Denoising in Digital Radiographic Images Using a Deep Convolutional Neural Network

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Outline

- Background
- Purpose
- Materials and methods
- Results
- Conclusion

Background

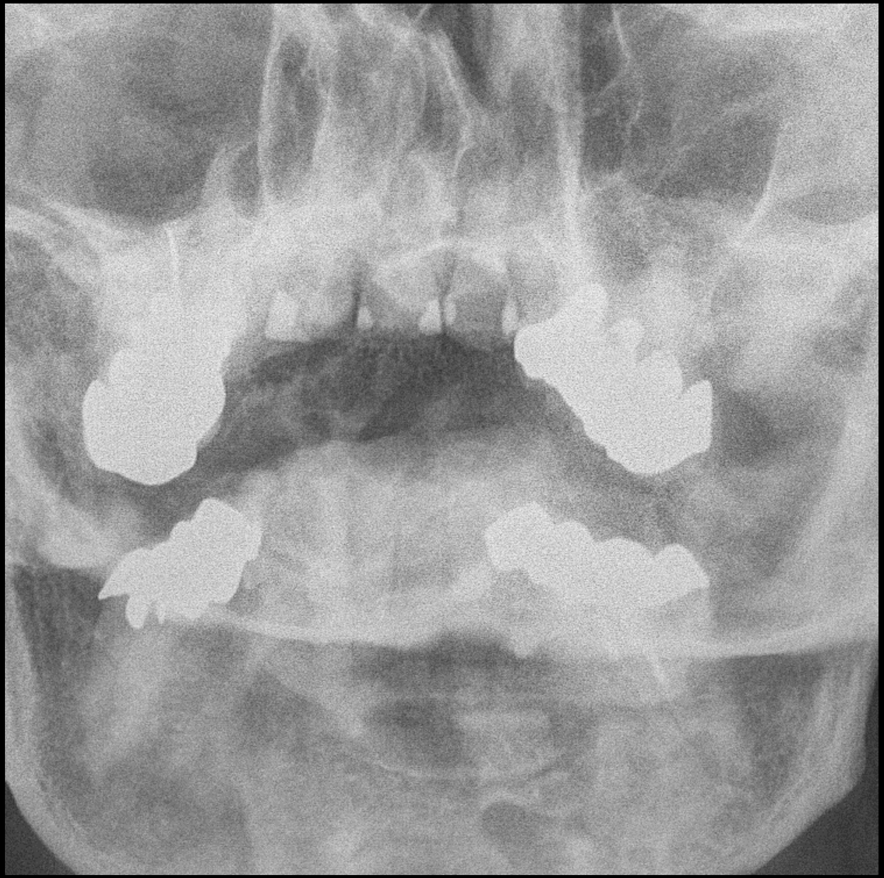
- Best practice medical X-ray imaging employs the principle of ALARA “as low as reasonably achievable” for dose selection
- This leads to inherently noisy images with dose just high enough to confidently achieve a diagnosis*
- Medical image processing often includes noise suppression with traditional methods leading to some loss in fine image detail
- Noise reduction with deep convolutional neural networks (CNN) has been shown to preserve more image detail**
- This can lead to improved image quality, improved contrast-to-noise, easier to read radiographs and the potential for additional dose reduction

* https://www.carestream.com/blog/2020/04/21/understanding-and-managing-noise-sources-in-x-ray-imaging/
** Hu Chen, Yi Zhang, "Low-Dose CT with a Residual Encoder-Decoder Convolutional Neural Network (RED-CNN)", 2017, https://arxiv.org/ftp/arxiv/papers/1702/1702.00288.pdf

Purpose

To characterize image quality improvements and dose reduction of denoising based on a deep convolutional neural network (CNN) in radiographic imaging

Current image processing



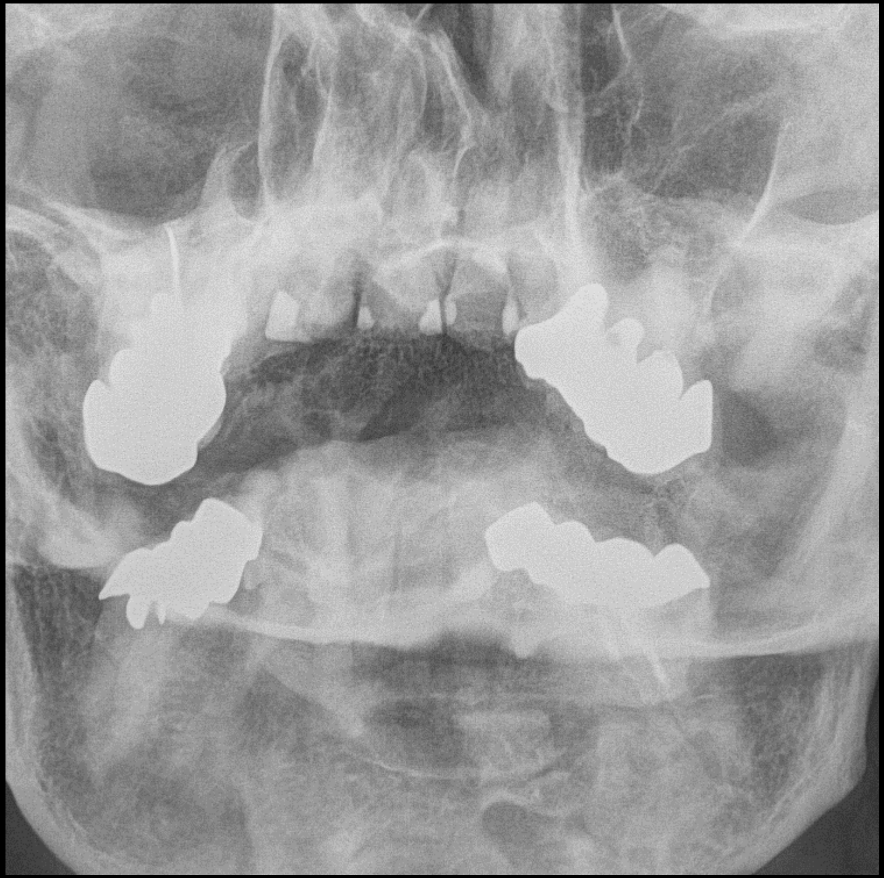
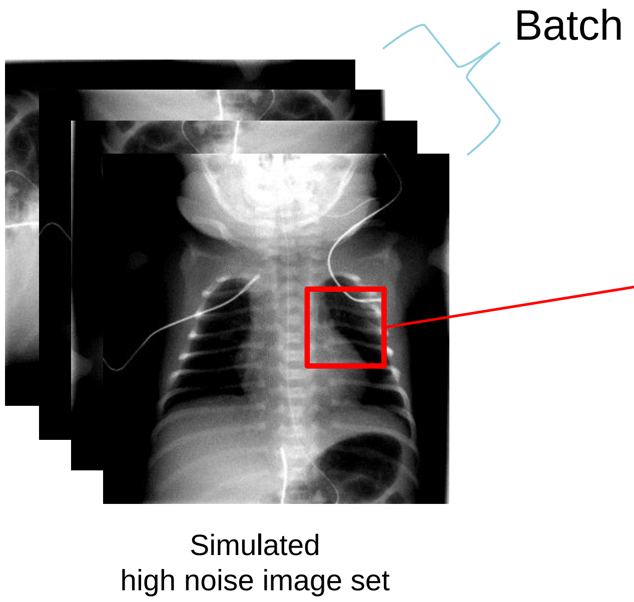
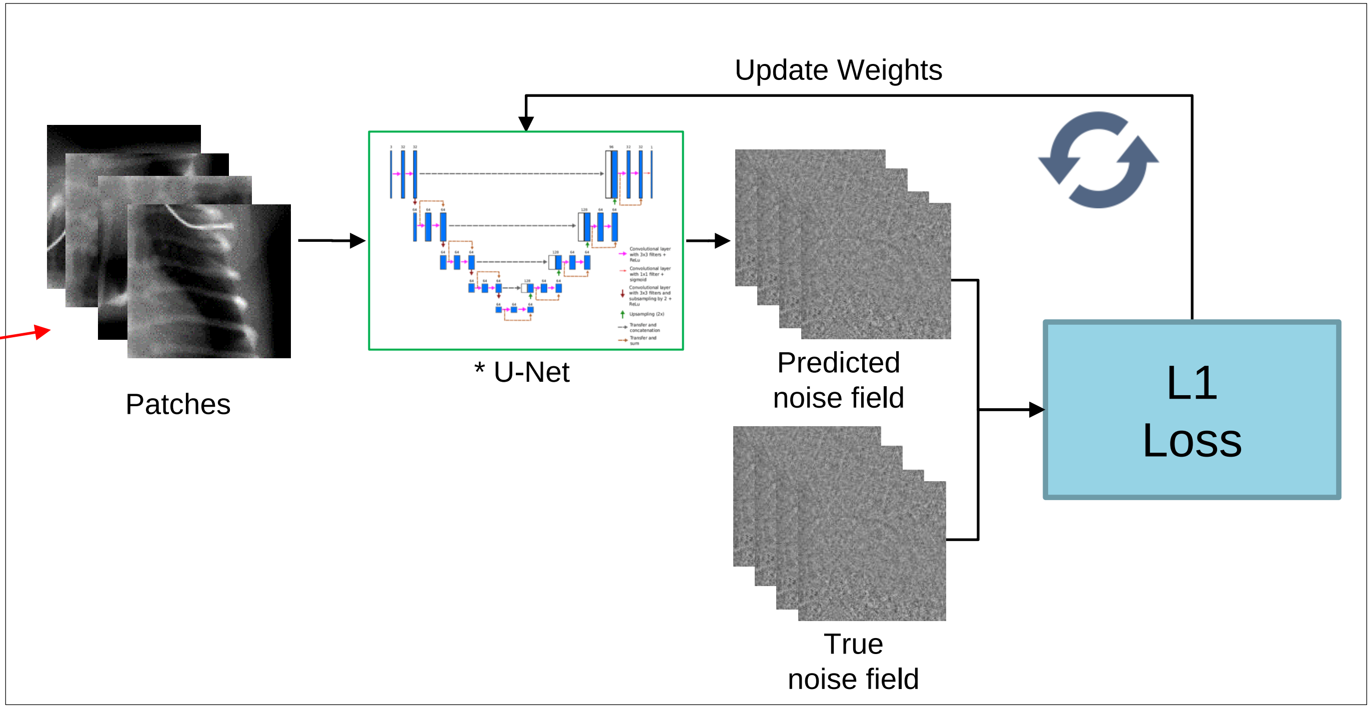


Image processing with denoising by CNN

MATERIALS AND METHODS

Model Description for Deep CNN

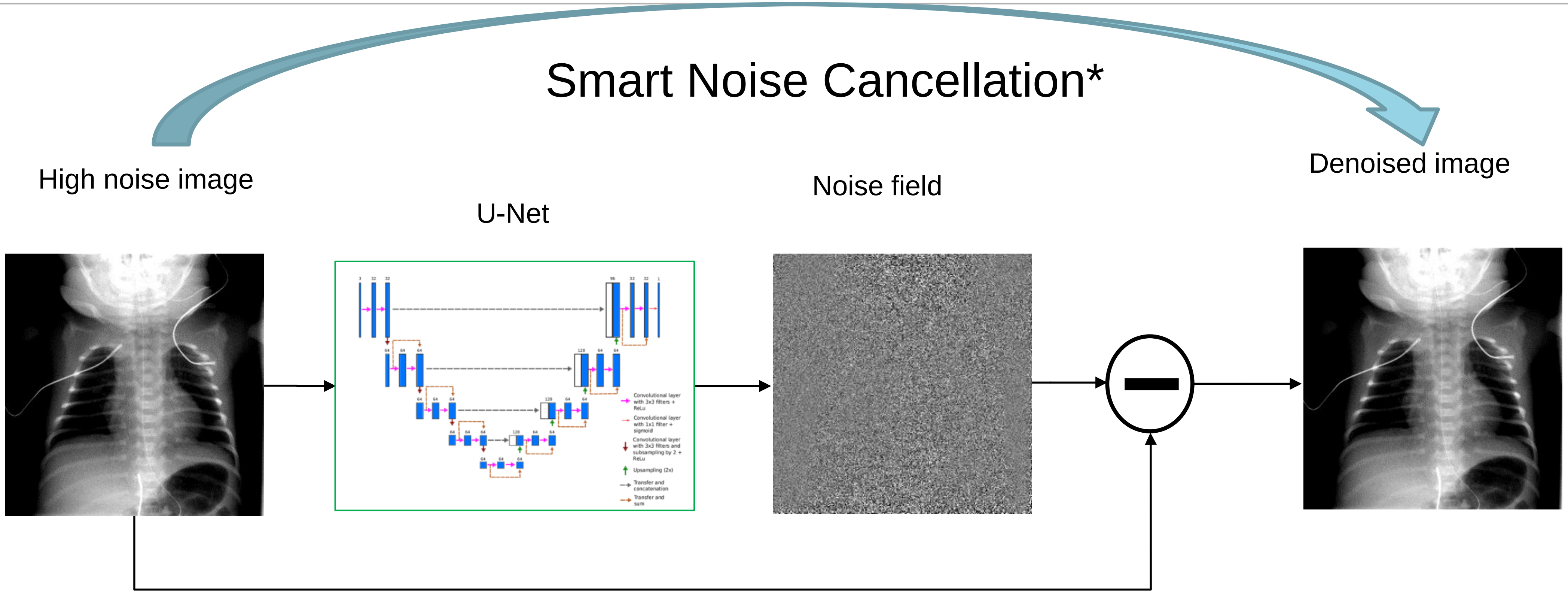




- Training set: 250+ image / noise field pairs per detector type
- Batch size: 32 images
- 480 randomly sampled 128×128 patches per image
- Trained for 200 epochs for a total of > 24 million evaluated unique patches
- Models were developed <u>independently</u> for Carestream DRX family of detectors, based on choice of scintillator, pixel pitch and electronic noise (referred to as detector type)

* Ronneberger, et al., "U-Net: Convolutional Networks for Biomedical Image Segmentation", 2015

Prediction



* Creating the denoised image from the noisy image using the U-Net is referred to as Smart Noise Cancellation throughout the presentation

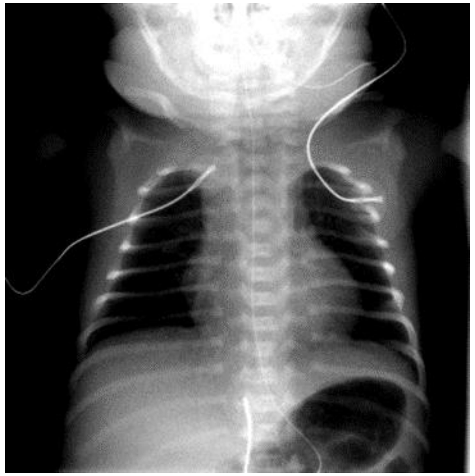
Terminology

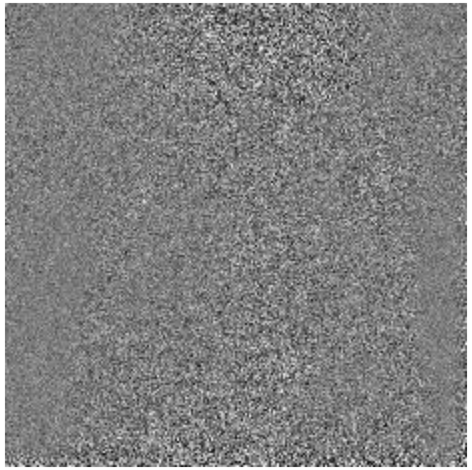
- Smart Noise Cancellation: Denoising module based on deep convolutional neural network
- Eclipse: The engine behind Carestream’s Radiography Software. Eclipse uses AI technology and proprietary algorithms to significantly increase the value of the entire imaging chain from capture to diagnosis. Eclipse powers features for imaging intelligence, workflow efficiency and healthcare analytics
- Eclipse + Smart Noise Cancellation: The Eclipse engine powers our new feature called Smart Noise Cancellation

Training Data

- 250+ anonymized raw clinical images typical for general radiography and pediatrics
- Training pairs were generated using noise simulations*

Input images	**Aim images**	**Aim noise field**
Image simulations with the appropriate amount of added noise corresponding to lower dose	Original images scaled by the dose reduction factor without added noise	Difference between input and aim images





* US Patent 7480,365 B1, K. Topfer, J. Ellinwood, “Dose Reduced Digital Medical Image Simulations”

Testing Data

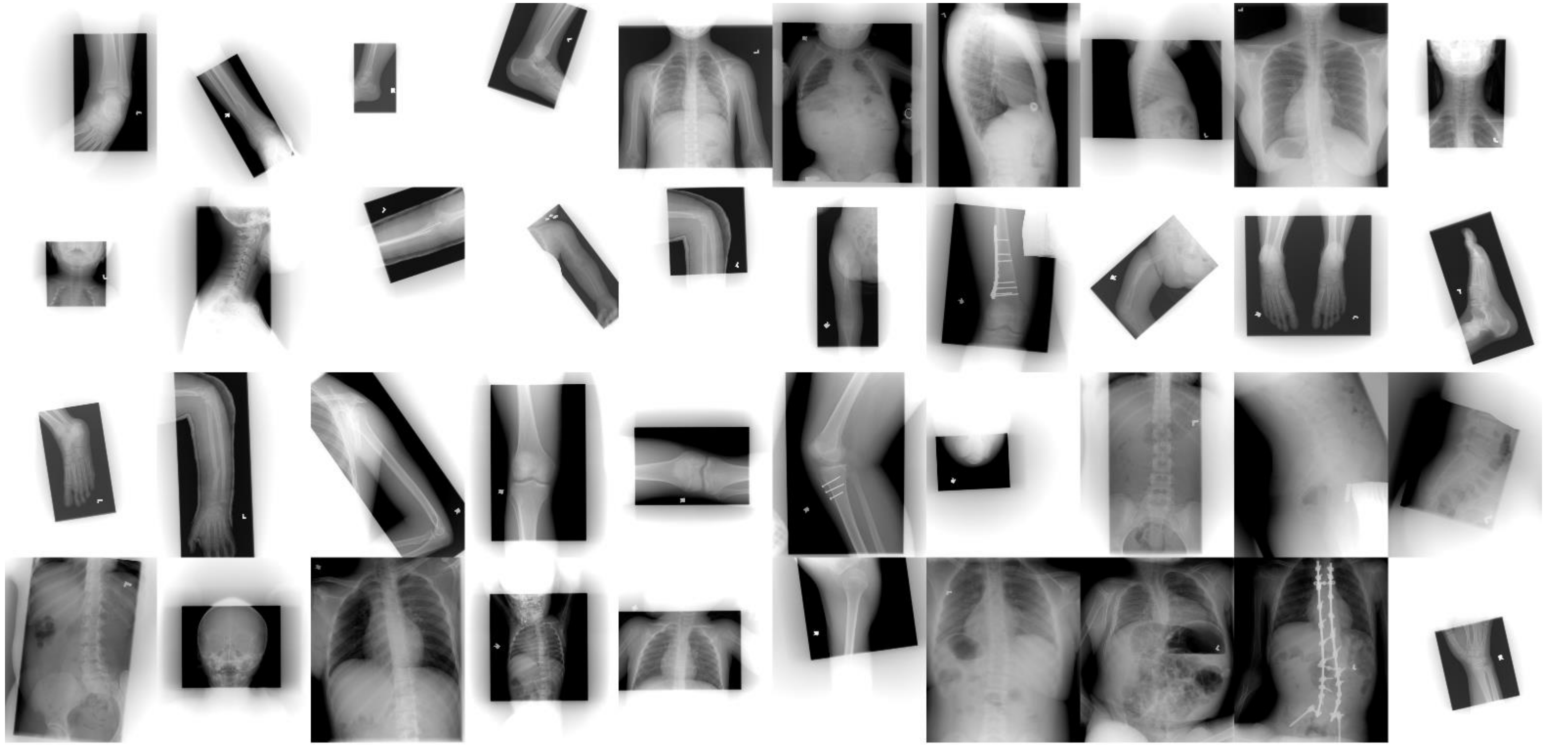
- Over 400 test images per detector type
  - Anonymized raw clinical images typical for general radiography and pediatrics independent of training set
  - Test phantom set for quantitative evaluation
  - Simulated disease features on clinical backgrounds

  - Test images and associated quantitative analyses can help to define the potential dose reduction

Testing Data – Clinical Images

- Smart Noise Cancellation was assessed visually in clinical images
- Visual evaluation of the predicted noise field for lack of residual edges and structure
- Comparison of processed images with and without the Smart Noise Cancellation module for sharpness, noise, low-contrast and fine detail, and image artifacts

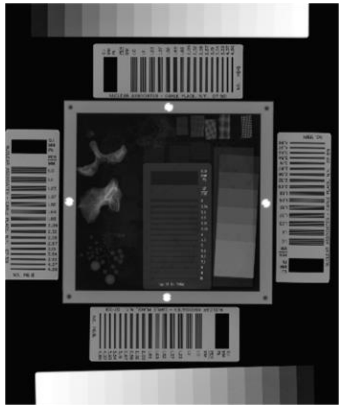
Montage of typical clinical test images



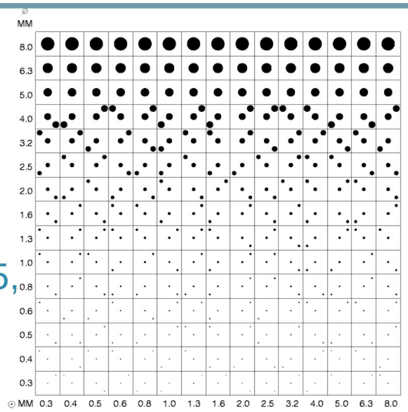
Testing Data – Phantom Set and Techniques

Step tablets	Artinis CDRAD phantom*	MTF target according to IEC 62220-1
Uniform area noise reduction	Contrast-detail evaluation	High contrast sharpness

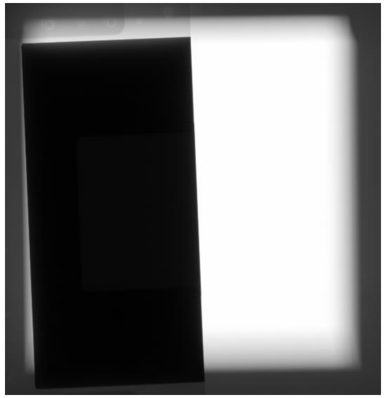
80 kVp,
0.5 mm Cu
1mm Al,
1.8 m SID
0.5, 1, 2, 10 mAs



70 kVp,
10 cm
PMMA,
8:1 grid
1, 1.25, 2.5,
5,10 µGy



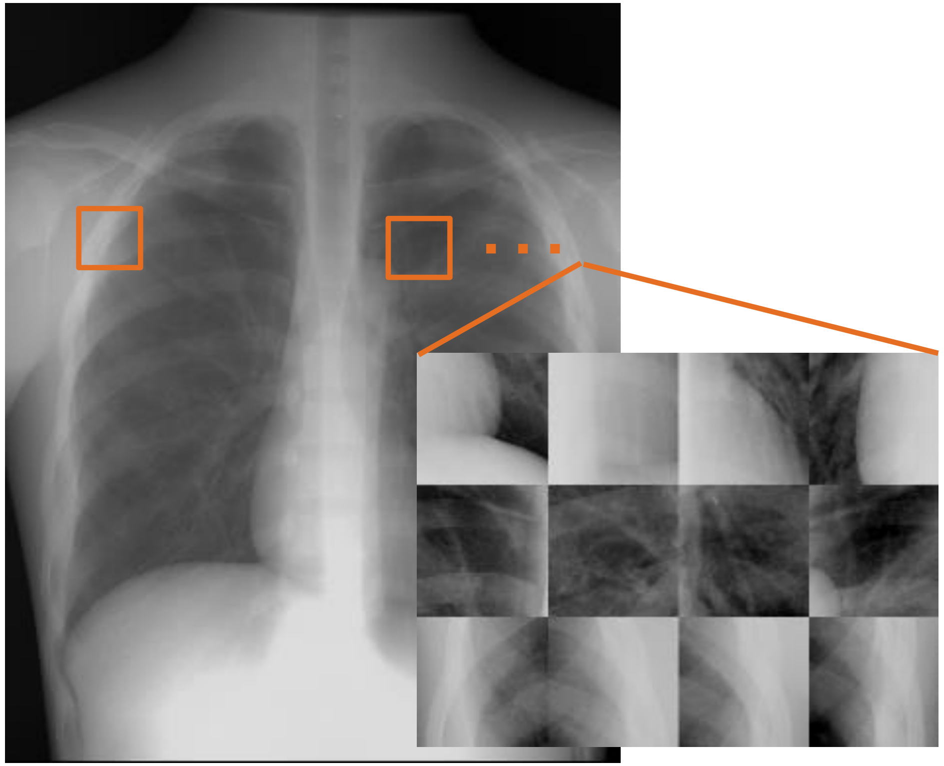
70 kVp,
21 mm Al
(RQA-5)
1.8 m SID
8 µGy



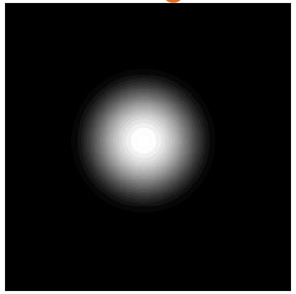
* R. van der Burght, M. Floor, M. Thijssen and R. Bijkerk. Manual CDRAD 2.0 Phantom & Analyser software version 2.1, Rev. 1709, Artinis Medical Systems, 2017

Testing Data – Disease Feature Simulation

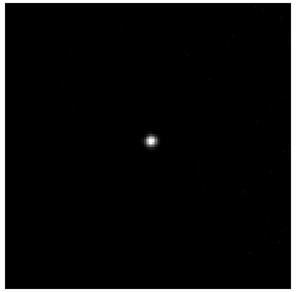
“Golden” clinical image	Disease Features	Simulated image captures
Chest image without noise, scatter and blur; 12 backgrounds were extracted for analysis	10 mm lung nodule* and 0.5 mm high-contrast feature at 2 contrast levels	Combined backgrounds and disease features

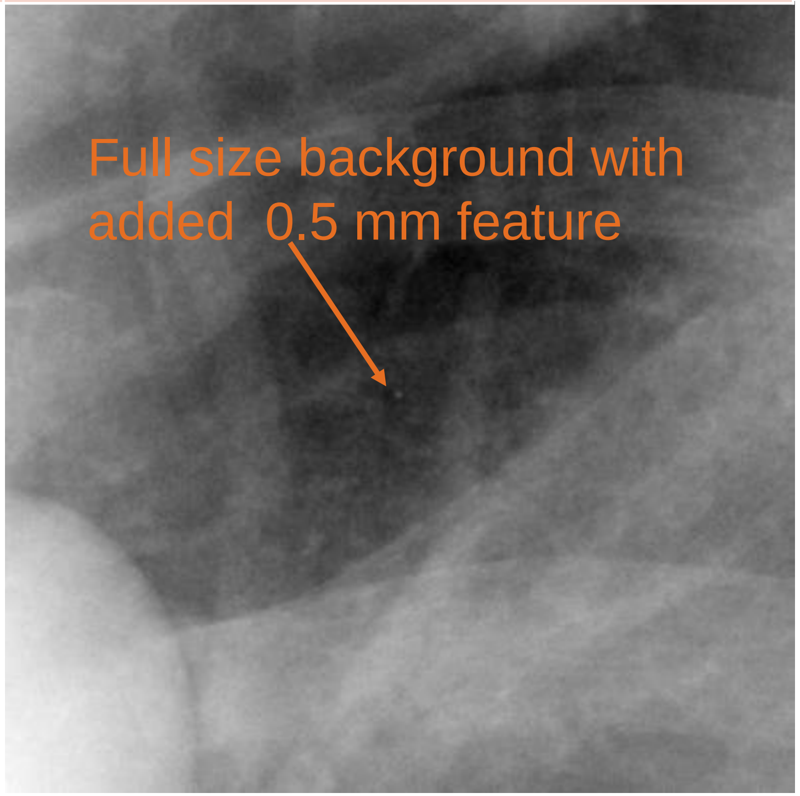


10 mm lung nodule*



0.5 mm high contrast feature

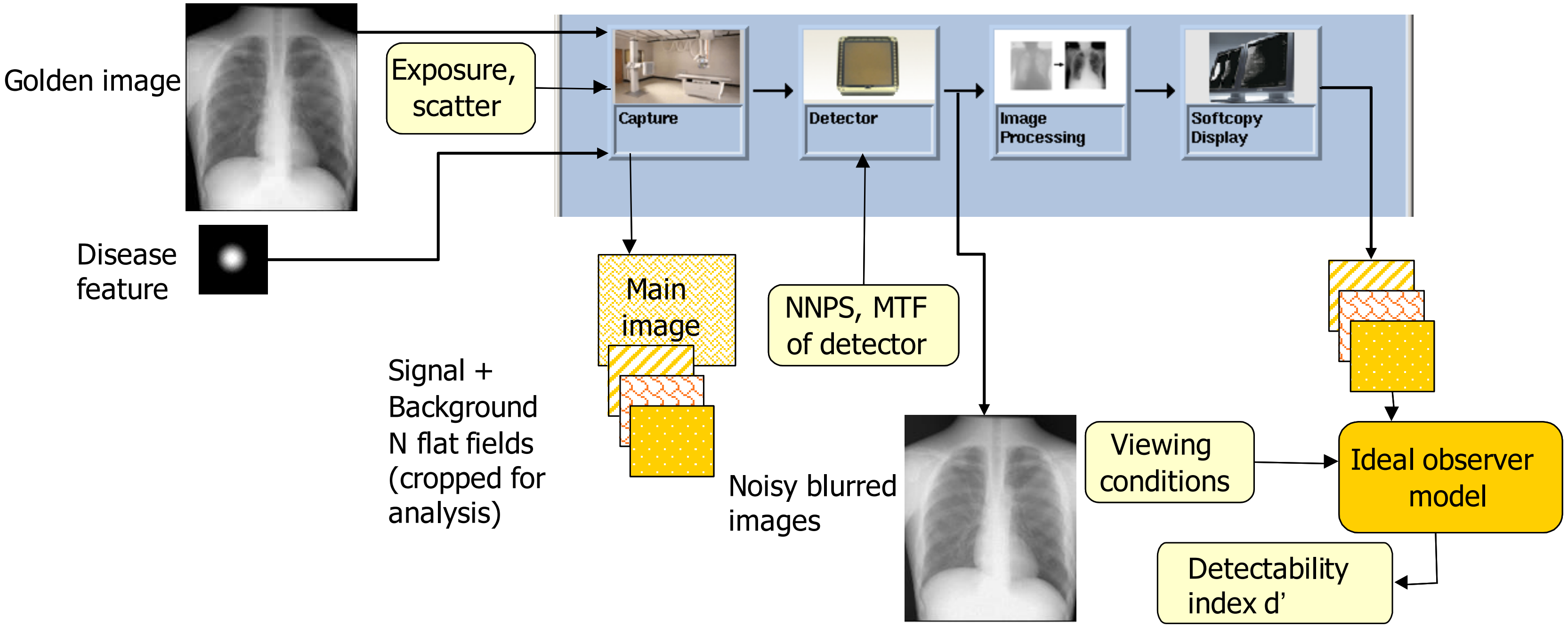




*E. Samei, M. J. Flynn, and W. R. Eyler, “Simulation of subtle lung nodules in projection chest radiography,” Radiology, 202, 117-124 (1997)

Disease Feature Simulation System Model

- Simulation of the entire image chain from “golden” images with added disease features*
- Adding scatter, detector noise and blur, corresponding to 800 and 400 speed captures on a specific detector type
- Image chain includes image processing, with and without Smart Noise Cancellation, display and viewing conditions
- Channelized Hotelling observer => detection of disease features, detectability index d’



*Töpfer, K., Keelan, B. W., Sugiro, F.,“ An advanced system model for the prediction of the clinical task performance of radiographic systems,” Proc. SPIE 6515, 651512-1-12 (2007)

Evaluation Metrics

- Image Noise

  - Analysis on linear raw images
  - Robust standard deviation and mean of the marked ROIs was obtained
  - Plot of noise vs mean, analysis in linear exposure space

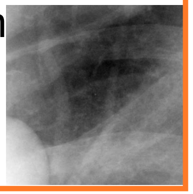
- Contrast-Detail Analysis
  - Automatic scoring of CDRAD images using CDRAD Analyser 2.0 software
  - 10 replicates per exposure, 5 e-5 significance level
  - Feature size, D_i, vs. lowest visible contrast, C_i
  - Quality score IQF_{inv}:

$$IQF_{inv} = \frac{100}{\sum_{i=1}^{15} C_i \times D_{i,th}}$$

$D_{i,th}$: threshold diameter of hole (mm), detail
C_i: depth of hole (mm), contrast

- Sharpness – Modulation Transfer Function (MTF)
  - Analysis on linear raw images
  - MTF analysis according to IEC 62220-1 Standard
  - MTF vs spatial frequency under RQA-5 beam conditions

- Detectability Index d’
  - Average over results from 12 chest backgrounds
  - Calculated for 10 mm lung nodule and 0.5 mm feature at 1x and 1.3x contrast
  - Calculated at 400 and 800 speed with Eclipse processing and compared with 800 speed with Eclipse + Smart Noise Cancellation



RESULTS

Results – Visual Evaluation of Noise Field

Noisy image

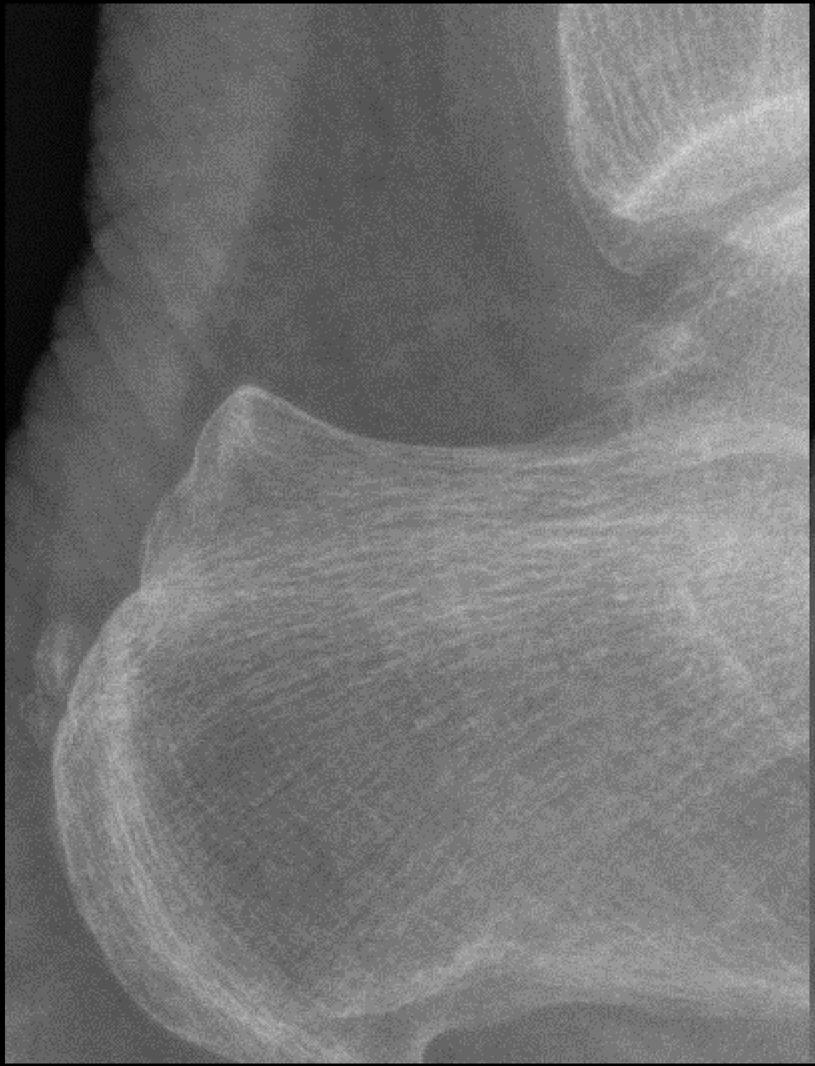
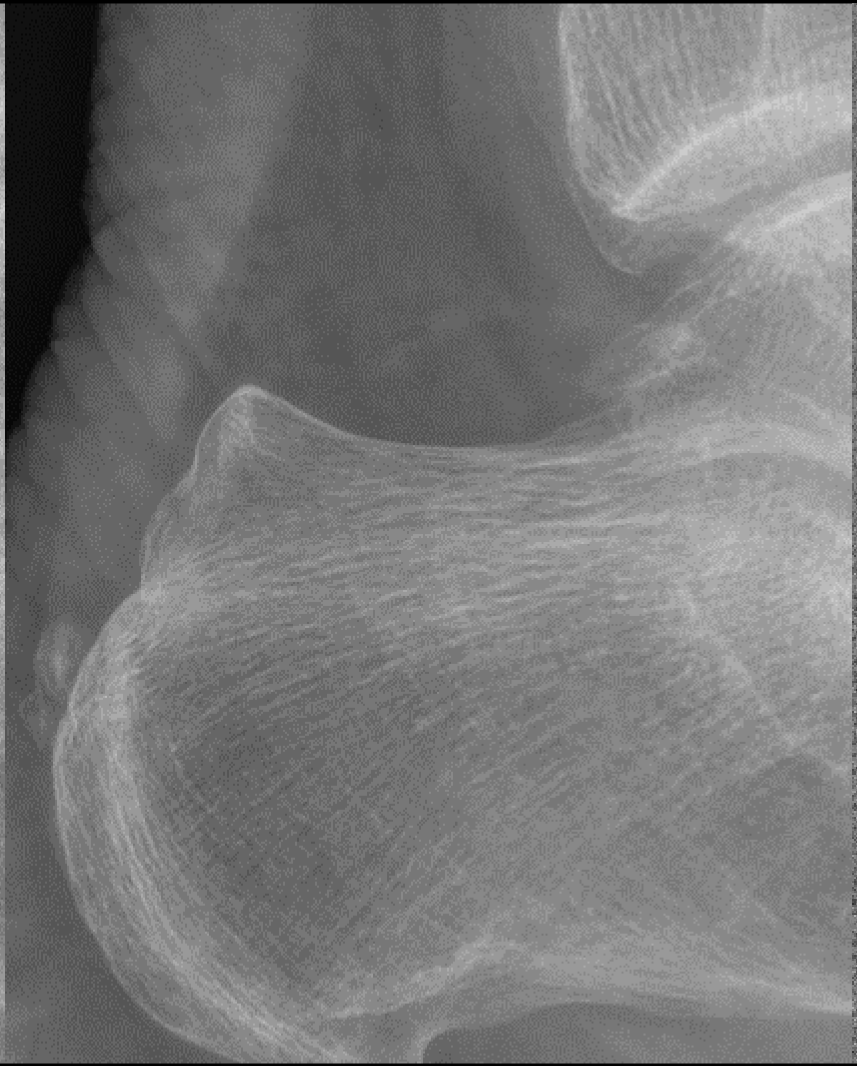
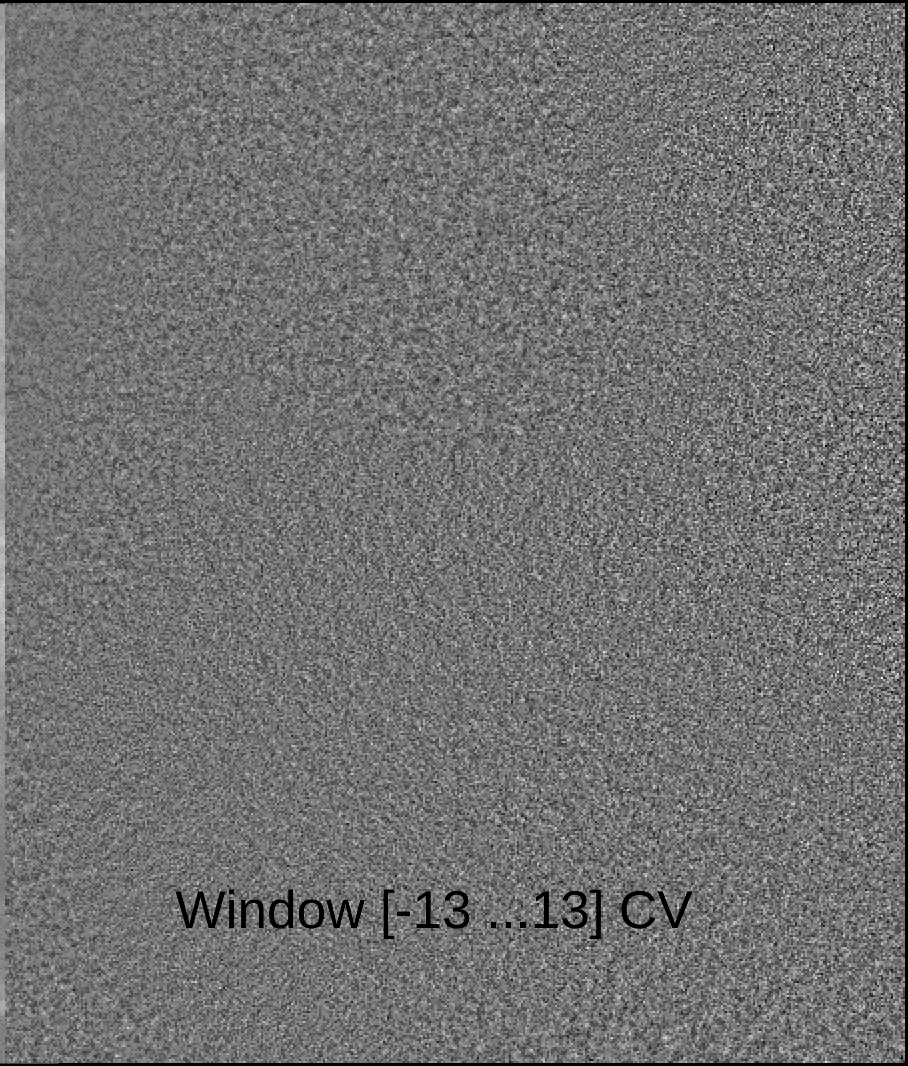


Image after Smart Noise Cancellation

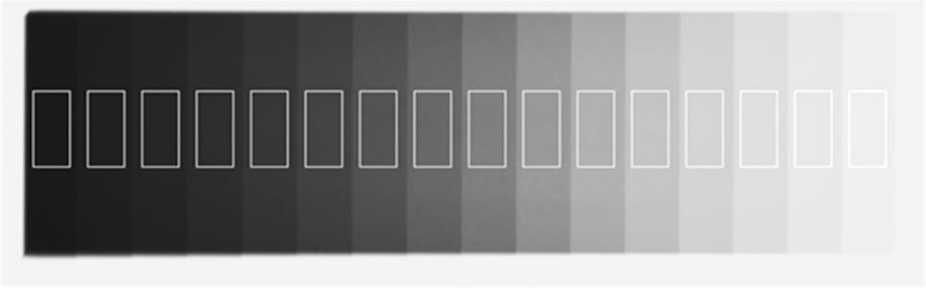


Predicted noise field

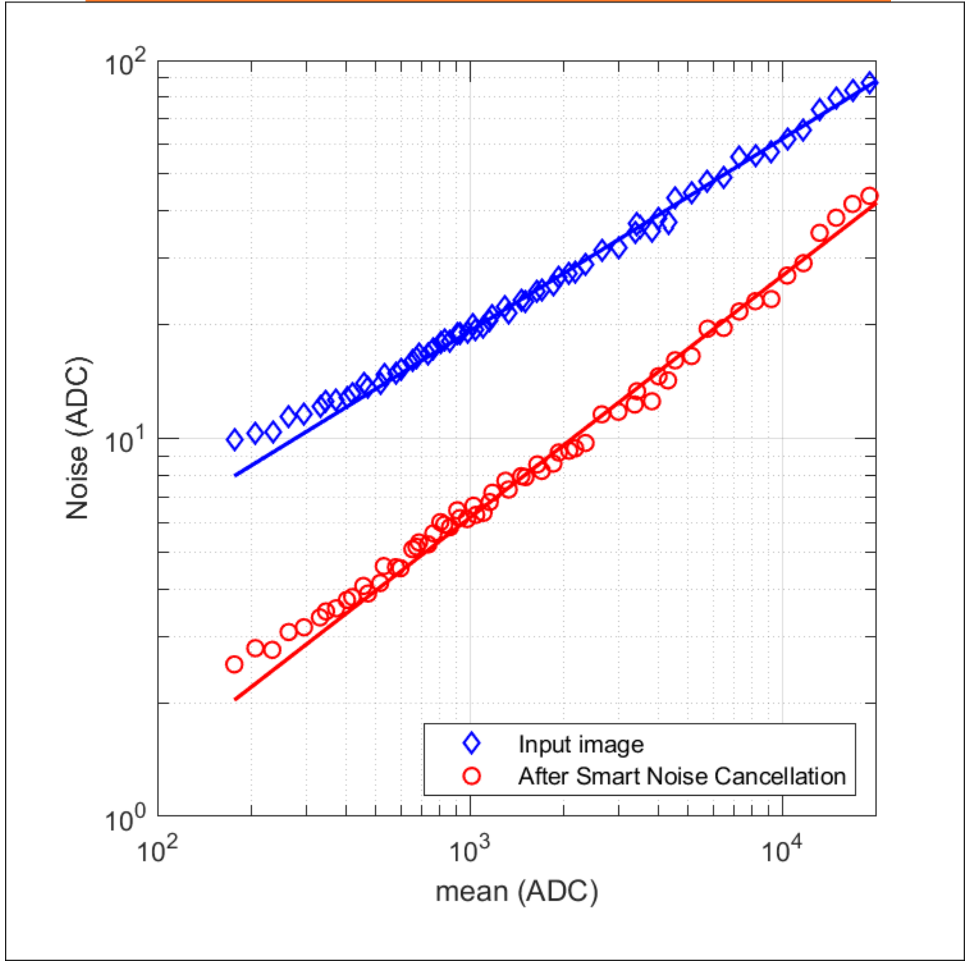


Results – Uniform Area Noise Reduction

- Analysis of Al step tablet at 4 different exposure levels
- Comparison before and after Smart Noise Cancellation, results displayed for DRX Plus 3543C
- The solid blue line before noise reduction indicates quantum limited behavior (Noise $\propto$ mean$^{0.5}$)
- Flat field noise reduction ranged between 4x at low exposures and 2x at higher exposures!
- In terms of quantum noise, 2x noise reduction corresponds to the image appearance of a 4x higher exposure!

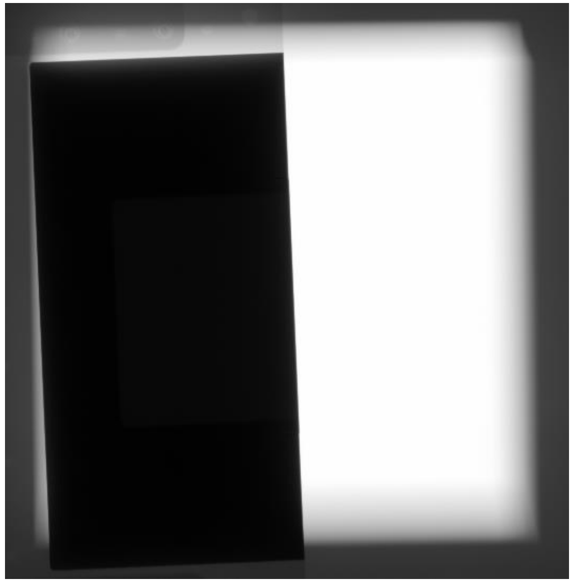


2x to 4x noise reduction with Smart Noise Cancellation



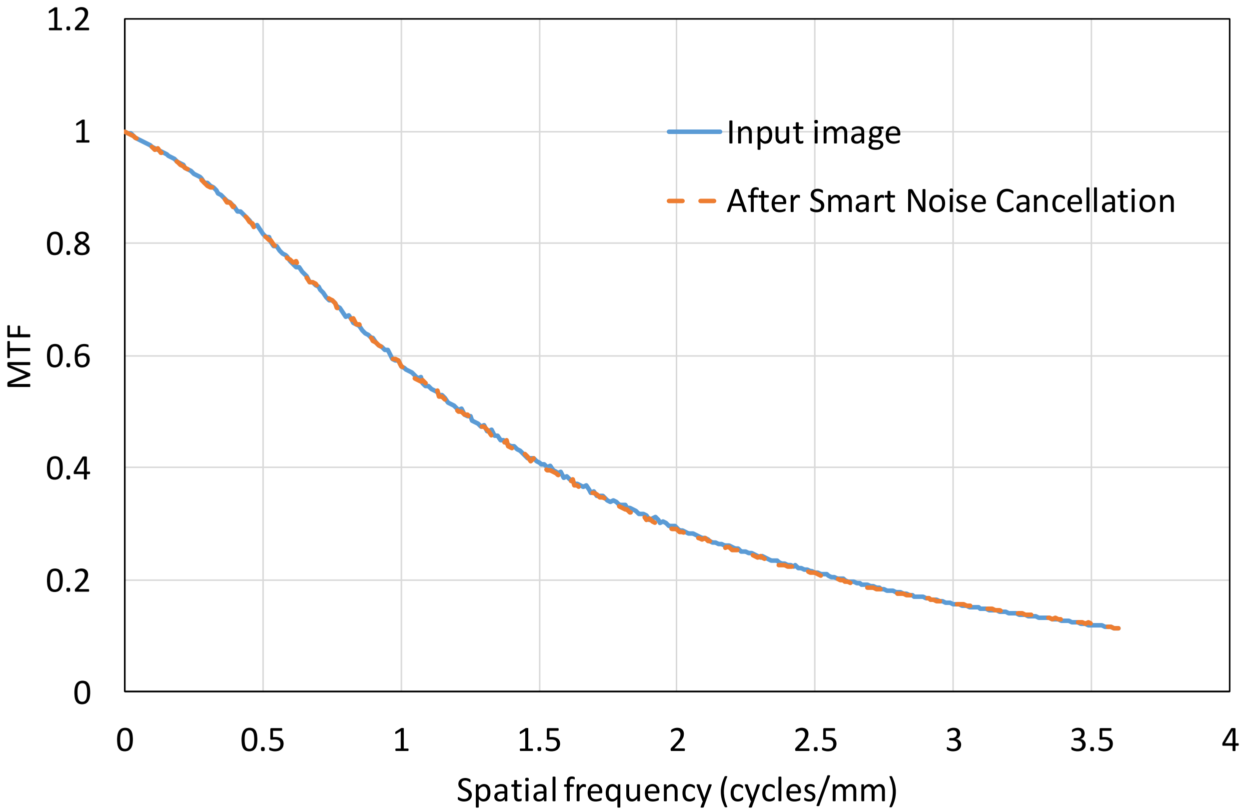
Results – High Contrast Sharpness

- MTF was computed in linear exposure space before and after Smart Noise Cancellation
- RQA-5 beam
- There was no MTF loss after Smart Noise Cancellation



MTF phantom

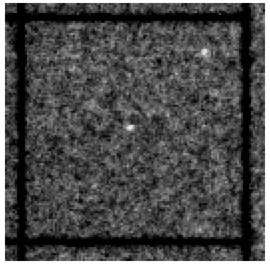
High-contrast sharpness is preserved with Smart Noise Cancellation



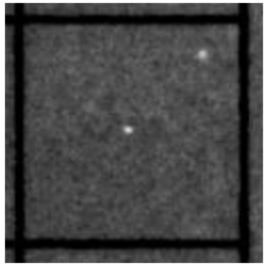
Results – Contrast-Detail Analysis

- Contrast-detail curves and IQF_{inv} scores were obtained from the CDRAD Analyser 2.0 Software before and after Smart Noise Cancellation
- Quality score plotted as a function of air kerma at detector
- Improved detection after Smart Noise Cancellation, mainly for larger low-contrast features

Scoring

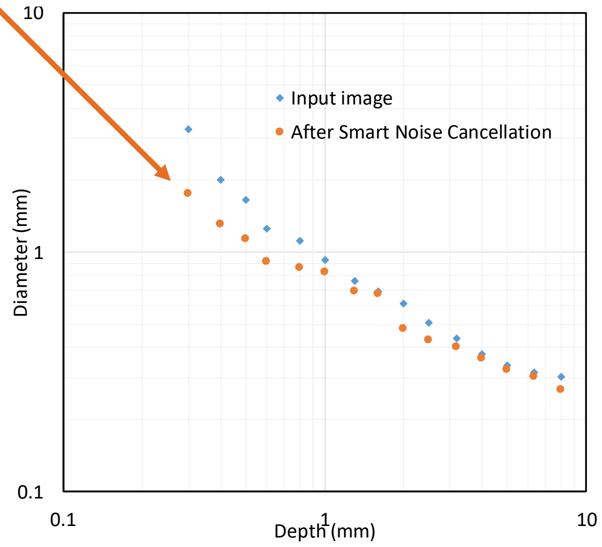


Input

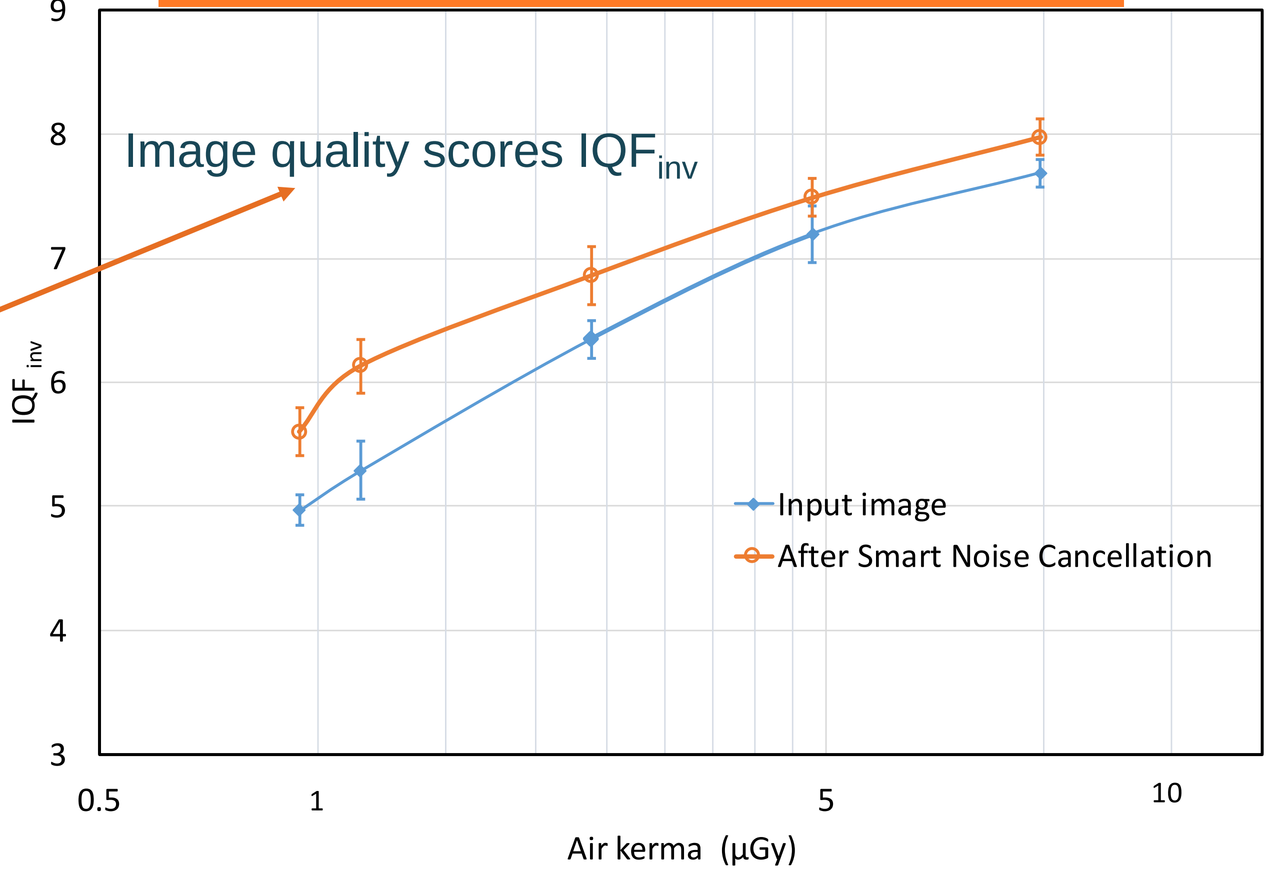


After Smart Noise Cancellation

Contrast-Detail Curve



Increased detection scores IQF_{inv} with Smart Noise Cancellation

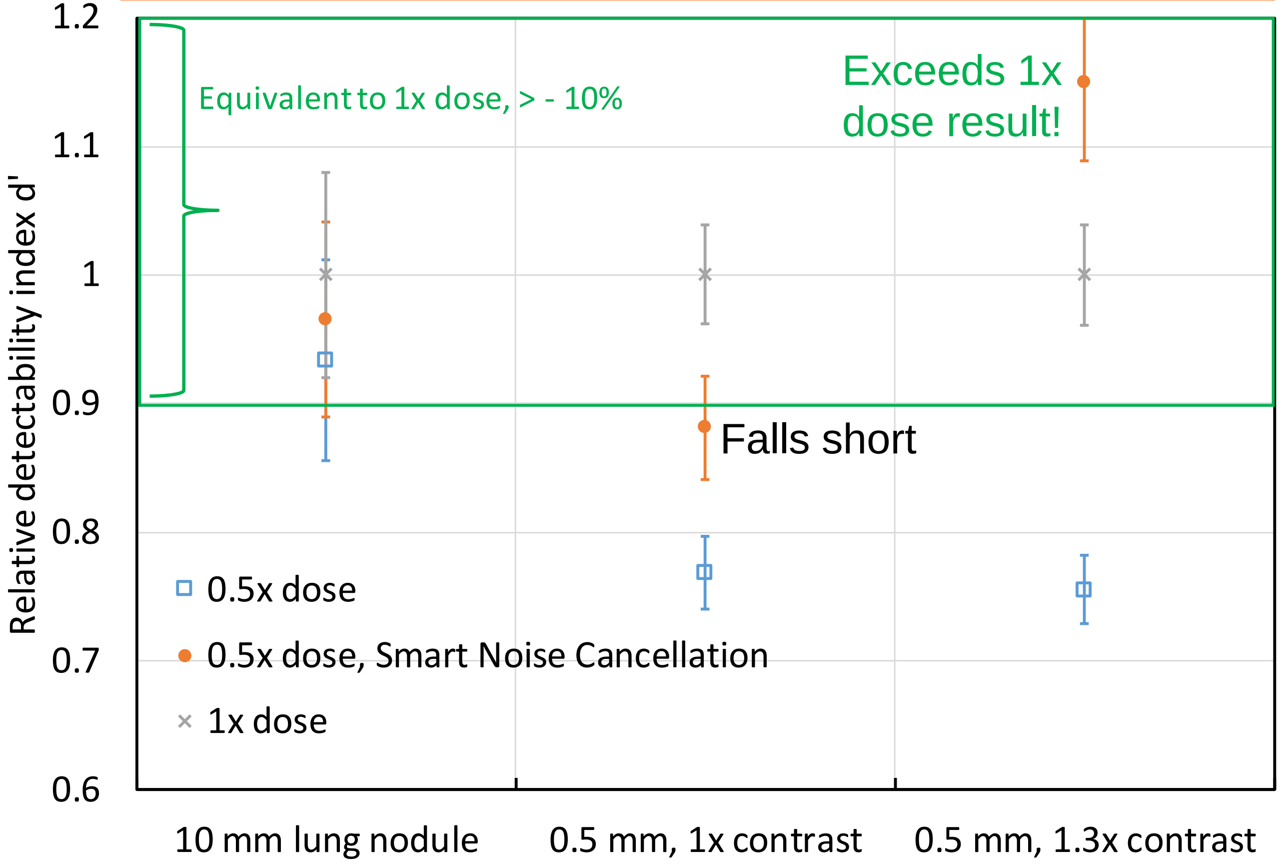


Carestream DRX Plus 3543C Detector, 70 kVp

Results – Detectability of Disease Features, d’

- All data is normalized to the d’ result for 1x dose, default image processing (gray symbol)
- A 10% loss in d’ can be detected in larger reader study and is therefore significant
- The region between 0.9 and 1.2x in relative d’ is marked by the green rectangle as at least equivalent to 1x dose
- Results support up to 2x dose reduction with Smart Noise Cancellation for larger features, e.g. 10 mm lung nodule, and the higher contrast small feature, see orange symbols relative to gray symbols.
- Smart Noise Cancellation is not able to recover disease features below threshold or increase visibility of features at threshold, see results for 1x contrast of the 0.5 mm feature

Improved detectability of disease features with Smart Noise Cancellation



Results for DRX Plus 2530C Detector

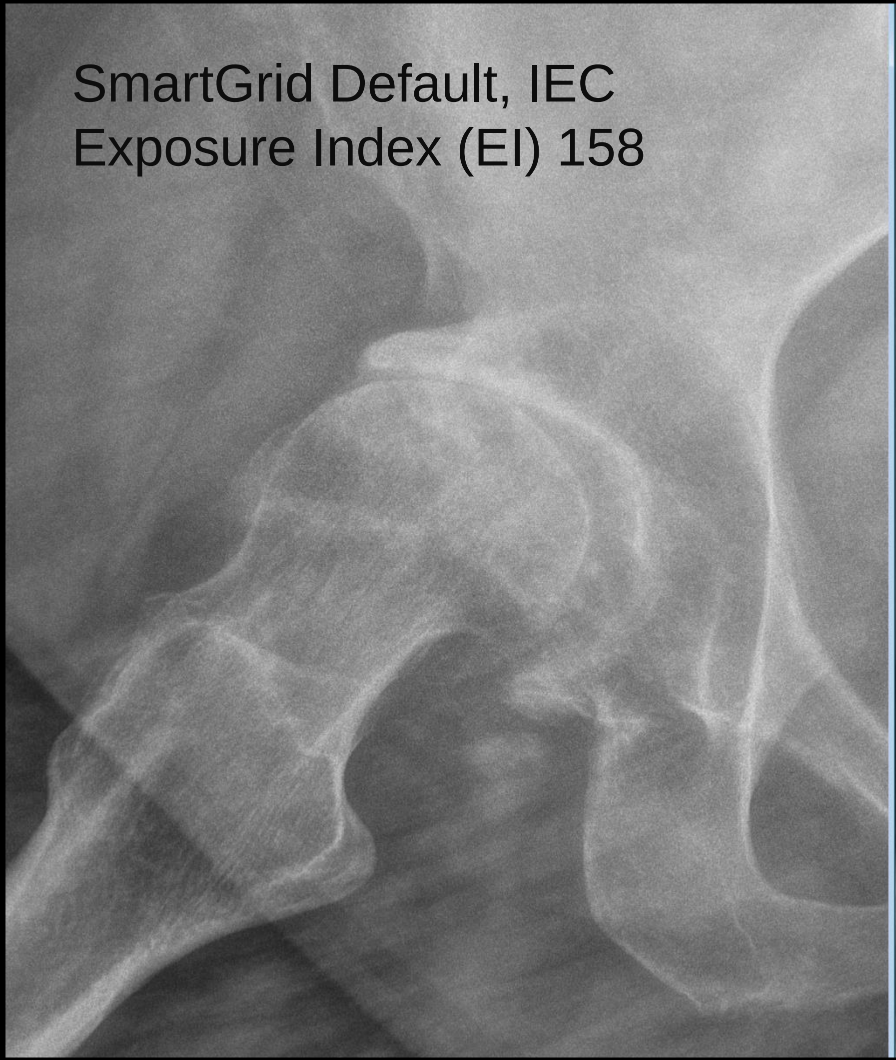
IMAGE EXAMPLES

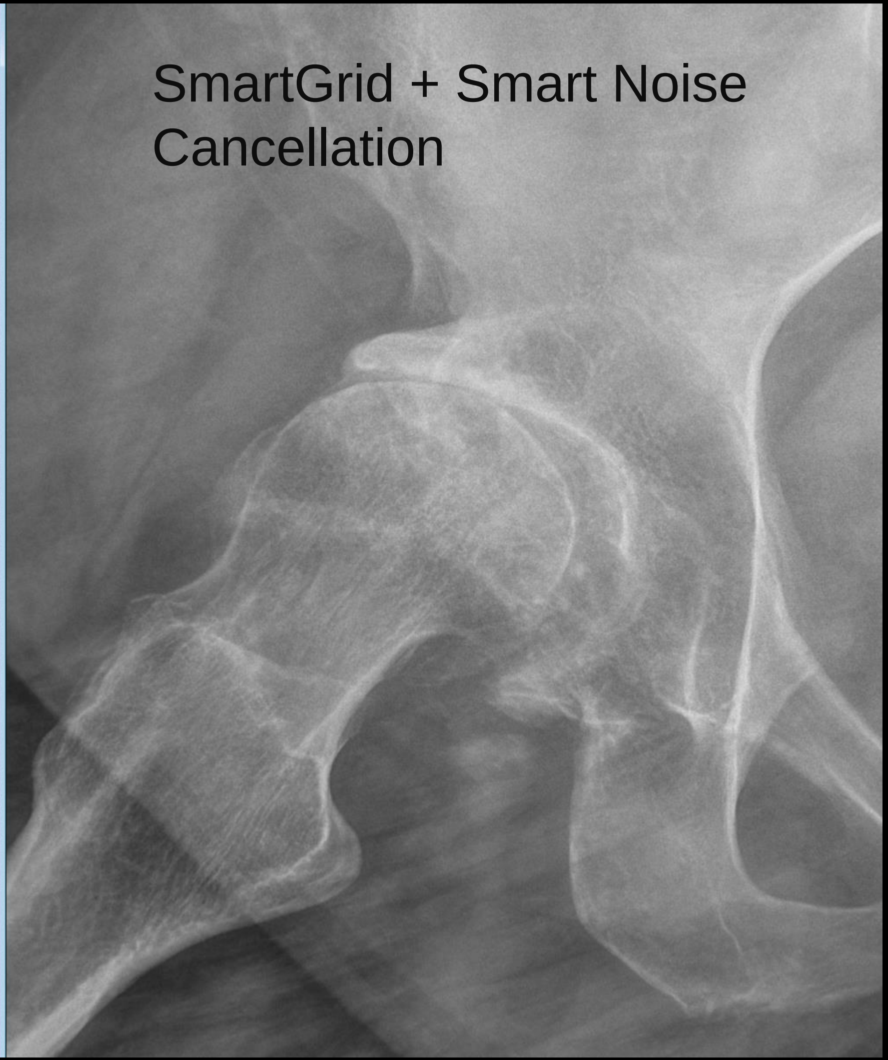
Smart Noise Cancellation and Scatter Suppression

- Anti-scatter grids improve image quality by reducing the impact of scattered radiation
- Radiographs, however, are frequently acquired without grids due to challenges in grid alignment, x-ray cutoff, and workflow impact
- Software-based scatter suppression has been available in recent years*
- While these solutions led to improvements in anatomy contrast, they also resulted in increased image noise
- The combination of scatter suppression software with Smart Noise Cancellation** addresses the noise issue, leading to image quality equivalent to captures with grid, but at < 50% of the dose.
- Image examples show scatter suppression performance using three methods:
  - Physical grid (6:1 and 12:1 grid ratios)
  - SmartGrid (Carestream software-based scatter suppression)
  - SmartGrid+ (Smart Grid with Smart Noise Cancellation)

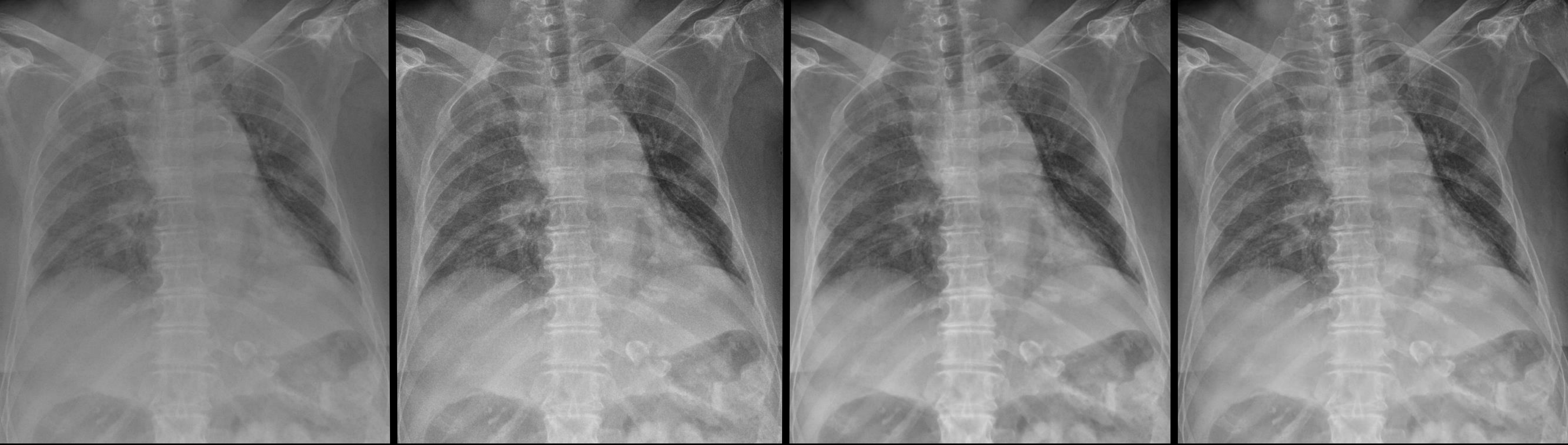
* https://www.carestream.com/blog/wp-content/uploads/2020/01/whitepaper-SmartGrid-Image-Quality-Impact.pdf
** "Performance Comparison of Physical Anti-Scatter Grid and AI-Based Virtual Scatter Reduction Across Patient Size" - RSNA Featured Paper 20009415

SmartGrid DRX Plus 3543C Clinical Case





Contrast enhancement and noise reduction

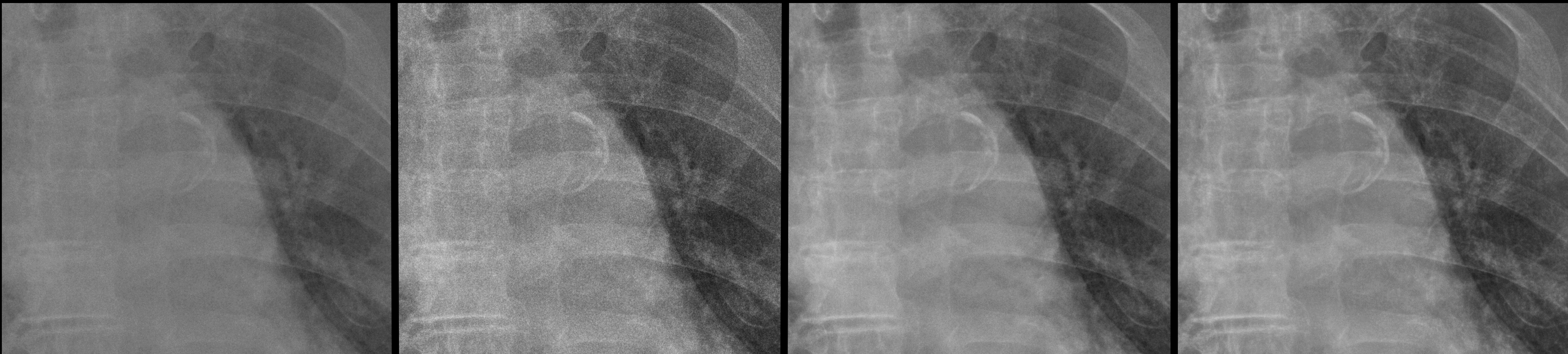


100 kVp, 0.5 mAs IEC EI 193.1
Default

100 kVp, 0.5 mAs IEC EI 193.1
SmartGrid

100 kVp, 1.2 mAs, 6:1 grid
IEC EI 192.1 Default

100 kVp, 0.5 mAs, IEC EI 193.1
SmartGrid + Smart Noise Cancellation



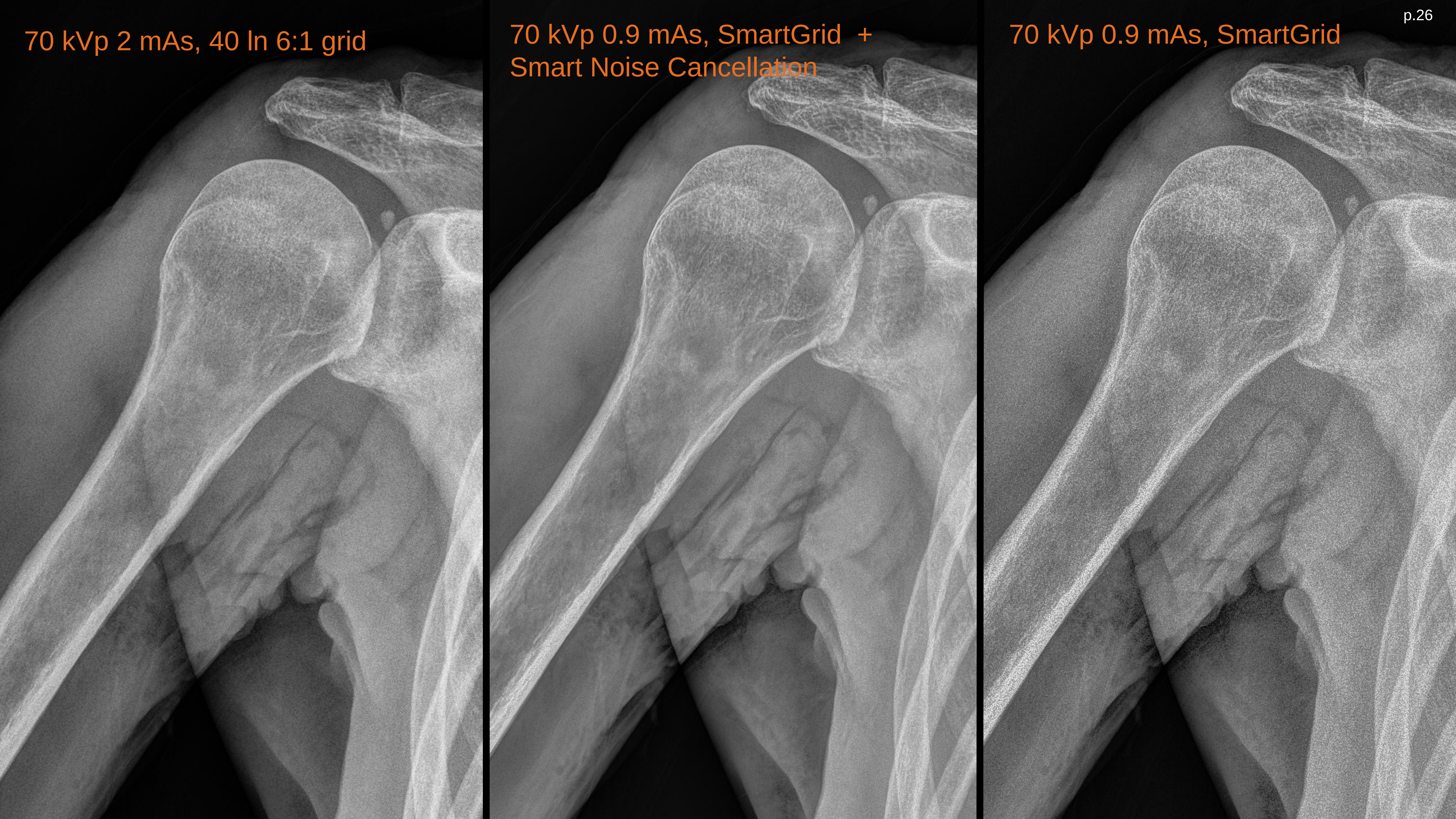

70 kVp 2 mAs, 40 In 6:1 grid
70 kVp 0.9 mAs, SmartGrid +
Smart Noise Cancellation
70 kVp 0.9 mAs, SmartGrid

Image Enhancement and Dose Reduction in Neonatal Imaging

- Image enhancement and dose reduction are particularly important in the neonatal ICU
- The youngest, most vulnerable patients in terms of radiation, get imaged repeatedly to check for placement of tubes and lines and other changes
- The Carestream DRX Plus 2530C Detector was designed for this market with a smaller 98 micron pixel pitch and a cesium iodide scintillator, already providing excellent low dose performance and resolution
- The following slide shows how Smart Noise Cancellation can enhance these benefits even further; please note the low IEC EI of 80

Smart Noise Cancellation, DRX Plus 2530C Detector

55 kVp 1 mAs IEC EI 80

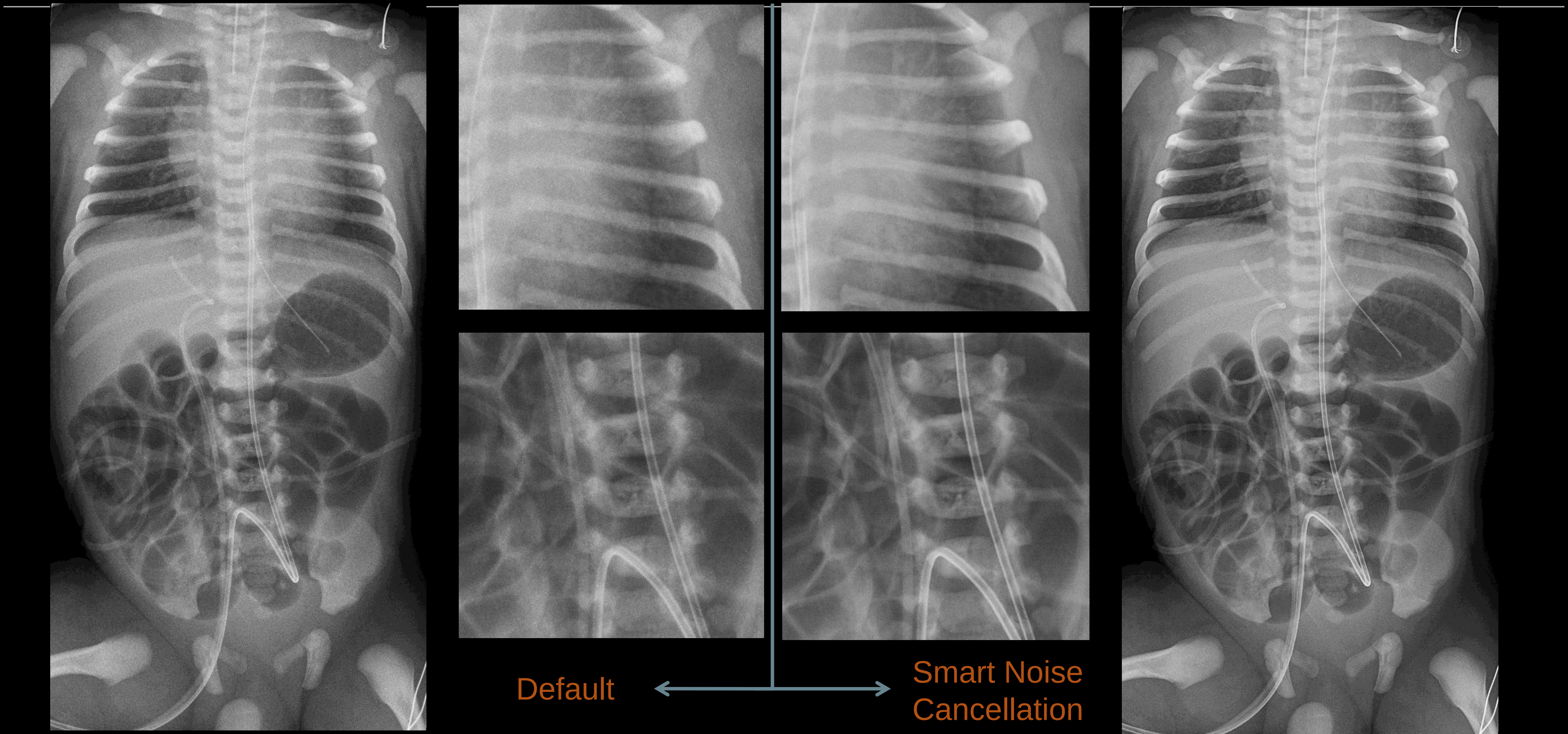
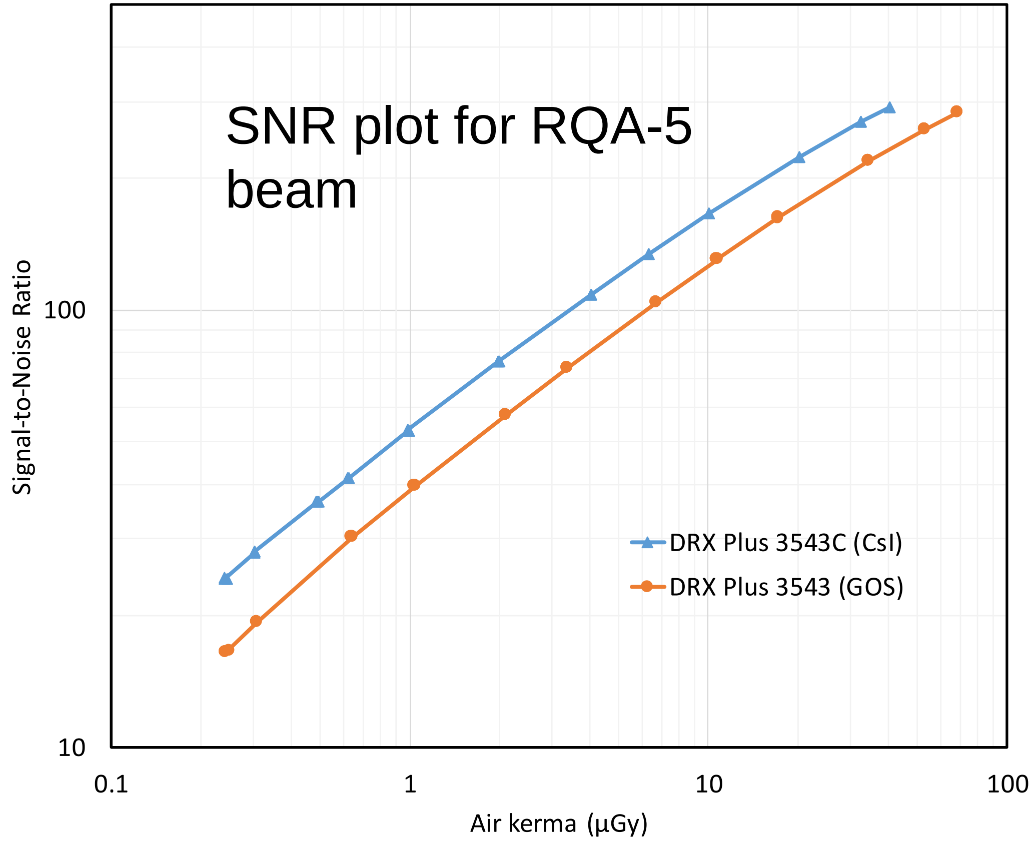


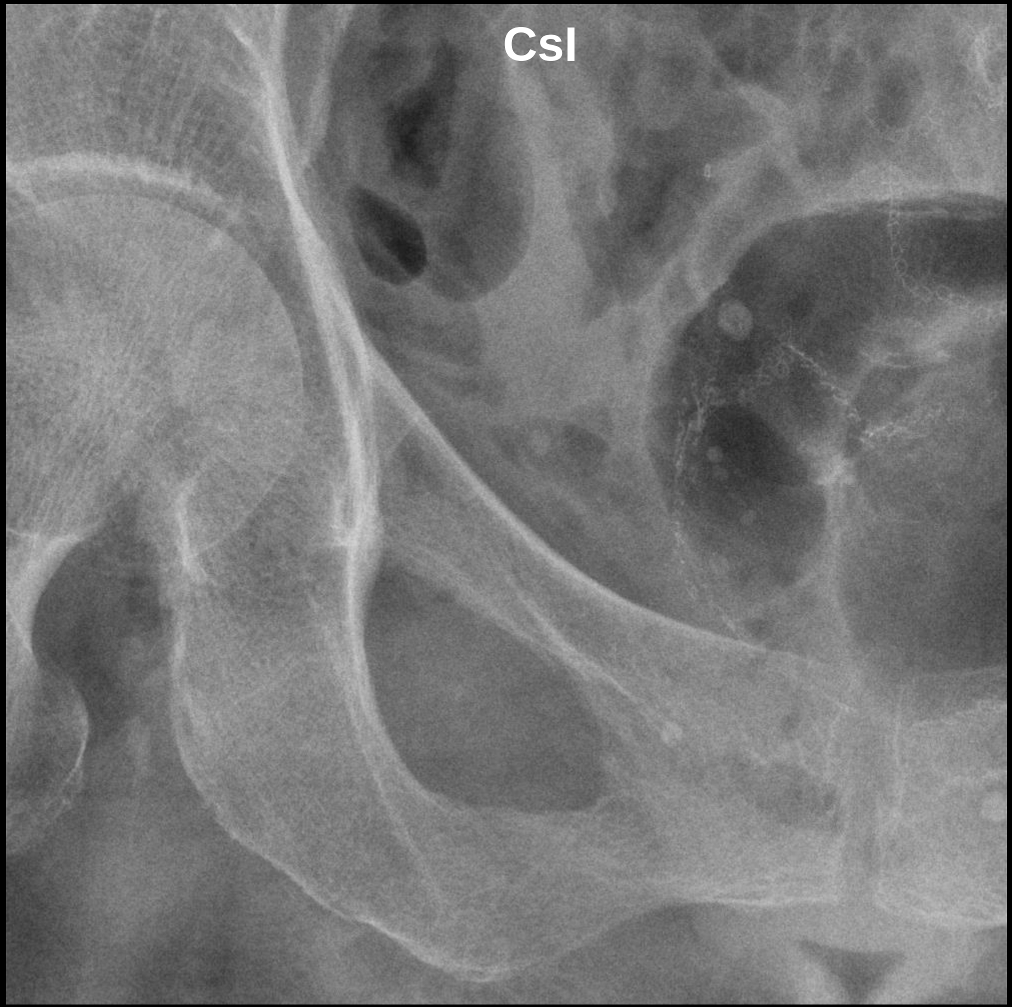
Image Comparison of Scintillator Technology

- Carestream's detector portfolio has a choice of two scintillators
- Gadolinium oxysulfide (GOS) is a cost-effective offering with good image quality and reduced dose compared with computed radiography (CR)
- The cesium iodide (CsI) scintillator is a premium offering for the highest image quality and lowest dose
- Detectors with CsI have higher X-ray absorption and improved light management due to the columnar structure of the scintillator compared with GOS
- As a result, images on CsI have a higher signal-to-noise ratio (SNR) than images on GOS at the same input exposure (dose)

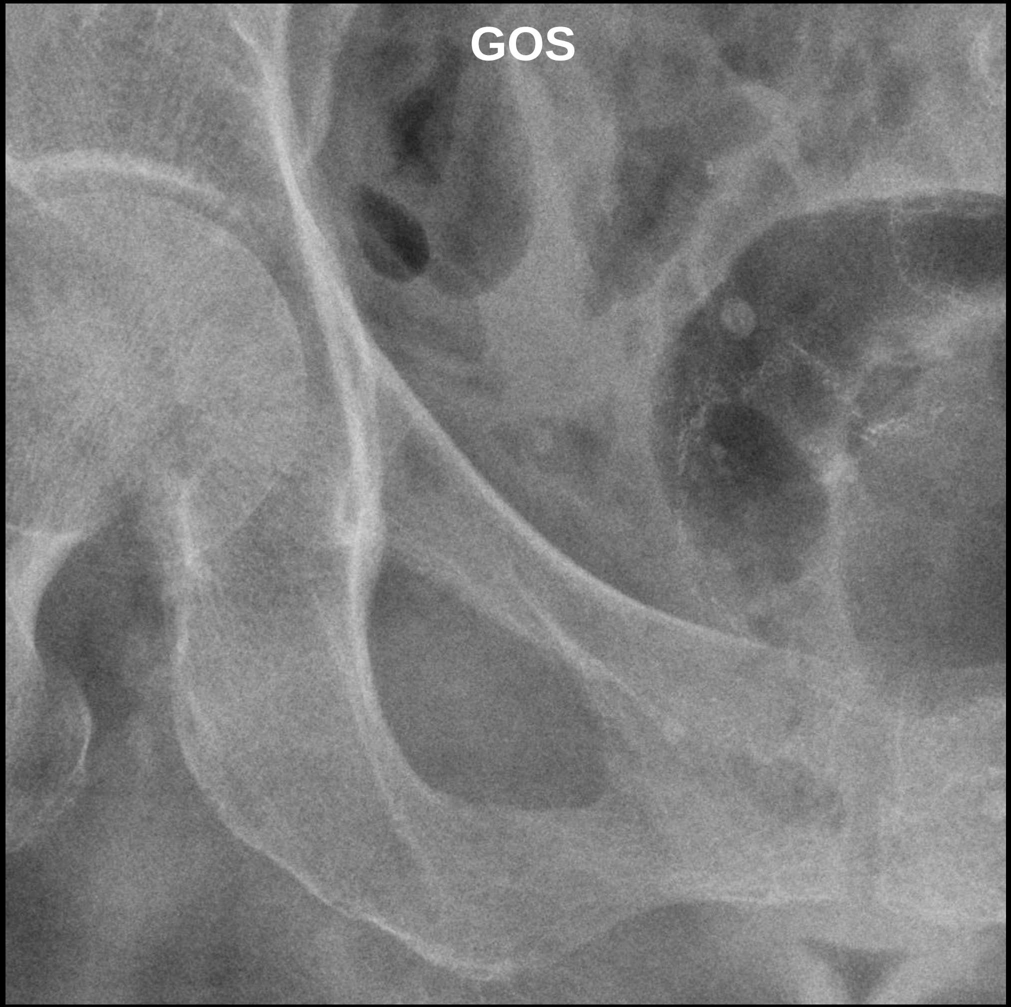
Eclipse with Smart Noise Cancellation on GOS detectors can produce equivalent image quality to Eclipse on CsI detectors at the same exposure



CsI @ 500 speed ≠ GOS @ 500 speed

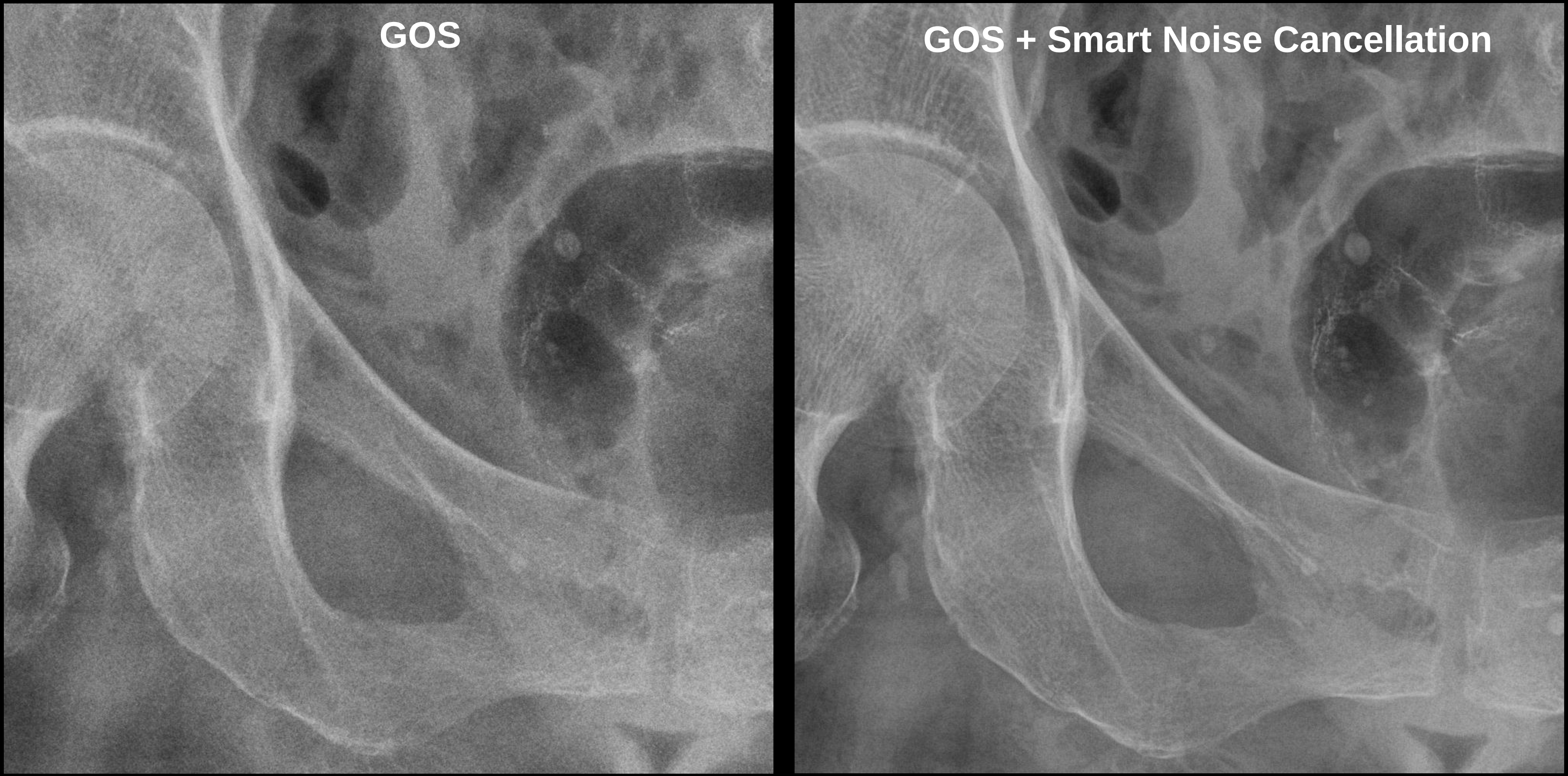


75 kVp 6.3 mAs, 40 ln/cm 6:1 Grid, IEC EI 129



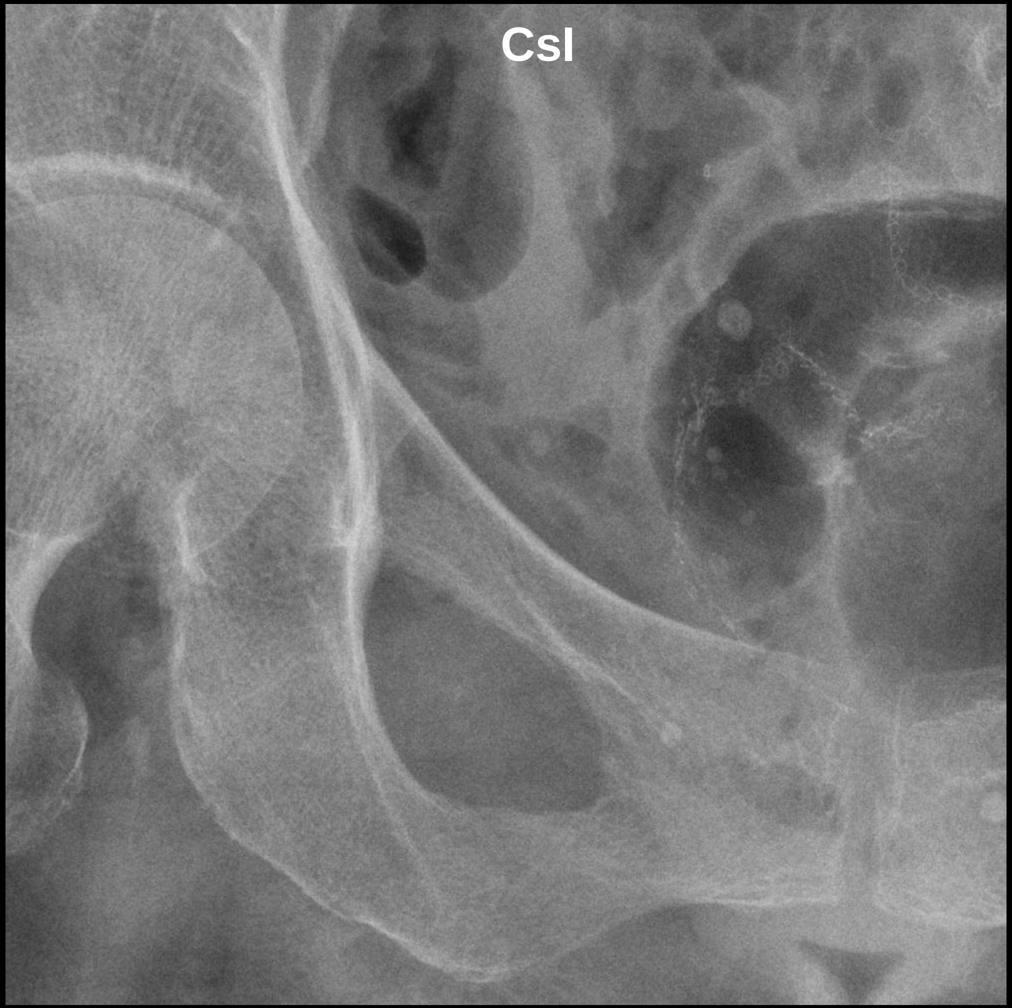
75 kVp 6.3 mAs, 40 ln/cm 6:1 Grid, IEC EI 126

GOS @ 500 speed – Smart Noise Cancellation Effect

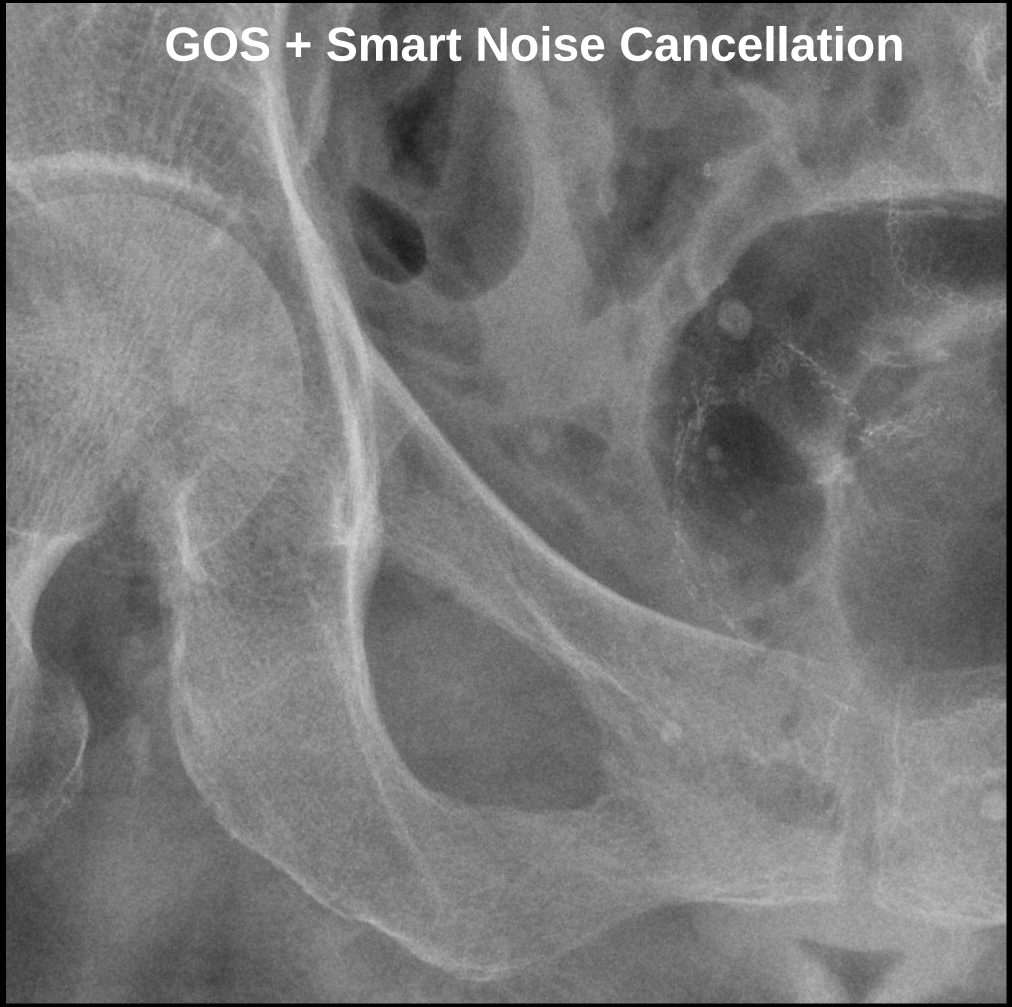


75 kVp 6.3 mAs, 40 ln/cm 6:1 Grid, IEC EI 126

CsI @ 500 speed = GOS @ 500 speed



75 kVp 6.3 mAs, 40 ln/cm 6:1 Grid, IEC EI 129

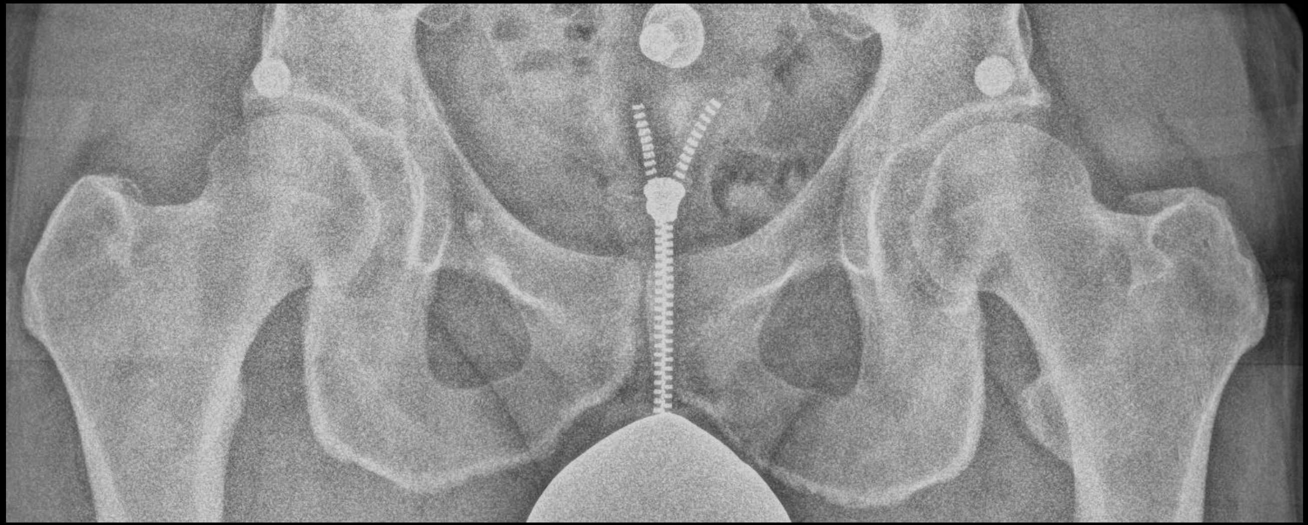


75 kVp 6.3 mAs, 40 ln/cm 6:1 Grid, IEC EI 126

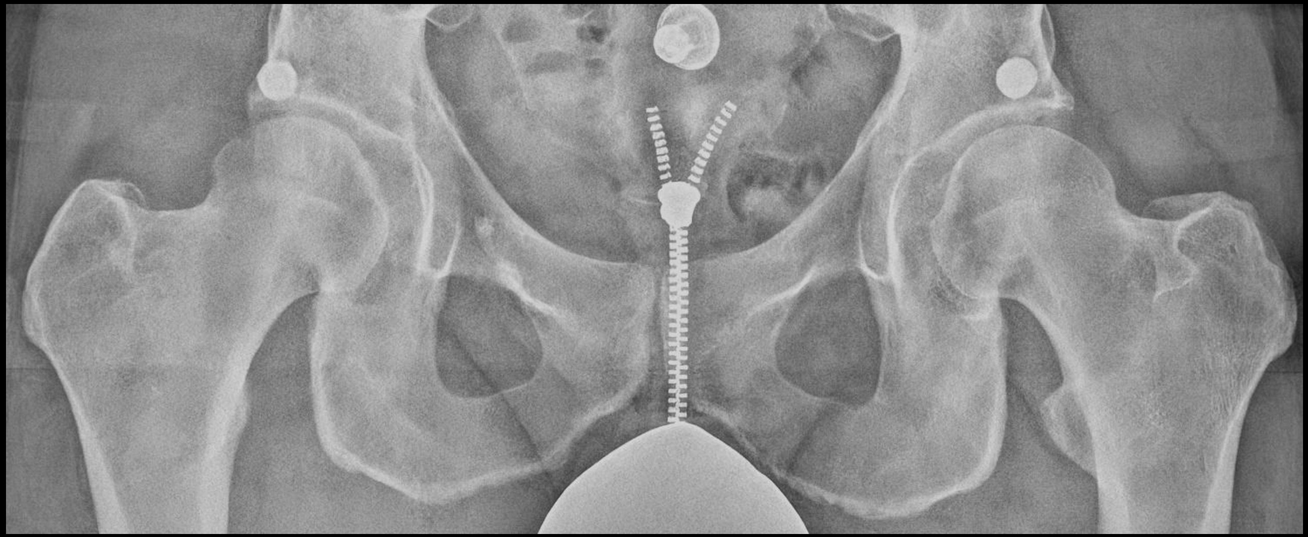
Carestream DRX-L Detector for Single Shot LLI

Eclipse, full image

Eclipse



Eclipse + Smart Noise Cancellation



This GOS based detector benefits from Smart Noise Cancellation for the lowest possible dose

Summary and Conclusions

- The performance of a deep convolutional neural network in terms of noise reduction was characterized using anonymized clinical images, representative of general radiography and pediatrics, and a set of phantoms
- The network achieved:
  - 2 to 4x noise reduction in flat areas of the images, depending on exposure
  - Preservation of edge content and high contrast sharpness in the images
  - 10% to 20% improvement in contrast-detail scores on the CDRAD 2.0 phantom
  - Improvements in the detectability of disease features for a 10 mm lung nodule and a higher contrast 0.5 mm feature
- A comparison of the detectability index d' at 1x dose with Eclipse processing and at 50% dose with Smart Noise Cancellation and Eclipse suggests that up to 50% dose reduction can be achieved relative to the nominal setting (400 speed or 2.5 µGy for CsI detectors and 320 speed or 3.1 µGy for GOS detectors).
- Improvements in the image quality of clinical images with Smart Noise Cancellation and Eclipse image processing were demonstrated for:
  - A combination of Smart Grid scatter suppression software with Smart Noise Cancellation
  - Applications in the neonatal ICU
  - Detectors with GOS scintillator, which can achieve low noise positions traditionally only seen on detectors with CsI scintillator

Carestream