Impact of Advanced Detector Technology and Iterative Reconstruction on Low Dose Quantitative Assessment of Lung Computed Tomography Density in a Biological Lung Model

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Abstract

Purpose—Quantitative computed tomography (QCT) derived measures of lung density are valued methods for objectively characterizing lung parenchymal and peripheral airways disease and are being used in a growing number of lung disease focused trials. Detector and reconstruction improvements in CT technology have allowed for significant radiation dose-reduction in image acquisition with comparable qualitative image quality. We report the impact of detector type and reconstruction type on QCT lung density measures in relation to decreasing dose indices.

Methods—Two sets of studies were completed in an in-vivo pig model with a SOMATOM Definition Flash CT system: (1) prior to system upgrade with conventional detectors (UFC) and filtered back projection (FBP), and (2) post system upgrade with integrated electronic detectors (STELLAR) and iterative reconstruction (SAFIRE). CT data was acquired across estimated CT volume dose indices (CTDIvol) ranging from 0.75 mGy to 15 mGy at both inspiratory and expiratory breath holds. Semi-automated lung segmentations allowed calculation of histogram median, kurtosis and 15th percentile. Percentage of voxels below −910HU and −950HU (inspiratory), and −856HU (expiratory) were also examined. The changes in these QCT metrics from dose reduction (15 mGy down to 0.75 mGy) were calculated relative to paired reference values (15 mGy). Results were compared based on detector and reconstruction type.

Results—In this study, STELLAR detectors improved concordance with 15 mGy values down to 3 mGy for inspiratory scans and 6 mGy for expiratory scans. The addition of SAFIRE reconstruction in all acquired measurements resulted in minimal deviation from reference values at 0.75 mGy.

Conclusion—The use of STELLAR integrated electronic detectors and SAFIRE iterative reconstruction may allow for comparable lung density measures with CT dose indices down to 0.75 mGy.

Keywords

Quantitative computed tomography; low-dose computed tomography; lung density measures; emphysema; air trapping

Introduction

Quantitative computed tomography (QCT) derived measures of lung structure are becoming valued methods for objectively assessing volumetric distribution of emphysema, air-trapping, inflammation, and/or fibrosis^{1–3}. These measures are derived from analysis of the Hounsfield units (HU), a representation of the attenuation of x-rays through the lungs, within an acquired CT volume. Low attenuation areas, specifically, the percentage of voxels within the lung below a certain threshold (usually –950 HU or –910 HU) on inspiratory breath held QCT scans, provide regional information as a repeatable and objective measure representative of emphysema^{4–8}. Similarly, thresholds (usually –856 HU) on expiratory breath held QCT scans are used to represent regional distribution of air trapping⁹. These measures are being utilized in a growing number of multi-center trials for classification of different subtypes of disease^{10–14}. Lung density has also been measured with the 15th percentile point and was recommended as a measure for longitudinal studies monitoring for a significant shift over time^{15,16}. However, QCT has its challenges due to its sensitivity to a wide range of variables including radiation dose¹⁷.

Advancements in CT technology have been aimed at improving image quality acquired with low dose protocols by reducing image noise. Integrated electronic detectors have been developed to decrease electronic noise and detector crosstalk by combining the analog-to-digital converter with the detector elements onto the same chip¹⁸. Comparisons between integrated electronic detectors versus conventional detectors with distributed electronics were recently reported in phantom studies showing decreased noise levels using integrated electronic detectors across a wide range of doses¹⁹. Studies in human subjects showed similar reductions in noise with reported CT volume dose indices (CTDIvol) of 4, 5, and 10 mGy^{20,21}. Iterative reconstruction is a multi-iteration noise reduction strategy that has been shown to result in comparable qualitative data in images acquired with a greatly reduced dose. Previously, our lab has reported the impact of reconstruction method using a lung specific phantom^{22,23}. Studies combining integrated electronic detectors and iterative reconstruction have also reported significantly decreased image noise^{24,25}.

Several multi-center trials are underway that use QCT to objectively assess lung structure and function incorporating longitudinal data acquisition and analysis; however, to incorporate these new technologies, it is important to understand their effect on QCT lung measures. In this study, we present a systematic exploration of the impact of detector hardware and iterative reconstruction on QCT measurements across several different doses. Data was acquired using in-vivo pig lungs as a biologically-relevant, human surrogate

incorporating the additional challenges of human data acquisition, including, non-uniform x-ray attenuation at the apex of the lung due to surrounding skeletal structures, cardiac motion, and vascular perfusion. This study complements a previously reported study performed with a phantom comparing the effect of iterative reconstruction versus filtered back project on quantitative density measures with the use of integrated circuit detectors²³. In this study we seek to determine, in a biologically relevant model, if incorporating advanced detector and reconstruction technology allows equivalent QCT lung density measures to be achieved at reduced CTDIvols, ranging from 0.75 mGy to 15 mGy. By utilizing an anesthetized pig model, we are able to study a very similar thoracic environment to the human while at the same time being able to control repeatable airway inflation pressures at the time of scanning.

Methods

Animal procedures

Two wild-type, male Yucatan miniature-pigs weighing 37 kg and 44 kg were utilized for this study to simulate the complex, anatomical contributors to x-ray attenuation which affect CT image quality in human chest studies (i.e. thoracic skeletal system, cardiac motion, and pulmonary blood flow). Animals were placed under anesthesia induced with a mixture of telazol (2.2 mg/kg), ketamine (1.1 mg/kg), and xylazine (1.1 mg/kg) and maintained with inhaled isoflurane (0.5-5%). Each pig was intubated with a balloon-cuffed endotracheal tube (7-8 mm) and mechanically ventilated with a volume-controlled ventilator (Model 613, Harvard Apparatus Bioscience Company, Holliston, MA) at 100% oxygen, tidal volume of approximately 10 mL/kg, and respiratory rate of 10-16 breaths per minute. Enforced breath holds were used during imaging with a positive end expiratory pressure (PEEP) of 25 cmH₂O to mimic an inspiratory breath hold and a PEEP of 5 cmH₂O to mimic an expiratory breath hold. Breath hold pressures were enforced with a water column and monitored with in-house LabVIEW software to ensure a constant pressure during scanning. A paralytic (rocuronium bromide: 1.0 mg/kg for induction and 2.0-2.5 mg/kg/hr to maintain) was delivered under a surgical plane of anesthesia to prevent muscle spasm and reduce variation in the low pressure expiratory breath hold as needed. Monitoring was performed with electrocardiogram (ECG: 80 to 100 beats per minute), oxygen saturation pressure (SP-O₂: 99-100%), and end-tidal carbon dioxide pressure (ET-CO₂: 35-45 mmHg). Animals were positioned supine into the CT scanner and imaged with the protocol listed below. All procedures were approved for by the Institutional Animal Care and Use Committee (IACUC).

Computed tomography imaging protocol

This study was performed with a SOMATOM Definition Flash CT scanner (Siemens Healthineers, Erlangen, Germany) in two iterations. Iteration one (pre-upgrade) included second generation solid state detectors with distributed electronics (Ultra-Fast Ceramics: UFC) and software allowing for filtered back projection (FBP) reconstruction (Syngo CT 2011A). Iteration two (post-upgrade) involved a scanner upgrade incorporating 3rd generation detectors with integrated electronics (STELLAR) and a software upgrade allowing for both FBP and Sinogram Affirmed Iterative Reconstruction (SAFIRE) (Syngo

CT 2012B). SAFIRE included a strength parameter ranging from 1 to 5, with 1 resulting in the noisiest image and 5 resulting in the smoothest image.

The positioned animal was adjusted such that the center of the thorax was iso-center in the imaging field of view. A consistent base set of parameters were used including; scan collimation of 128×0.6 mm, 0.75 mm slice thickness with 0.5 mm increment, pitch of 1.0, 0.5 second rotation time, and tube voltage of 120 kVp. Seven different tube current time products (effective mAs) were chosen ranging from 11 to 222 mAs resulting in volumetric CT dose indexes (CTDIvol) increasing incrementally; 0.75, 1.5, 3, 6, 9, 12, and 15 mGy (effective dose range of 0.3 to 7.2 mSv). All CTDIvol measures were acquired directly from the scanner calibrated with a 32 cm body phantom. Target dose datasets were acquired in sets of three, acquired in a single breath hold, as illustrated in Figure 1. Within the set of three, the first scan was acquired as a high dose (HD) reference scan with a CTDIvol of 15 mGy immediately followed by two target dose (TD) scans at a desired CTDIvol. Study points were included utilizing a target dose of 15 mGy in order to allow an estimate of the variability in data at the radiation dose level utilized as the reference standard. Each set of 3 scans was delayed ten seconds to allow for stress relaxation of the lung after the breath hold was enforced^{26,27}. For each target dose, recruitment was performed for 2 minutes (PEEP: ~ 10 cmH₂O) followed by a set of three inspiratory scans (PEEP: 25 cmH₂O). Normal breathing occurred for one minute followed by another set of three expiratory scans (PEEP: 5 cmH₂O). To maintain lung validity, each target dose set with inspiratory and expiratory breath holds was followed by 5 minutes of normal breathing.

The complete image protocol detailed in Figure 1 was repeated three separate times for each animal in different imaging sessions to insert biological variability across datasets. One animal (44 kg) was utilized to acquire data pre-upgrade with the use of UFC detectors and FBP and a second animal (37 kg) was imaged after the CT scanner upgrade with the use of STELLAR detectors and iterative reconstruction (SAFIRE). Pre-upgrade scans were reconstructed with a medium sharp standard FBP kernel (B35f), which has been recommended for QCT lung protocols², resulting in one reconstruction per acquired pre-upgrade scan. Post-upgrade scans were also reconstructed using a B35f FBP kernel. Iterative reconstruction was also performed on the post-upgrade scans for an additional 4 SAFIRE reconstructions, including versions I30 vs Q30 and strengths 3 vs 5. The level of SAFIRE strength refers to the amount of noise reduction where a higher number indicates a greater strength and greater noise reduction.

Data and statistical analysis

All data was visually inspected and the CT scans that contained significant motion artifact were removed from the analysis. Lung segmentation masks were generated using the Pulmonary Analysis Software Suite (PASS)²⁸ for each 15 mGy reference scan. These masks were then applied to the two target dose scans (TD₁, TD₂) acquired within the same breath hold. Lung density histogram statistics were extracted from each scan using the corresponding mask. For inspiratory scans the histogram metrics were: median, kurtosis, the Hounsfield Unit (HU) value at the 15th percentile point, and the frequency of voxels below -910 HU and -950 HU as percentages of the total lung voxels (RA-910, RA-950). For

expiratory scans: median, kurtosis, the HU value at the 15th percentile point, and the frequency of voxels below -856 HU (RA-856) were analyzed.

Analysis was performed focusing on the difference between the metric of interest derived from the 15 mGy reference scan relative to each target dose (TD₁, TD₂) scan from a single breath hold to eliminate cofounders, such as changes in the lung over the course of the study. As the data acquisition process, illustrated in Figure 1, was repeated 3 times (session A, B and C), this resulted in a total of six difference measures per CTDIvol target i.e. TD^A₁-HD^A, TD^A₂-HD^A, TD^B₁-HD^B, TD^B₂-HD^B, TD^C₁-HD^C, and TD^C₂-HD^C. Optimal response was defined as near zero differences between the TD scan and the 15 mGy reference scan. Note, note that 15 mGy was used for the reference HD and as one of the TD levels so as to observe within breath-hold variability at the reference level. Comparisons were made to assess the effect of detector type (Ultra-Fast Ceramics vs. STELLAR) and reconstruction type (FBP with and without STELLAR detectors, SAFIRE- I30, Q30 – and strength – 3, 5 – with STELLAR detectors) on QCT density measures across all acquired CTDIvols.

Results

Across three separate acquisition studies (to account for positioning variability), a total of 21 inspiratory scan sets and 21 expiratory scan sets were acquired for each animal (21 HD, 21 TD₁ and 21 TD₂) resulting in 126 scans per animal. Of these, four scans (2 pre-upgrade and 2 post-upgrade) were removed from analysis due to motion artifact causing poor alignment between the 15 mGy reference scan derived mask and the TD scans. Table 1 summarizes the average and standard deviation of the raw QCT metric values over all the 15 mGy reference scans for a given detector and reconstruction type.

Figure 2 depicts the change in image quality in an axial cross section through the thorax in the scan acquired with the lowest CTDIvol (0.75 mGy) demonstrating qualitative differences across detector and reconstruction type. Figure 3 displays the corresponding data for the highest CTDIvol (15 mGy). Data acquired pre-upgrade, reconstructed with FBP (UFC – FBP B35f), was compared with data acquired post-upgrade, reconstructed with FBP (STELLAR – FBP B35f), to parse out differences due to detector alone. Data acquired post-upgrade was used to compare differences between FBP and iterative reconstruction, including versions I30 vs Q30 and strengths 3 vs 5. Results are presented as average raw differences between the TD scan and the 15 mGy reference scan. In addition, a generalized additive model fit by penalized least squares was developed (supplemental results) which allows extrapolation of the results across a continuous range of CTDIvols from 0.75 to 15 mGy.

Inspiratory datasets

No clear patterns of change were observed for median lung density across all CTDIvols and all datasets. TD median values compared to HD median values ranged from deviations of -4 HU to +4 HU with a majority of scans showing minor shifts of 1 or 2 HU on average as demonstrated in Table 2. As a measure of histogram shape, a smaller kurtosis indicating a wider, flatter distribution was observed with the use of UFC detectors compared to STELLAR detectors across all CTDIvols. This trend was observed in the analyzed QCT

metrics (Table 3: UFC FBP B35f vs STELLAR FBP B35f) and was seen among the raw reference scan data displayed in Table 1. Overall, kurtosis showed increasing values on average as CTDIvol increased indicating a taller, skinnier distribution at high CTDIvols compared to low CTDIvols.

QCT metrics commonly used to evaluate emphysema using inspiratory quantitative CT include: RA-910, RA-950 and 15th percentile. Figures 4–6 indicate the difference between the target dose QCT metrics and the QCT metrics of the reference scans (average and standard deviation of values are reported in supplemental tables 1–3). For RA-910, isolating the effect of detector, STELLAR detectors showed a reduction in differences of approximately one-third at 0.75 mGy (average and standard deviation from UFC: $5.4 \pm 0.6\%$ to STELLAR: $3.7 \pm 1.2\%$). STELLAR and UFC detectors showed differences from the reference scan of less than 1% for CTDIvols of 15 mGy down to 6 mGy. Comparing across reconstruction type, iterative reconstruction showed reduction in differences at low CTDIvols with both the I30 and Q30 version at both strengths. Figure 4 shows optimal response across all CTDIvols using SAFIRE with the Q30 version and a strength of 5 for which the QCT metric differences in RA-910 between the 15mGy reference and all target doses was less than $\pm 1\%$. For RA-950, minimal differences were seen between the reference scan and each target scan with a majority of values less than 1% across all acquired scans; however, raw QCT metrics also showed a small percentage of overall voxels with HU units less than -950 HU throughout the lungs (Table 1).

For the 15th percentile point, the largest differences from the reference scan were observed using UFC detectors and FBP with an average difference of -16.3 ± 2.6 HU at 0.75 mGy. Figure 6 shows minor improvement at low CTDIvols due to detector alone with the smallest differences seen at CTDIvols greater than 3 mGy. The additional use of iterative reconstruction with both versions and a strength of 3 showed smaller differences from the reference scan at 0.75, 1.5, and 3 mGy when compared to differences seen with FBP. Minimal differences from the reference scan (< 2 HU) were observed down to 3 mGy with a SAFIRE strength of 3 and down to 1.5 mGy with a SAFIRE strength of 5, using the iterative reconstruction versions I30 and Q30.

For both RA-910 (Figure 4) and 15th percentile point (Figure 6) comparing across inspiratory scans, the best response was observed with the use of STELLAR detectors and SAFIRE reconstruction version Q30 strength 5, which allowed CTDIvol to decrease down to 0.75 mGy. With conventional FBP, STELLAR detectors demonstrated improvement over UFC detectors at low CTDIvol for all acquired QCT metrics; however, sizable differences still remained at CTDIvols less than 3 mGy.

Expiratory datasets

Larger deviations from the reference scan values were observed for median lung density in the expiratory datasets, compared to differences seen among inspiratory datasets, with values ranging from -23 HU to $+22$ HU (Table 4). The largest differences were observed for datasets acquired with 6 mGy (9.0 ± 8.66 HU) followed by datasets acquired with 0.75 mGy (8.36 ± 7.31 HU). In addition, small kurtosis values (< 2) were observed for all expiratory datasets indicating wide, flat histograms across all datasets.

QCT metrics commonly used to evaluate air-trapping using expiratory quantitative CT include: RA-856 and 15th percentile. Figures 7–8 indicate the differences between the target dose QCT metrics and the QCT metrics of the reference data (average and standard deviation of values are reported in supplemental tables 4 and 5). The average differences between the TD and reference scans for RA-856 was largest with the UFC detectors and FBP ($1.7 \pm 0.5\%$) at a CT DIvol of 0.75 mGy and only slightly reduced ($1.4 \pm 0.3\%$) with STELLAR detectors. STELLAR detectors paired with iterative reconstruction at a strength of 5 resulted in differences less than $\pm 1\%$ across all CT DIvols for both the I30 and Q30 versions.

The 15th percentile point showed wide variability overall, specifically among datasets acquired with STELLAR detectors, limiting the identification of clear trends across CT DIvol, detector, and reconstruction type (Figure 8). With the use of iterative reconstruction, the majority of average differences between TD and reference scans were centered on zero; however, an overall range between ± 10 HU across both the I30 and Q30 versions and the 3 and 5 strengths was observed.

Overall, expiratory datasets showed variability in QCT metrics comparing TD scans with reference scans across all CT DIvols. Minor improvements at low CT DIvols were seen due to detector alone. At low CT DIvols, the best response was observed with the use of SAFIRE I30, strength 5 showing comparable QCT metrics down to 0.75 mGy.

Discussion

The use of SAFIRE iterative reconstruction and STELLAR integrated electronic detectors allowed for minimal differences in CT derived lung density metrics in a biological model when comparing a high CT DIvol of 15 mGy to a low CT DIvol of 0.75 mGy. For CT derived emphysema and air-trapping measurements, SAFIRE (version I30) iterative reconstruction with a strength of 5 demonstrated minimal differences in these quantitative CT metrics throughout a wide range of CT DIvol's compared to a 15 mGy reference scan reconstructed with FBP. Based on detector alone, the STELLAR detectors demonstrated reduced differences at low CT DIvols; however, large differences still remained at CT DIvols equal or less than 3 mGy for inspiratory scans and 6 mGy for expiratory scans.

The understanding of variations in QCT lung density metrics across different imaging protocols and different detector and image reconstruction technologies is increasingly important as CT technology advances. This is particularly relevant for longitudinal trials that track changes over time, which may be impacted through the incorporation of new CT technology during a long data collection time period^{10–14}. In this study, we focused our measurements on density measures frequently used in multi-center trials of lung disease. Previously, we have reported the effect of reconstruction (FBP vs. SAFIRE I30 strength 5) on median density measures within a phantom across materials of known density. No significant effect between FBP and SAFIRE was observed for phantom material densities ranging from 120 and –856 HU across all CT DIvols with significant effects reported for densities between –937 and –1000 HU^{22,23}. In comparison, we have incorporated biological variability and reported differences between FBP and SAFIRE for RA-856, RA-910 and

RA-950 for CTDIvols less than 3 mGy. However, we did not see similar trends in changes in median lung density.

This study utilized normal pigs and hence the magnitude of emphysema and air-trapping were low, yet they are included here to demonstrate patterns of change relative to radiation dose level and scanner technology that would be relevant to normal control subjects. It is a limitation of our study that the stability of quantitative emphysema and air-trapping were not confirmed in subjects demonstrating disease levels typically observed in human subjects with chronic obstructive pulmonary disease. As previous work has demonstrated that error can vary systematically with the magnitude of CT detected low attenuation areas, it will be important to validate these results in diseased subjects²⁹. In addition, in this study we explored global lung measures, but in the context of characterization of emphysema or air-trapping in diseased patients, the impact of heterogeneity measurements for emphysema/air-trapping throughout the lung would also be an important consideration.

Several previous studies have demonstrated the difference in image quality between conventional detectors and integrated electronic detectors and between image reconstruction methods. A majority of these studies have demonstrated reductions in noise with the use of integrated electronic detectors over conventional detectors and iterative reconstruction over FBP^{20,21,24,25}. While CT image noise levels were not quantified in this study, reduced noise levels were visually observed at low CTDIvols (0.75 mGy), see Figure 2, similar to previously reported studies.

The CTDIvols reported in this study were measured using a 32cm body phantom and used test subjects of similar size and shape. Hence this study reflects comparison of technology, reconstruction type, and CTDIvol, without incorporating subject size variation as a variable factor. Current, tightly controlled, multi-center trial protocols compensate for increased image noise associated with increased body habitus by setting CTDIvol levels based on three ranges of body mass index^{2,30}. Alternatively, automatic exposure control systems are now available clinically as a dose optimization method which incorporates body size and composition. Exposure optimization is achieved via tube current modulation (TCM) for a more consistent noise characteristic throughout a scan based on body composition. However, further investigation is required to understand the impact of different TCM methods on quantitative CT lung metrics.

Phantoms have been created to provide systematic information across CT protocols and scanners^{22,23}; however, challenges exist in accurately replicating biological variability due to cardiac motion, lung volume, and vascular perfusion. Pigs have previously been used as surrogates for the testing and development of imaging protocols due to their similarities to humans³¹. We chose two animals for this study to acquire data prior to and following the installation of the upgraded detectors and advanced software. Data was acquired across several days to incorporate realistic variability within the context of a biological subject undergoing separate imaging studies serving as a clinically relevant translational step between phantom studies and human patients. In this way, extrapolation of our results has a translatable application to data acquired in multi-center trials. As imaging protocols change to incorporate new technologies to minimize dose, our results demonstrate the effect these

new technologies might have on quantitative metrics when acquired in a normal human subject/patient. In an ideal system, it would be expected that when the TD was 15mGy (the same as the CTDIvol of the reference scan), acquired in the same breath hold, that the difference would be zero. Yet, this experimental approach incorporates biological variability factors that can contribute to with-in breath-hold variability including; (a) variation in the stage of the cardiac cycle (end-systole versus diastole) between the reference scan acquisition time and one or both TD acquisition times, (b) variation in heart rate due to breath-hold progression resulting in increased cardiac motion captured during TD acquisition times, or (c) stress relaxation. Our results reflect values very close to zero for the 15mGy TD scans, with the exception of the 15th percentile in the expiratory lung volume data which varied between $\pm 4\text{HU}$. As demonstrated in supplemental table 5 of the 15th percentile difference measures, there is a trend towards a positive difference between the TD and HD data which would be consistent with increased density as a result of cardiac variability. In future work, this may be mitigated by alternating the order of with-in breath-hold scans (e.g. do not always have the HD reference scan acquired before the two TD scans, as was done in this study).

In conclusion, we presented a systematic investigation to determine the effect STELLAR detectors with integrated electronics and various levels of SAFIRE iterative reconstruction have on quantitative CT (QCT) lung density measures compared to UFC detectors with distributed electronics and FBP. Our study findings indicate that it may be possible for longitudinal studies using the SOMATOM Definition Flash CT scanner and QCT measures of lung density to achieve comparable quality QCT image data at radiation dose levels down to 0.75 mGy by incorporating SAFIRE iterative reconstruction and STELLAR detectors. These results warrant further investigation of QCT stability at this reduced dose in diseased human subjects.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1.

For each target dose, two sets of scans were acquired within two breath holds (inspiratory and expiratory). For each breath hold, a high dose (HD) reference scan was acquired with a CTDIvol of 15 mGy followed by two target dose (TD₁, TD₂) scans. Seven target dose levels were collected; 0.75, 1.5, 3, 6, 9, 12, and 15 mGy. Normal breathing occurred between inspiratory and expiratory breath holds and after each target dose. This complete protocol was repeated three separate times.

Figure 2.

Qualitative comparison of image quality across inspiratory CT datasets (axial cross-section with isolated airway inset) from the lowest targeted CTDIvol (0.75 mGy). The top panel compares data with ultra-fast ceramic (UFC) detectors (left) with the STELLAR detectors (right) reconstructed with FBP and a B35f kernel showing mild improvement in image noise as depicted by the speckled appearance of the gray levels. The middle panel displays the datasets that used SAFIRE (strength 3) reconstruction (with STELLAR detectors) showing moderate noise improvement over FBP with STELLAR detectors across both versions (I30 –

left, Q30 – right). The bottom panel also displays datasets using SAFIRE (strength 5) reconstruction (with STELLAR detectors) showing optimal qualitative noise reduction across both versions (I30 – left, Q30 – right).

Figure 3.

Qualitative comparison of image quality across inspiratory CT datasets (axial cross-section with isolated airway inset) from the highest targeted CTDIvol (15 mGy). The top panel compares data with ultra-fast ceramic (UFC) detectors (left) with the STELLAR detectors (right) reconstructed with FBP and a B35f kernel. The middle panel displays the datasets that used SAFIRE strength 3 (I30 – left, Q30 – right). The bottom panel also displays datasets using SAFIRE strength 5 (I30 – left, Q30 – right).

Figure 4.

Difference measures (TD minus reference dose) of the frequency below -910 HU (RA-910) for inspiratory datasets by detector type (Ultra-Fast Ceramics: UFC versus STELLAR) and reconstructed with either filtered back projection (FBP) (upper), iterative reconstruction (SAFIRE) strength of 3 (middle) and 5 (lower).

Figure 5.

Difference measures (TD minus reference dose) of the frequency below -950 HU (RA-950) for inspiratory datasets by detector type (Ultra-Fast Ceramics: UFC versus STELLAR) and reconstructed with either filtered back projection (FBP) (upper), iterative reconstruction (SAFIRE) strength of 3 (middle) and 5 (lower).

Figure 6.

Difference measures (TD minus reference dose) of the 15th percentile point for inspiratory datasets by detector type (Ultra-Fast Ceramics: UFC versus STELLAR) and reconstructed with either filtered back projection (FBP) (upper), iterative reconstruction (SAFIRE) strength of 3 (middle) and 5 (lower).

Figure 7.

Difference measures (TD minus reference) of the frequency below -856 HU (RA-856) for expiratory datasets by detector type (Ultra-Fast Ceramics: UFC versus STELLAR) and reconstructed with either filtered back projection (FBP) (upper), iterative reconstruction (SAFIRE) strength of 3 (middle) and 5 (lower).

Figure 8.

Difference measures (TD minus reference) of the 15th percentile point for expiratory datasets by detector type (Ultra-Fast Ceramics: UFC versus STELLAR) and reconstructed with either filtered back projection (FBP) (upper), iterative reconstruction (SAFIRE) strength of 3 (middle) and 5 (lower).

Table 1

Average and standard deviation values across the 15 mGy reference scans for the key clinical metrics evaluated: median, the kurtosis of the histogram, the Hounsfield Unit (HU) value at the 15th percentile point (15th Percentile), and the frequency of voxels below -950 HU (RA-950), -910 HU (RA-910) and -856 HU (RA-856). Note two different animals were used; one for the data acquisition with the ultra-fast ceramic (UFC) detectors and the second animal for data acquisition with the STELLAR detectors.

QCT Metric	INSPIRATORY SCANS					EXPIRATORY SCANS			
	Median [HU]	Kurtosis	RA-950 [%]	RA-910 [%]	15th Percentile [HU]	Median [HU]	Kurtosis	RA-856 [%]	15th Percentile [HU]
UFC - FBP B35f	-815 (17.1)	9.95 (2.16)	0.49 (0.06)	1.15 (0.26)	-865 (12.8)	-629 (30.7)	1.68 (0.91)	1.39 (0.5)	-759 (18.5)
STELLAR - FBP B35f	-825 (11)	12.5 (1.96)	0.46 (0.03)	1.12 (0.29)	-869 (8.7)	-630 (12.2)	0.99 (0.3)	1.94 (0.56)	-774 (8.9)
STELLAR - SAFIRE (3) I30f	-837 (9.6)	13.92 (2.12)	0.66 (0.03)	2.42 (0.6)	-879 (7.2)	-642 (12.3)	1.24 (0.33)	3.68 (0.83)	-786 (9.1)
STELLAR - SAFIRE (3) Q30f	-828 (10.9)	13.24 (2.11)	0.57 (0.03)	1.06 (0.2)	-870 (8.4)	-634 (12.1)	1.07 (0.32)	2.05 (0.61)	-776 (8.9)
STELLAR - SAFIRE (5) I30f	-837 (10.8)	14.11 (2.3)	0.66 (0.02)	2.14 (0.53)	-877 (8.2)	-643 (12.4)	1.29 (0.34)	3.63 (0.83)	-787 (9.2)
STELLAR - SAFIRE (5) Q30f	-829 (10.8)	13.64 (2.19)	0.59 (0.03)	0.94 (0.13)	-869 (8.5)	-636 (12.3)	1.12 (0.33)	1.96 (0.59)	-776 (9.1)

Median lung density difference measures showing differences between the 15 mGy reference scan and each target dose (TD₁, TD₂) scan for all inspiratory scans (TD minus reference scan). Reported values are the average (standard deviation) differences across the three separate acquisition studies and are in Hounsfield units [HU].

Table 2

CTDIvol [mGy]	INSPIRATORY MEDIAN [HU]						
	0.75	1.50	3.00	6.00	9.00	12.00	15.00
UFC - FBP B35f	0.50 (2.65)	0.17 (1.35)	-1.67 (0.82)	0.67 (1.51)	-1.33 (1.03)	-0.17 (1.33)	0.67 (1.75)
STELLAR - FBP B35f	0.33 (1.37)	-1.00 (0.89)	-1.33 (1.63)	-1.33 (1.63)	-1.33 (0.82)	-1.50 (1.378)	-1.67 (1.21)
STELLAR - SAFIRE (3) I30f	0.75 (2.06)	-0.83 (1.60)	-1.00 (1.27)	-0.67 (1.86)	-1.33 (1.21)	-1.50 (1.38)	-1.33 (0.82)
STELLAR - SAFIRE (3) Q30f	1.00 (1.41)	-0.67 (1.37)	-1.00 (1.27)	-1.00 (1.55)	-1.17 (0.98)	-1.33 (1.37)	-1.67 (1.21)
STELLAR - SAFIRE (5) I30f	0.50 (1.64)	-0.50 (1.64)	-1.17 (1.47)	-1.00 (1.55)	-1.17 (0.98)	-1.50 (1.38)	-1.33 (0.82)
STELLAR - SAFIRE (5) Q30f	0.67 (1.75)	-0.57 (1.38)	-0.83 (1.17)	-0.67 (1.86)	-1.33 (1.21)	-1.17 (1.17)	-1.33 (1.21)

Histogram kurtosis difference measures (TD minus reference scan) comparing the histogram kurtosis of the 15 mGy reference scan with the histogram kurtosis of each target dose (TD₁, TD₂) scan. Reported values are the average (standard deviation) differences across the three separate acquisition studies.

Table 3

INSPIRATORY KURTOSIS									
CTDIvol [mGy]	0.75	1.50	3.00	6.00	9.00	12.00	15.00		
UFC - FBP B35f	-0.73 (0.53)	-0.37 (0.34)	-0.17 (0.06)	-0.02 (0.24)	0.06 (0.14)	0.02 (0.16)	0.06 (0.18)		
STELLAR - FBP B35f	-0.50 (0.64)	-0.43 (0.30)	-0.10 (0.08)	0.14 (0.10)	0.25 (0.14)	0.22 (0.12)	0.30 (0.14)		
STELLAR - SAFIRE (3) I30f	0.25 (0.65)	0.09 (0.27)	0.22 (0.09)	0.27 (0.10)	0.31 (0.13)	0.24 (0.11)	0.29 (0.14)		
STELLAR - SAFIRE (3) Q30f	-0.01 (0.53)	-0.03 (0.27)	0.16 (0.09)	0.25 (0.10)	0.31 (0.14)	0.24 (0.12)	0.29 (0.15)		
STELLAR - SAFIRE (5) I30f	0.51 (0.46)	0.36 (0.27)	0.39 (0.12)	0.35 (0.10)	0.35 (0.14)	0.26 (0.11)	0.29 (0.15)		
STELLAR - SAFIRE (5) Q30f	0.42 (0.50)	0.31 (0.27)	0.37 (0.12)	0.34 (0.10)	0.36 (0.14)	0.25 (0.12)	0.29 (0.15)		

Table 4

Median lung density difference measures (TD minus reference scan) comparing the 15 mGy reference scan with each target dose (TD₁, TD₂) scan for all expiratory scans. Reported values are the average (standard deviation) differences across the three separate acquisition studies and are in Hounsfield units [HU].

CTDIvol [mGy]	EXPIRATORY MEDIAN [HU]						
	0.75	1.50	3.00	6.00	9.00	12.00	15.00
UFC - FBP B35f	7.50 (3.83)	3.33 (4.63)	1.67 (5.47)	6.83 (4.36)	2.17 (5.78)	4.33 (4.27)	5.50 (2.12)
STELLAR - FBP B35f	8.67 (8.64)	0.67 (12.44)	3.83 (6.59)	9.75 (11.15)	3.00 (5.66)	4.17 (3.87)	1.83 (4.79)
STELLAR - SAFIRE (3) I30f	8.00 (8.37)	0.67 (12.44)	3.33 (5.96)	9.50 (10.79)	3.33 (5.35)	4.50 (4.14)	1.50 (4.46)
STELLAR - SAFIRE (3) Q30f	9.00 (8.39)	1.33 (12.16)	4.00 (6.23)	9.75 (10.60)	3.33 (5.13)	4.67 (4.27)	1.50 (4.51)
STELLAR - SAFIRE (5) I30f	8.17 (8.42)	0.80 (13.18)	3.67 (6.31)	9.50 (10.79)	3.17 (5.12)	4.17 (4.12)	1.83 (4.75)
STELLAR - SAFIRE (5) Q30f	8.83 (8.42)	1.00 (12.18)	3.33 (5.96)	9.75 (10.60)	3.17 (5.12)	4.50 (4.14)	1.50 (4.76)