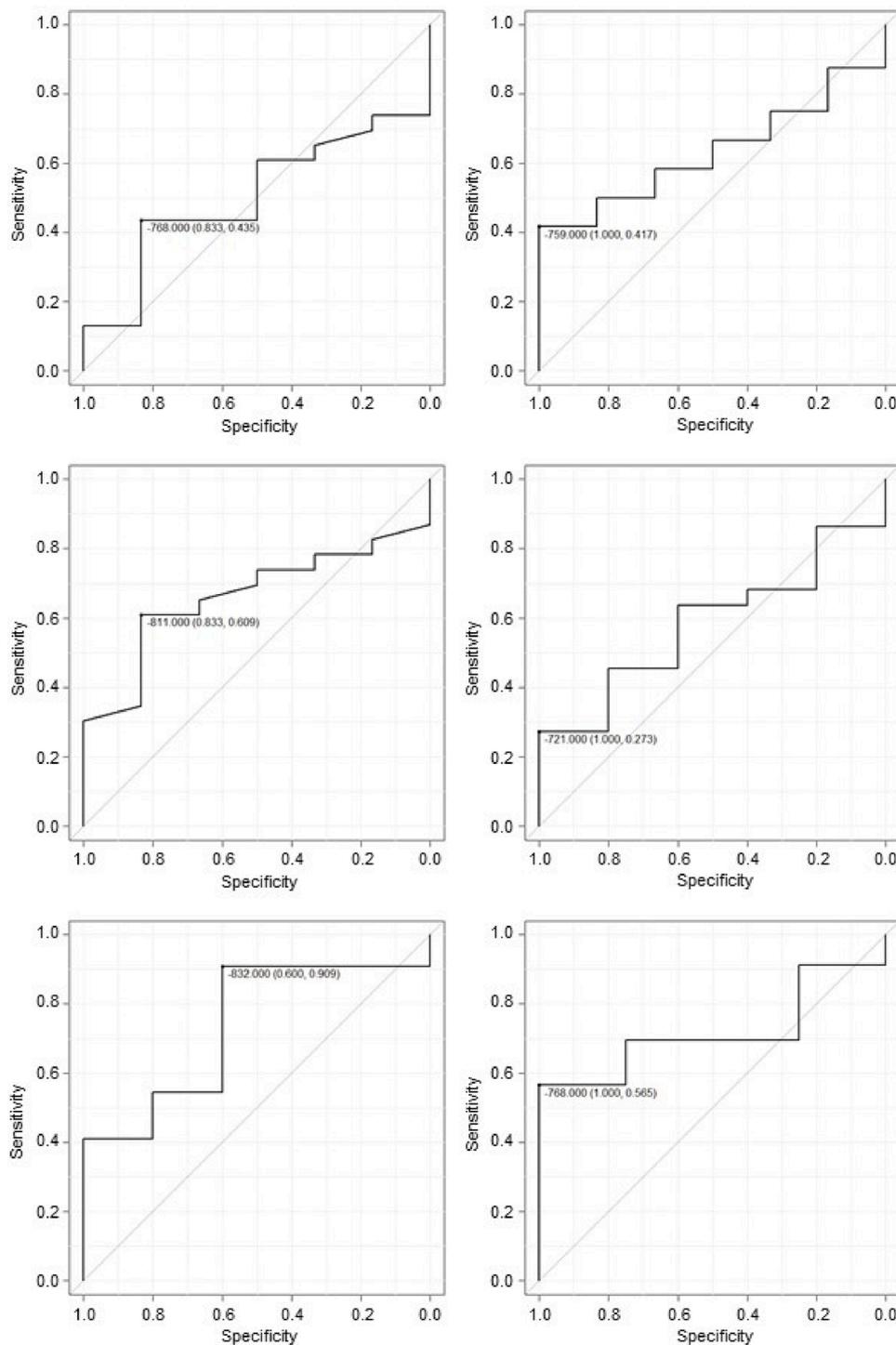


Fig. 6. (continued).

coefficients: RUL 0.626, RML 0.625, RLL 0.548, LUL 0.734, Lingula 0.668, and LLL 0.638). CT HU measurements and 2-view CXR scores in each lobe also showed moderate to strong correlation, but the coefficients were smaller than those of portable chest radiographs (correlation coefficients: RUL 0.506, RML 0.404, RLL 0.556, LUL 0.590, Lingula 0.612, and LLL 0.393).

ROC analysis results of CT HU measurements for diagnosis of pulmonary edema (CXR score 0 versus CXR scores 1–5) are shown in Fig. 6a and b. The largest area under the curve (AUC) for portable CXR was 0.995 in LUL with the cutoff value of -825 HU (sensitivity = 100 % and specificity = 95.1 %). The second highest AUC of 0.978 was observed in

the RUL with the cutoff value of -822 HU (sensitivity = 87.5 % and specificity = 100 %). The AUCs were 0.869, 0.861, 0.882, and 0.890 for RML, RLL, Lingula, and LLL, respectively. For two-view CXR, the highest AUC was observed in RLL as 0.736 (sensitivity = 60 %, specificity = 90.9 %). The AUCs in the RUL, RML, LUL, Lingula and LLL were 0.504, 0.663, 0.632, 0.582, and 0.717, respectively.

#### 4. Discussion

Our study demonstrates a moderately strong correlation between CT HUs and CXR pulmonary edema grade in every lobe by analyzing a

series of near-concurrent chest CTs and CXRs. Additionally, we showed that CT HU measurements demonstrate excellent accuracy in differentiating between no edema (grade 0) and mild to severe edema (grades 1–5) in the upper lobes with AUCs as high as 0.995 in the LUL. Moreover, our work showed that by using a HU cutoff of -825 in the LUL, quantitative CT analysis yielded a higher sensitivity (100 %) and specificity (95 %) to qualitative (visual) CT analysis (sensitivity 84 % and specificity 78 %) for pulmonary edema. To our knowledge, our study is the first to demonstrate the superiority of quantitative CT for this purpose.

Prior work supports our finding of a strong correlation between CT Hounsfield unit measurements with CXR assessment of pulmonary edema. Kato et al. used CXR and pulmonary capillary wedge pressure to divide patients into two groups: edema and no edema and then measured CT HUs in each patient. They found that worsening CT measurements of pulmonary edema correlated linearly with mean pulmonary capillary wedge pressure [9]. Morooka et al. also correlated CT Hounsfield unit measurements not only with pulmonary artery wedge pressure measurements but also with NYHA functional classification of heart failure [8]. They concluded that CT HU measurements were significantly higher in the patients with CHF NYHA classification of II or greater. Moreover, they showed that CT HU measurements increased with severity of edema and PCWP measurements in their canine model.

Our study also demonstrates a correlation between CT HU and worsening pulmonary edema on CXR. While there was no significant difference in AUCs amongst all lobes, the right and left upper lobes demonstrated the highest accuracy. The decreased accuracy in the lower lobes is likely related to atelectasis either due to gravity or adjacent pleural effusions. Previous studies have documented that while there is no cranio-caudal gradient of lung density measurements, the dependent portions of the lungs demonstrated higher attenuation values in normal subjects without pulmonary edema [8,10]. This has been postulated to be attributed to the gravitational effects on the lower lobes causing compression of the lung parenchyma in addition to increase in lung blood volume with subsequent increases in lung density. Thus, the upper lobes may more reliably reflect changes in total lung water given the absence of additional factors which may confound density measurements.

We observed that while both portable and 2-view CXR techniques demonstrated moderate to strong correlation between CT HU and CXR score in each lobe, there was a stronger correlation with the portable CXRs than the 2 view CXR. Additionally, we noted that the CT HU for mild pulmonary edema (CXR score of 1) seen on portable CXRs was greater than the CT HU for mild pulmonary edema seen on 2-view CXR. While the cause of this phenomenon is uncertain, the results suggest that 2-view CXRs are more sensitive for early pulmonary edema than portable CXR. Indeed, the very earliest findings of pulmonary edema on CXR, namely pulmonary vascular redistribution and vascular engorgement, occur before water extends into the alveoli. With purely vascular engorgement, we would not expect the CT lung density to increase significantly. Portable CXR is less able to demonstrate these subtle, early findings, particularly because of supine positioning and smaller lung volumes. Thus, early edema on portable CXR likely corresponds to early alveolar edema which is associated with an increase in CT lung density. These findings also suggest that CT is less sensitive for the earliest findings in pulmonary edema. It may be that quantitative measurement of the branch pulmonary artery size in these patients would be better able to distinguish patients with early pulmonary edema.

We found that qualitative (visually assessed) CT evaluation was less sensitive and specific (sensitivity 84 %) than portable CXR for the presence of pulmonary edema. However, quantitative CT evaluation was as sensitive as portable CXR (sensitivity 100 %). Additionally, quantitative CT demonstrated a very high specificity (95 %), better than qualitative CT (specificity 78 %). To our knowledge, no prior studies have evaluated the sensitivities of these two imaging modalities. The results suggest that CT readers using only visual assessment tend to

underestimate the presence of pulmonary edema, and radiologists may benefit from quantitative methods such as CT HU measurements of the lung attenuation, an easy and simple ROI measurement in LUL taking a few seconds. A cutoff value of -825 HU in the LUL has a sensitivity of 100 % and a specificity of 95 % in diagnosing pulmonary edema. Thus, CT HU measurements may be used to improve assessment of the earliest signs of edema.

The current study has several limitations, the first being that our study did not include correlation with an invasive measurement of cardiogenic pulmonary edema such as pulmonary capillary wedge pressure. However, prior studies have established a strong correlation between CT HU measurements and wedge pressure measurements as well as NYHA functional classification of cardiogenic pulmonary edema [8]. Second, the near concurrent images (CXR and CT) were obtained up to three hours apart. Although unlikely, the possibility for changes in medication or treatment during the time period between studies could not be eliminated. Third, CT measurement may be affected if the patient has underlying lung disease such as subtle emphysema (underestimation) and pulmonary fibrosis (overestimation). Similarly, the presence of effusions and atelectasis could confound the interpretation of edema on CXR, particularly one-view portable CXR. Lastly, lung volumes could not be controlled for and the potential effects of mechanical ventilation on lung density measurements are unclear. Presumably, ventilator settings such as tidal volume and pressure settings could alter lung density measurements independent of the severity of pulmonary edema.

In conclusion, we have shown that quantitative CT analysis strongly correlates with pulmonary edema identified by CXR. Moreover, quantitative CT analysis was more sensitive and specific than qualitative CT analysis for pulmonary edema. In particular, a cutoff of -825 HU in the left upper lobe showed a 100 % sensitivity and 95 % specificity for the presence of pulmonary edema. These findings suggest that radiologists should employ quantitative CT analysis more routinely in assessment of pulmonary edema, as a qualitative analysis will miss a number of cases. Further work is needed to validate these findings in an independent cohort.

#### CRediT authorship contribution statement

**Maria Barile:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Writing - original draft, Writing - review & editing. **Tomoyuki Hida:** Data curation, Formal analysis, Investigation, Writing - original draft, Writing - review & editing. **Mark Hammer:** Data curation, Formal analysis, Investigation, Methodology, Writing - original draft, Writing - review & editing. **Hiroto Hatabu:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing - original draft, Writing - review & editing.

#### Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.ejro.2020.100273>.

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