iDose[4] iterative reconstruction technique

Breakthrough in image quality and dose reduction with the 4th generation of reconstruction

Abstract

Recent technological advances have markedly enhanced and expanded the clinical application of computed tomography (CT) [1]. While the benefits of CT have been well documented and support many aspects of modern healthcare, increasing radiation doses to the population have raised attention to the need for reduction of radiation exposure from CT [2,3]. In response, the radiology community (radiologists, physicists and manufacturers) has worked to adhere to ALARA (As-Low-As-Reasonably-Achievable) principles in CT imaging [4,5,6,7].

Dose management is simplified with Philips Healthcare's DoseWise philosophy [8] and the advances embodied in the Ingenuity, Brilliance, and Mx CT platforms. Multiple components of the imaging chain have been enhanced to increase volume imaging speed, dose efficiency, and image quality, thereby enabling opportunities for lower-dose scan protocols. As the performance of the imaging chain was increased, the limitations of image quality resulting from conventional filtered back projection (FBP) reconstruction algorithms — especially at lower doses — became apparent.

In this article, we provide an in-depth review of an innovative, 4th generation iterative reconstruction technique. iDose[4] — the latest addition to Philips' DoseRight tools — that provides significant improvements in image quality combined with dose reduction capabilities. Benchmarking tests relative to alternate technologies help demonstrate the benefits of this 4th generation iterative reconstruction technique in preventing photon starvation artifacts (streaks, bias) prior to image creation and in maintaining image texture to overcome the artificial or "plastic" look of images that have been frequently reported when using previous-generation iterative reconstruction techniques. Evidence from phantom tests and rigorous clinical evaluations with global clinical collaborators demonstrate the potential of iDose[4] to improve image quality and/or lower radiation dose levels beyond those previously achievable with conventional, routine-dose acquisitions, filtered back projection reconstructions.

Improved resolution	up to 68% resolution improvement
Lower dose with natural appearance	up to 80% lower dose
Artifact prevention	4th generation
Easy-to-use, under a minute	up to 20 IPS

Figure 1: Key clinical benefits of iDose[4].

PHILIPS

sense and simplicity

Introduction

Filtered back projection (FBP) has been the industry standard for CT image reconstruction for decades. [9] While it is a very fast and fairly robust method, FBP is a sub-optimal algorithm choice for poorly sampled data or for cases where noise overwhelms the image signal. Such situations may occur in low-dose or tube-power–limited acquisitions (e.g., scans of morbidly obese individuals). Noise in CT projection data is dominated by photon count statistics. As the dose is lowered, the variance in the photon count statistics increases disproportionately [10]. When these very high levels of noise are propagated through the reconstruction algorithm, the result is an image with significant artifacts and high quantum mottle noise.

Over time, incremental enhancements were made to FBP to overcome some of its limitations. These improvements continued until recently, when a completely different approach to image reconstruction was explored through the clinical implementation of iterative reconstruction (IR) techniques. IR techniques attempt to formulate image reconstruction as an optimization problem (i.e., IR attempts to find the image that is the "best fit" to the acquired data). The noisiest measurements are given low weight in the iterative process; therefore, they contribute very little to the final image. Hence, IR techniques treat noise properly at very low signal levels, and consequently reduce the noise and artifacts present in the resulting reconstructed image. This results in an overall improvement of image quality at any given dose. With IR techniques, the noise can be controlled for high spatial resolution reconstructions; hence providing high-quality, low-contrast, and spatial resolution within the same image. While IR techniques have been used for many years in PET and SPECT imaging, the sampling density and the data set sizes in CT have historically caused IR techniques to perform extremely slowly when compared to FBP. However, recent innovations in hardware design and algorithm optimizations have permitted the clinical use of an IR technique in CT.

While different FBP and IR techniques have been made available commercially, their clinical value varies significantly. Figure 2 categorizes these various techniques by generation based on the clinical benefit(s) that each provides.

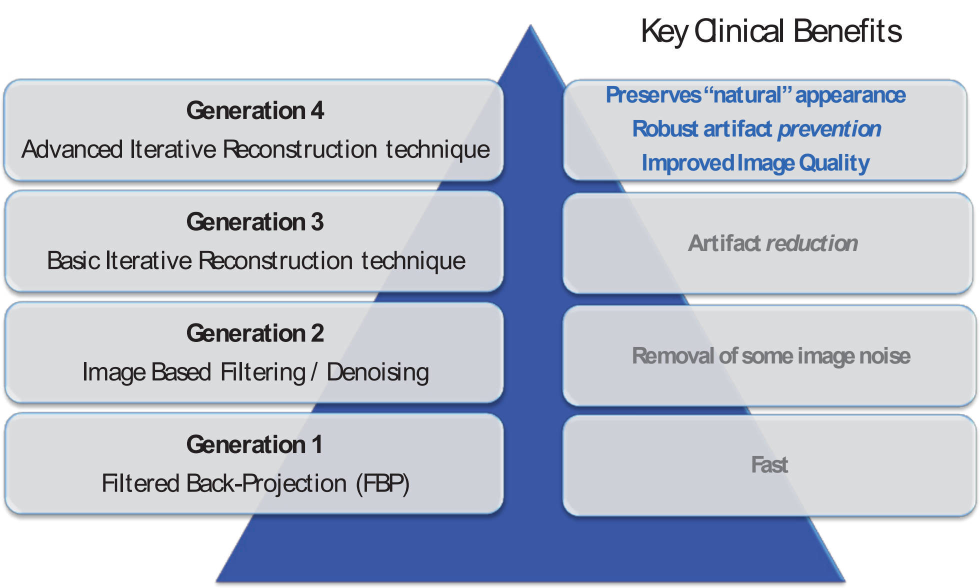


Figure 2: Classification of reconstruction techniques based on the clinical value provided.

Generations of reconstruction

There is continued debate in the scientific community with regard to the optimal reconstruction technique for CT, and in many cases there is also confusion regarding the algorithmic implementation utilized on commercial scanners. Classification of reconstruction techniques based on their clinical results provides a logical — and more meaningful — differentiation among these techniques. The classification provided in this article is based on the value that reconstruction algorithms provide in terms of improving image quality and reducing radiation dose. The results of benchmarking tests are provided to illustrate the clinical differences among the results of each technique. Additionally, algorithmic limitations are outlined to help better understand the reasons for the results.

1st-Generation Reconstruction: Filtered back projection

Filtered back projection (FBP), while fast and fairly robust at routine radiation doses, is prone to image noise and artifacts that result in non-diagnostic images at extremely low doses. The clinical example in Figure 3b-c demonstrates an ultra-low-dose acquisition (93% dose reduction, 0.4 mSv) where FBP (fig. 3b) results in a significant increase in artifacts and quantum mottle noise relative to the routine-dose acquisition (fig. 3a). 4th generation iterative reconstruction techniques, such as iDose4, prevent artifacts and limit quantum mottle noise, thus providing images (fig. 3c) that are diagnostically equivalent to the routine-dose acquisition.

The following five disadvantages of FBP in CT can be noted, especially when working with low doses [11]:

1. Taking the logarithm of the acquired data is required by FBP. This assumes non-zero photon detection; however, in low-dose acquisitions, some detectors may not measure any photons, meaning that artificial values may be forced upon the data. If the artificial value is not close to the true value associated with the scanned object, it may manifest as a streak across the image.
2. The properties of the logarithm inherently introduce a bias in the reconstructed image. This error, if not treated correctly, may manifest as a CT number shift (bias) in the central part of the image. While this bias is always present in images independent of the dose, it is more apparent in low-dose acquisitions.
3. FBP is a poor choice for poorly sampled or truncated data. This is also a reason that corrupt projections cannot be rejected from an FBP reconstruction.
4. FBP treats information from each ray equally — even those that are highly corrupted by noise. This equal treatment can cause streaks in reconstructed images.
5. FBP assumes ideal, noiseless data. The reconstruction filter amplifies projection noise proportional to the spatial resolution characteristics of the filter. In reconstructions targeted for high spatial resolution (sharp filter), the image noise levels reach unacceptable levels and make them suboptimal for low-contrast assessments. Hence, a compromise between spatial and low-contrast resolution exists.

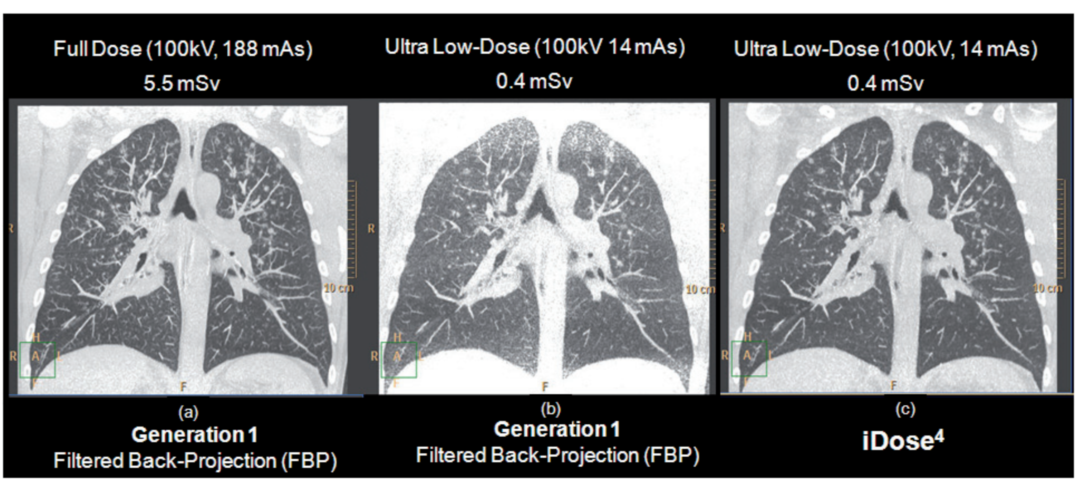


Figure 3: 1st Generation techniques (FBP) introduce artifacts and increased noise at ultra-low-dose acquisitions [Case Courtesy: UCL, Brussels].

2^{nd}-Generation Reconstruction: Image based denoising / filtering

As the optical efficiencies of CT scanners increased and the clinical community continued to pursue lower radiation doses and improved image quality, it became apparent that the limitations of 1^{st}-generation FBP techniques needed to be addressed. 2^{nd}-generation, image-based noise reduction techniques build upon FBP and attempt to overcome some of its limitations by applying corrections once an initial master image dataset has been created from the projection data. Using this "master dataset," noise reduction is applied and results in a final dataset with relatively lower noise. Recent 2^{nd}-generation implementations involve iterative noise reduction techniques [12, 13]. These techniques permit moderate dose reductions and remove some of the increased quantum mottle noise; however, these techniques are severely limited in their ability to reduce photon starvation artifacts, such as the streaks and image bias that commonly occur with aggressive dose reductions. Image-based artifact correction techniques may reduce the intensity of these artifacts; however, they are unable to reveal underlying clinical information. This inability to reveal information is due to the loss of that information during the process of reconstructing the initial master image dataset. In most cases, the artifacts are actually more apparent since the background noise is reduced while the artifacts are left unaffected given their characteristic similarity to anatomical information in the image domain.

Figure 4 demonstrates a clinical study performed at low dose (120 kVp, 70 mAs, Step & Shoot Complete) than would have historically been used to scan this particular obese patient (BMI =56.5 kg/cm^2). The resultant image quality from FBP with a typical reconstruction kernel (e.g., CC) demonstrates significant streak artifacts and quantum mottle noise that obscure the visualization of the underlying anatomical information (fig. 4a). FBP with a smoother reconstruction filter (e.g., CA) provides some amount of denoising by limiting high frequency noise — at the expense of reduced detail in the images; however, while quantum mottle noise is reduced (fig. 4b), the structured streaks are still present and they render the images non-diagnostic. In addition to the reduction in overall quantum mottle noise, image-based iterative noise-reduction techniques (fig. 4c) may reduce the intensity of streak artifacts by smoothing them; however, these techniques still do not reveal the underlying clinical information such as the sub-clavian vessels (orange arrowhead). Proper noise processing in the projection domain is required for preventing the manifestation of these artifacts in the reconstructed images. By synergistically performing iterative processing in both the projection and image domains, iDose[4] (fig. 4d) prevents streak artifacts, thus revealing the underlying anatomical information (green arrowhead).

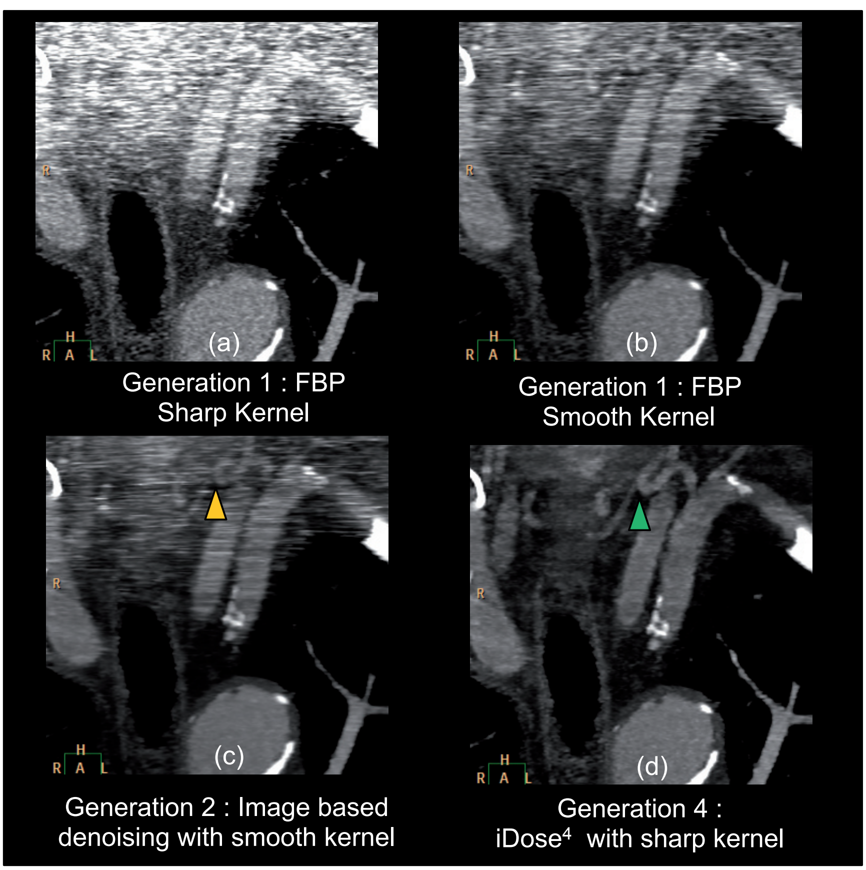


Figure 4: 2^{nd}-generation reconstruction techniques (image-based denoising) are unable to remove photon starvation artifacts, such as streaks and bias [Case Courtesy: Cleveland Clinic, USA]

3rd-Generation Reconstruction: Basic Iterative Reconstruction Techniques

The limitations of 2nd-generation reconstruction techniques (image based denoising) in overcoming low-dose streak and bias artifacts highlight that it is critical to address these artifacts in the projection domain. A common 3rd-generation technique uses an adaptive linear filter on very noisy projections in the projection domain in combination with noise models to reduce quantum mottle noise in the image domain. These 3rd-generation reconstruction techniques provided better reduction of streak artifacts and quantum mottle noise; however, these techniques result in (a) loss in spatial resolution (b) do not correct or prevent bias artifacts (c) shift in noise power spectrum.

To assess the contribution of the projection domain component in overcoming artifacts, tests of 3rd-generation reconstruction techniques were performed with low weighing of the image domain updates. Low-dose (120 kVp, 50 mAs) CT acquisitions were simulated on mathematical phantoms. Angular, high-attenuating signals from lateral projections caused by dense shoulders result in streak and bias artifacts. 3rd-generation reconstruction techniques (fig. 5b) demonstrated relative improvements in streak artifact reduction over previous generations (fig. 5a); however, they were unable to completely prevent the streak artifacts. The iDose4 reconstructions (fig. 5c) were completely free of streak artifacts, thus demonstrating that proper treatment of noise in the projection domain prevents such artifacts from ever manifesting in the reconstructed images. With the artifacts now prevented, the quantum mottle noise is now highly localized and may be removed in the image domain.

Although 3rd-generation reconstruction techniques may help to reduce streak artifacts to some extent, they are associated with a non-negligible loss in spatial resolution — particularly at the location of steep HU gradients, such as those at bone-soft-tissue or air-soft-tissue interfaces. This can be observed in subtraction images (result of 3rd-generation subtracted from an ideal, noiseless acquisition), where the presence of structural edges (fig. 6b) indicate a loss in spatial resolution caused by the reconstruction technique. From an algorithmic standpoint this occurs due to the adaptive linear filtering of noisy projections that reduces noise, but may also alter the sharp structural transitions associated with true anatomy.

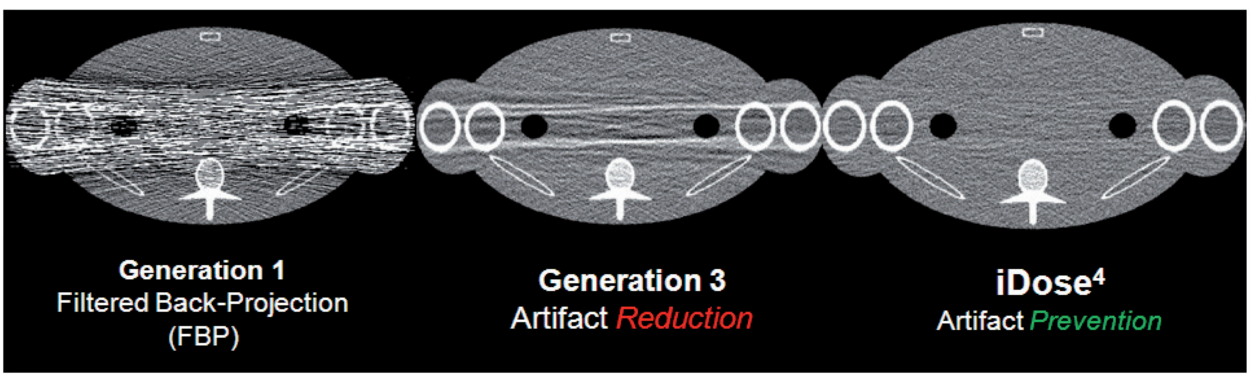


Figure 5: 3rd-generation reconstruction (basic iterative reconstruction technique) is unable to completely eliminate streak artifacts.

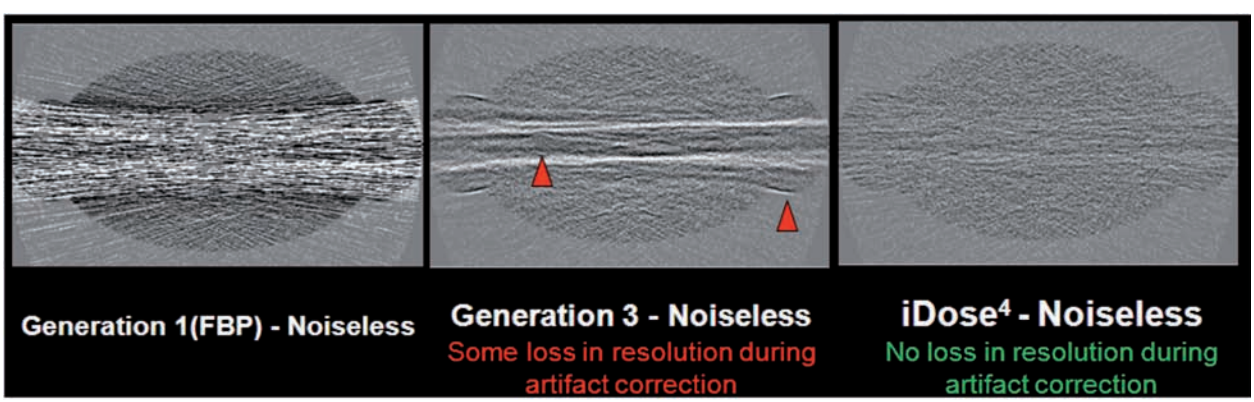


Figure 6: Generation 3 (basic iterative reconstruction technique) result in some loss in resolution.

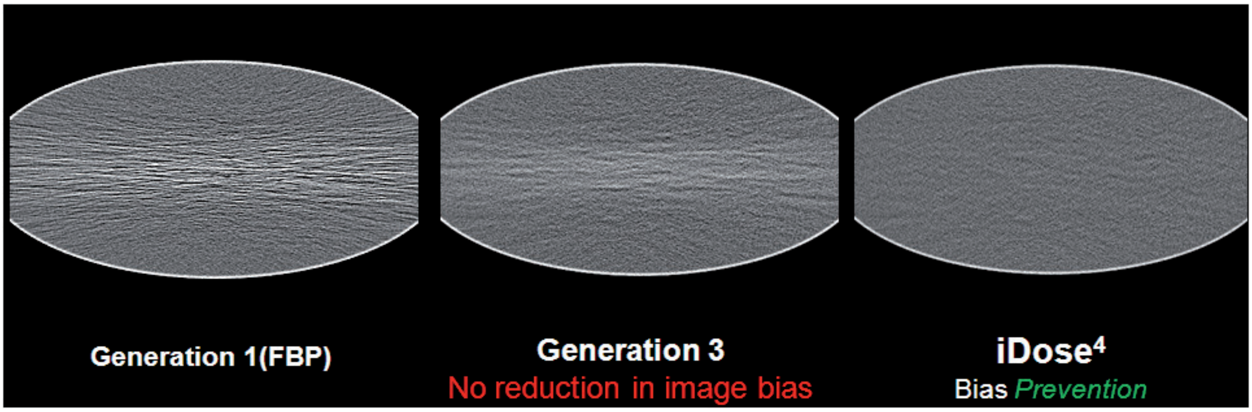


Figure 7: 3rd-generation reconstruction (basic iterative reconstruction technique) is unable to remove bias artifacts.

In addition to this potential reduction in spatial resolution, 3rd-generation techniques are unable to address bias artifacts since they do not explicitly account for the FBP logarithm function (see the section on 1st-generation reconstruction). From an algorithmic standpoint, this occurs when applying adaptive filtering on the line integrals in the log domain. Image bias can be observed in images as a shift in CT numbers towards the center of an image (fig. 7b).

Beyond the aforementioned limitations, another significant limitation of 3rd-generation reconstruction techniques is that they can markedly alter image texture — defined by the frequency of noise and commonly referred to as the "look and feel" of an image. Recent literature has questioned the clinical acceptance of images that exhibit a "plastic", "waxy", "blotchy", or "pixilated" texture.[14,15,16,17] Besides requiring a reader to adapt to the different image texture, there is concern that this texture may reduce diagnostic confidence or accuracy to an extent that depends on the degree of overlap between the spatial frequencies of the noise and the spatial frequencies of the abnormality of interest.[17] These problems have been reported to occur more frequently as the amount of "blending" or the "blending percentage" associated with the iterative reconstruction technique is increased.

Noise Power Spectrum (NPS) studies were performed to quantify the shift in the image texture resulting from different reconstruction techniques. The NPS quantifies the frequency distribution of quantum mottle noise in an image. Image quantum mottle noise is typically measured by placing a region-of-interest (ROI) and recording the standard deviation of HU within the ROI. This metric represents the sum of noise across all frequencies in the ROI, and it approximates the total noise in the image. Although two images may have the same total noise, the frequency distribution of the noise can be different — this distribution, also known as the NPS, is what characterizes the "look and feel" of an image. Details of the benchmark experiments performed are outlined in Appendix A. Those experiments concluded that 3rd-generation techniques can shift the NPS by as much as 19.4%, while iDose4 shifted the NPS by a maximum of 5.3% — an insignificant change — even at the maximum noise removal. This illustrates that 4th generation techniques, such as iDose4, preserve the image texture and "natural appearance" of images through better noise removal efficiency across the complete noise spectrum. From an algorithmic standpoint, this is achieved through edge-preserving, iterative processing and proprietary, 3D Multi-frequency correction techniques performed in both the projection and image domains.

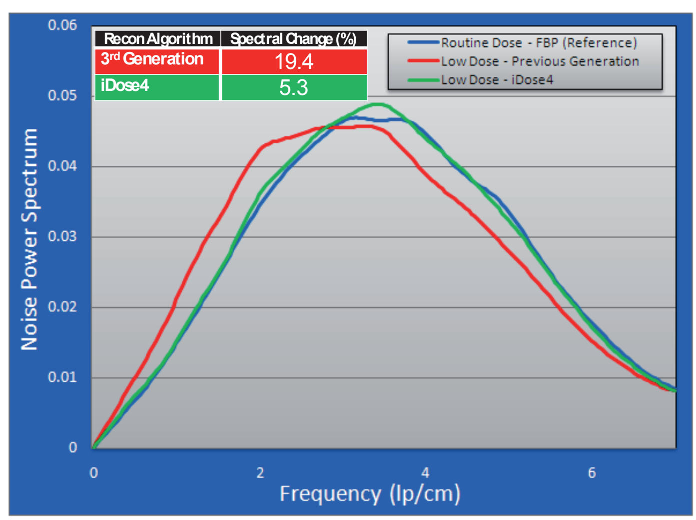


Figure 8: Noise power spectrum (NPS) of 3rd-and 4th generation reconstruction techniques relative to FBP NPS.

4th generation Reconstruction: iDose4 Iterative Reconstruction Technique

iDose4 is a 4th generation reconstruction technique that provides significant improvements in image quality and radiation dose reduction. The figure below (red: poor, yellow: mediocre, green: better) summarizes the previously discussed advantages of 4th generation reconstruction techniques in terms of artifact prevention and the efficiency of quantum mottle noise reduction across all frequencies.

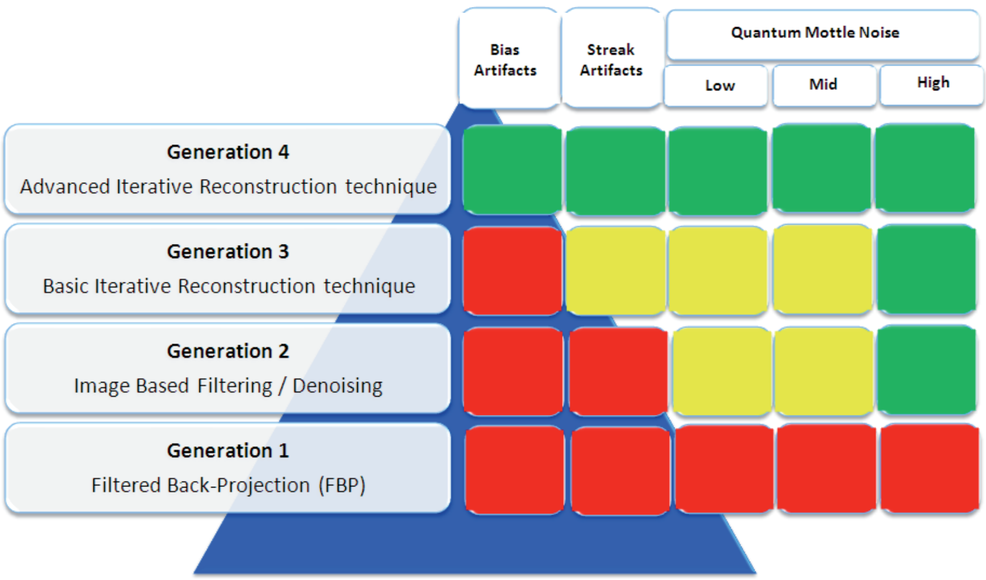


Figure 9: Summary of noise reduction and artifact prevention capabilities provided by each reconstruction generation.

Optimizing the implementation of iDose4 on the Philips CT scanner platforms has enabled the additional clinical benefit of being able to adapt the spatial resolution and dose reduction benefits to the specific clinical indication. For example, for pediatric imaging where radiation dose reduction is paramount, iDose4 enables significantly lower radiation dose while maintaining diagnostic image quality. In other cases, where image quality (e.g., spatial resolution) is of higher priority than the dose reduction, such as in the assessment of coronary stent patency, iDose4 enables significantly improved spatial resolution. Intermediate levels of dose reduction and spatial resolution improvement can be applied in combination for other clinical scenarios. Detailed experiments are outlined later in the Phantom Analysis section. Detailed clinical studies that evaluated these benefits are described in the Clinical Studies section. The following section provides an overview of the clinical applications of iDose4 illustrated through representative clinical examples.

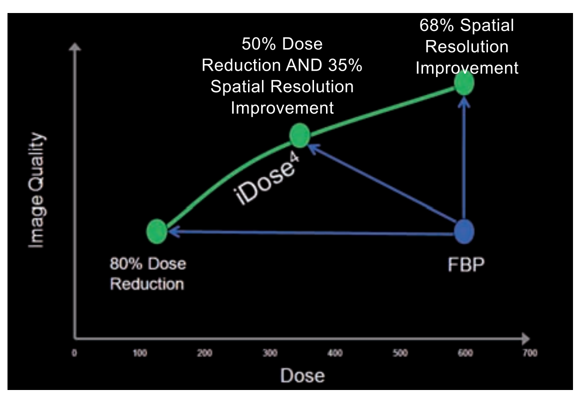


Figure 10: Adapting dose reduction and spatial resolution based on the clinical indication.

Up to 80% Dose Reduction

iDose⁴ enables significant dose reduction while preserving equivalent diagnostic image quality to a corresponding full dose scan (i.e., the lower-dose acquisition/ iDose⁴ reconstruction has similar noise, spatial resolution, low-contrast detectability, and NPS to a corresponding full-dose acquisition/ FBP reconstruction). Clinical evaluations demonstrate the capability of up to 80% dose reduction depending on the specific clinical protocol. Detailed clinical studies investigating maximum dose reduction achieved per clinical area are covered in the Clinical Studies section. Figure 11 demonstrates an example with 80% dose reduction for chest CTA while maintaining the diagnostic image quality.

The dose reduction benefits of iDose⁴ can be obtained in addition to those enabled by Philips' other DoseRight tools. The clinical example in Figure 12 demonstrates an ultra-low-dose, 0.25 mSv cardiac CTA enabled through the synergistic combination of several DoseRight tools: IntelliBeam Filters, SmartShape Filters, ClearRay Collimator, NanoPanel3D, Step&Shoot Cardiac, and iDose⁴. NanoPanel3D, Step&Shoot Complete and iDose⁴.

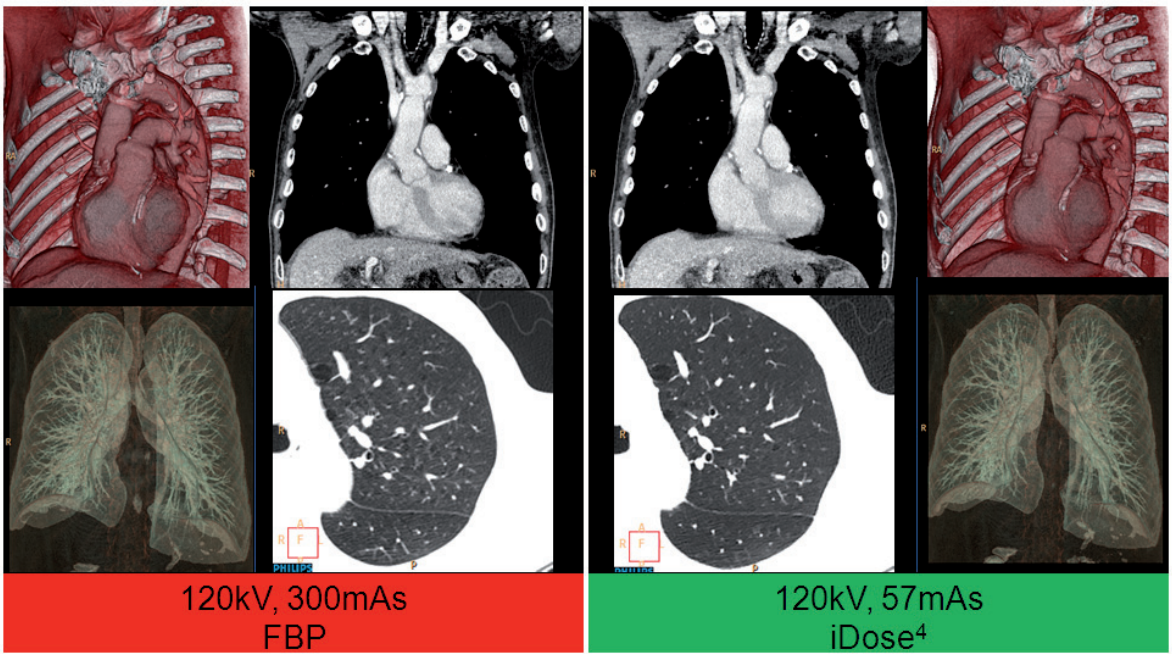


Figure 11: iDose⁴ enables up to 80% dose reduction while maintaining diagnostic image quality [Case Courtesy: AsahiKawa Hospital, Japan].

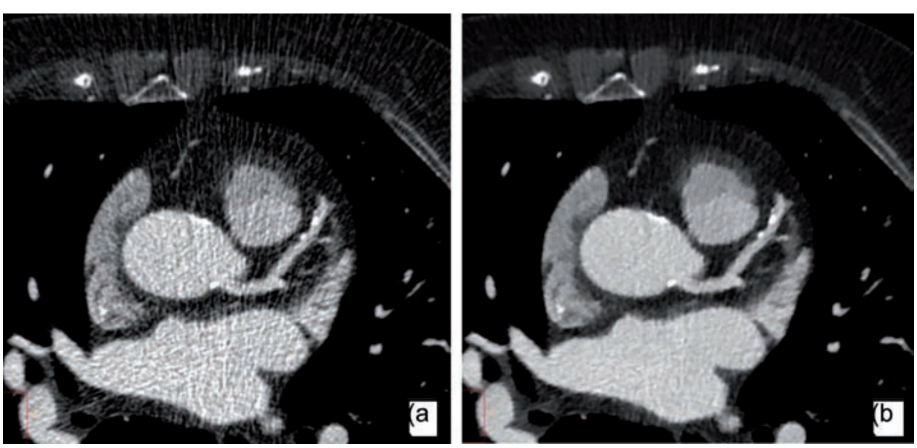
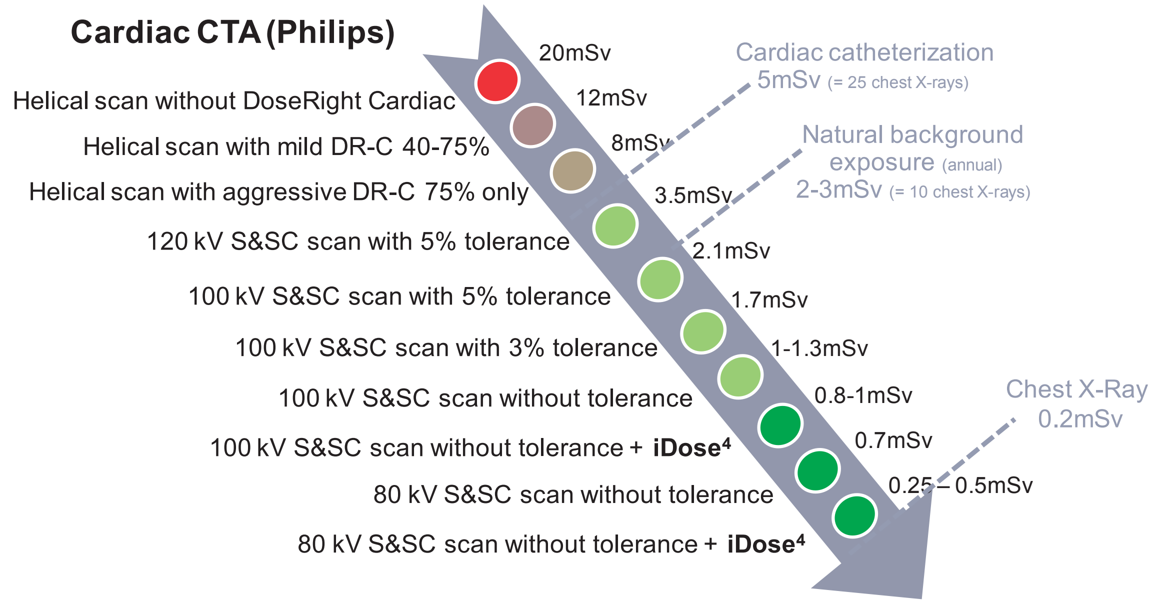


Figure 12: 0.25 mSv Cardiac CTA, 80 kVp, 80 mAs, 0.25 mSv, Step & Shoot Cardiac (a) FBP (b) iDose⁴ [Case Courtesy: Kunming University 2nd Affiliated Hospital, China].

The figure below illustrates the evolution of dose reduction technologies that have reduced the radiation dose associated with a typical cardiac CTA from approximately 20 mSv to less than 1 mSv in less than a decade.



Up to 68% Spatial Resolution Improvement

iDose4 can be used to significantly improve the spatial resolution of any acquisition, regardless of the dose with which it was acquired. iDose4 can be used to improve the spatial resolution (fig. 13a), the contrast-to-noise ratio (fig. 13b), or both beyond that which has been traditionally achievable. Detailed phantom studies demonstrate that, for routine dose acquisitions, the spatial resolution can be improved by up to 68%. These studies are detailed in the *Phantom Studies* section.

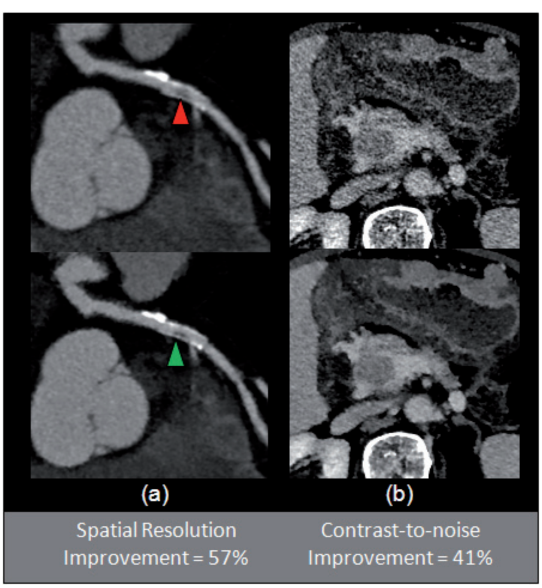


Figure 13: Image quality improvements (a) spatial resolution improvements providing improved assessment of in-stent restenosis (b) contrast-noise improvements [Case Courtesy: AsahiKawa Hospital, Japan].

Up to 50% dose reduction and Up to 35% improvement in spatial resolution

Routine clinical practice often requires the combination of dose reduction and image quality improvement benefits relative to routine-dose acquisitions and FBP reconstruction; hence, iDose[4] provides the functionality to combine these benefits in proportions best suited to the clinical indication. Figure 14 demonstrates a 45% dose reduction (86 mAs) combined with 29.9% contrast-to-noise ratio improvement, relative to the routine-dose (156 mAs) acquisition with FBP reconstruction.

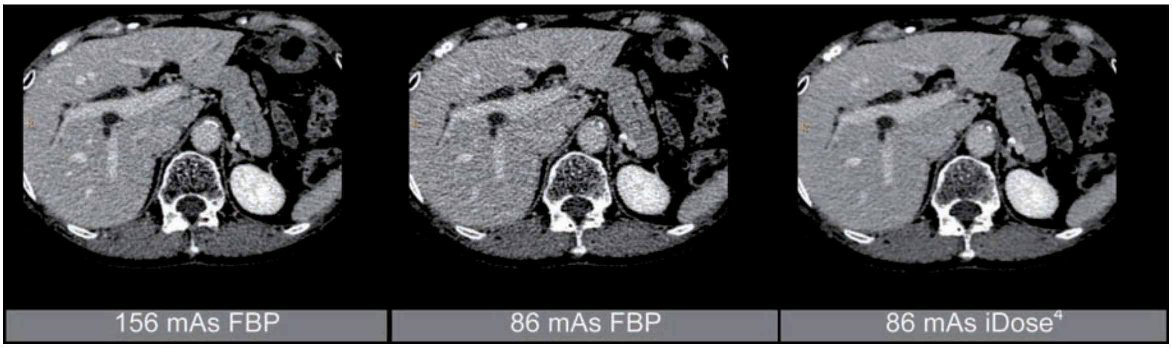


Figure 14: Combining dose reduction with image quality improvements [Case Courtesy: AsahiKawa Hospital, Japan].

Combining low-contrast and high spatial resolution characteristics

In FBP, the reconstruction filter amplifies any noise present in the projections proportional to the spatial resolution characteristics of the filter. High spatial resolution (sharp filter) reconstructions amplify image noise levels to clinically unacceptable levels and make them suboptimal for low-contrast assessments. Hence, the need to perform two reconstructions (i.e., soft filter (fig. 15a) and sharp filter (fig. 15b)). With iDose[4], the noise in sharp reconstructions can be maintained at a sufficiently low level to permit soft tissue (fig. 15c) and detailed, high-contrast assessment (fig. 15d) from a single reconstruction that provides improved image quality over either individual FBP reconstruction.

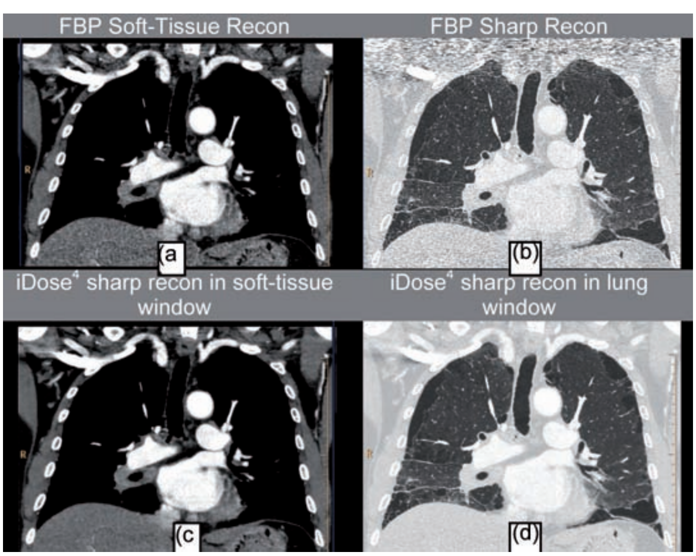


Figure 15: Iterative reconstruction technique capable of providing soft and sharp tissue structure [Case Courtesy: AsahiKawa Hospital, Japan].

Enabling increased effective tube power, faster acquisitions, or both

In tube-power-intensive acquisitions, such as those faced in imaging obese patients, the maximum power of a CT scanner tube may not be sufficient to provide the desired image quality for a given indication. The artifact prevention and noise reduction enabled through iDose[4], provides image quality that is equivalent to that associated with a significantly higher-dose acquisition without having to actually irradiate the patient with the higher dose. In such scenarios, the effective tube power is increased and can overcome either tube limits (e.g., bariatric imaging – fig. 16a) or skin dose concerns associated with higher-dose acquisitions (e.g., ER patients that may have their arms at their side – fig.16b).

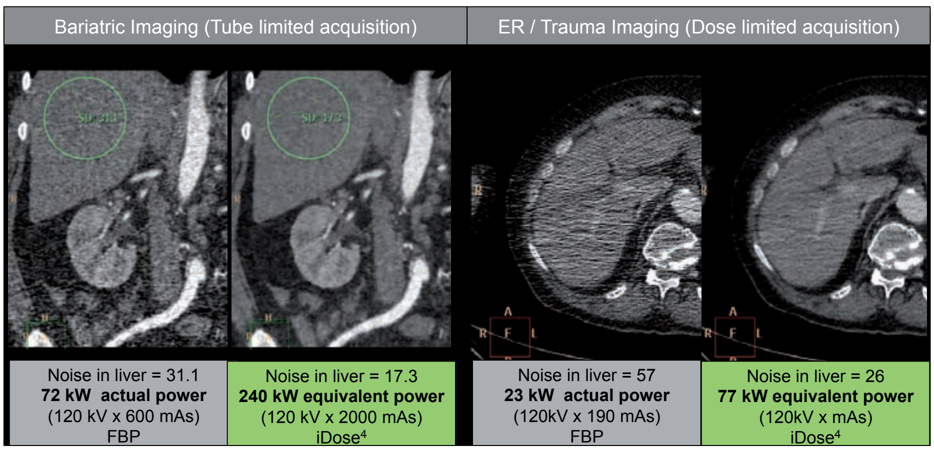


Figure 16: Increased effective power [Case Courtesy: (a) Pali Momi Medical Center, USA (b) Technical University of Munich, Germany].
Images reconstructed from the same scan data.

An additional practical limitation of tube-power-intensive acquisitions is the potential need to reduce the table speed to increase the dose per slice in order to obtain desired image quality. This limitation is eliminated through the ability of iDose[4] to lower power requirements (i.e., increase "effective power"). As illustrated in Figure 17, scan times for obese patients can be up to 50% longer without iDose[4]. In some cases, the increased scan times are not clinically practical (e.g., due to long breathhold times); however, the use of higher table speeds may result in the reduced image quality.

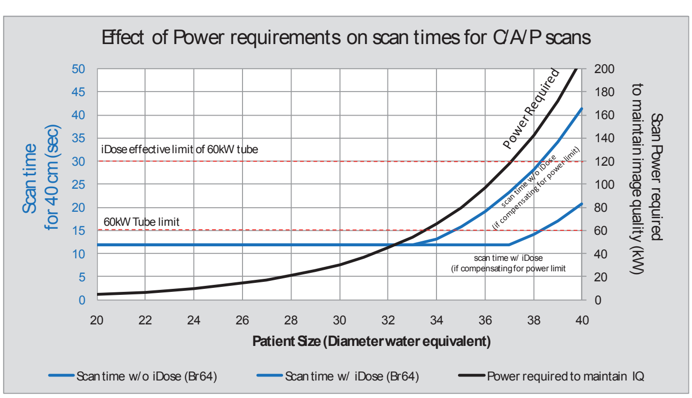


Figure 17: Improving effective tube power, enabling faster acquisitions, or both in tube power limitated acquisitions. The black curve indicates the power required so as to maintain constant overall noise independent of the patient size (this curve is a function of the x-axis and y-right-axis). The two blue curves represent the scan times required to perform a 40 cm long acquisition (this curve is a function of the x-axis and y-left axis). As can be observed, the blue curves start to rise when the "power required" exceeds the tube limit (in red).

iDose[4] algorithm description

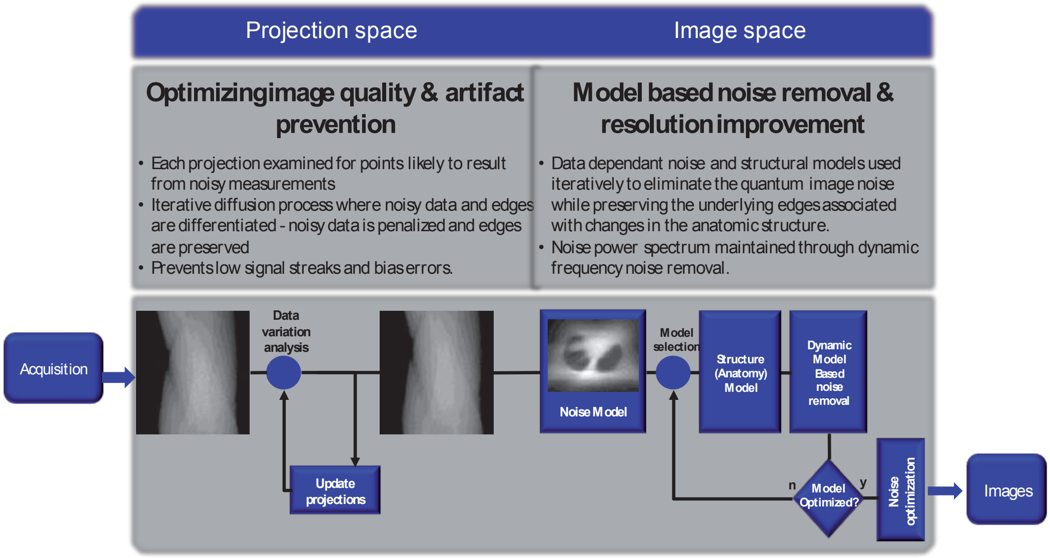
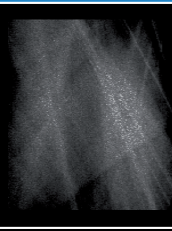
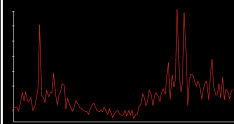
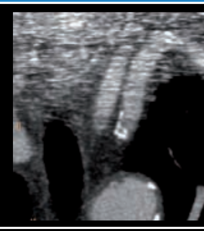
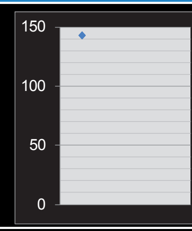
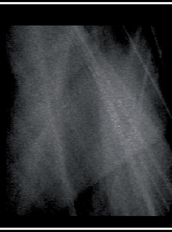
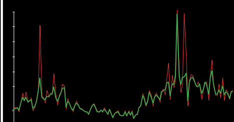
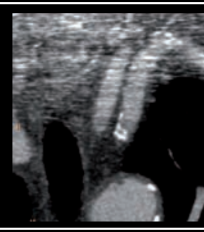
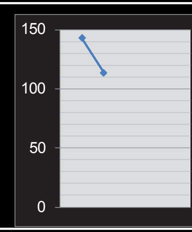
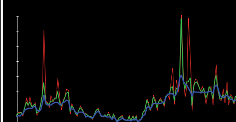
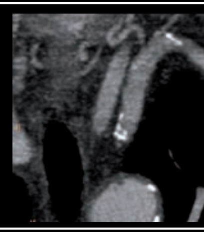
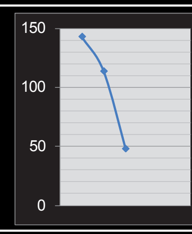
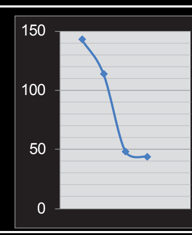
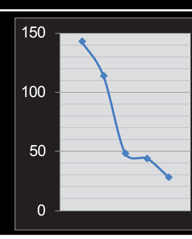


Figure 18: iDose[4] algorithm schematic.

iDose[4] provides an innovative solution in which iterative processing is performed in both the projection and image domains. The reconstruction algorithm starts first with projection data where it identifies and corrects the noisiest CT measurements – those with very poor signal to noise ratio, or very low photon counts. Each projection is examined for points that have likely resulted from very noisy measurements using a model that includes the true photons statistics. Through an iterative diffusion process, the noisy data is penalized and edges are preserved. This process ensures that the gradients of underlying structures are retained, thus preserving spatial resolution while allowing a significant noise reduction. In doing so, this process prevents the primary cause of low signal streaks. Also, since the corrections are performed on the acquisition data (unlogged projections); this method successfully prevents bias error. The noise that remains after this stage of the algorithm is propagated to the image space; however, the propagated noise is now highly localized and can be effectively removed to support the desired level of dose reduction. The next major component of the iDose[4] algorithm deals with subtraction of the image noise while preserving the underlying edges associated with true anatomy or pathology. This subtraction begins with an estimate of the noise distribution in the image volume. This estimate is used to reduce the noise while preserving the true structure. This estimate also allows the preservation of the image noise power-spectrum characteristic of a higher-dose acquisition and FBP reconstruction. Following this, a selector chooses among noiseless structural models, and the model that best fits the local topology of the image volume is chosen. Once the best model is chosen, it is used to reduce the noise in the image volume. To ensure uniform noise removal at all frequencies, multi-frequency noise removal is performed. The simplified schematic below demonstrates the effect of the various algorithm stages on the image quality.

Step-by-Step evolution of the image through the iterative algorithm stages

iDose⁴ process	Projection space update	Projection Signal	Image domain update	Image Noise (measured in carotid)
Original projection data		 Red		
Variation analysis of projection data				
1^{st} Update of projection data		 Green		
Variation analysis of projection data				
n^{th} Update of projection data		 Blue		
Parameter optimization and noise modeling				
1^{st} Update of image (subtraction of noise while validating against structure model)				
Analysis of model update				
n^{th} Update of image (subtraction of noise while validating against structure model)				

Note: The total number of iterations is greater than demonstrated in the simplified schematic above. [Case Courtesy: Cleveland Clinic, USA].

Phantom Analysis

Quantitative image quality metrics (low-contrast, spatial resolution, image noise) were assessed on phantoms to assess the impact of iDose[4] on the following aspects:

- Significant dose reduction while maintaining quantitative image quality metrics
- Moderate dose reduction with substantial improvements in image quality metrics
- Routine dose acquisitions with significant improvements in image quality metrics

Phantom studies presented in this section are a subset of the overall investigations performed that have been specifically selected to provide some representative examples. In order to capture test results on a wide range of clinical areas, the following tests were performed:

Quantitative Image Quality Metrics	Clinical Protocol	Test Target
Spatial resolution, Noise	Chest/Abdomen/Pelvis (Std Res, High Res)	Spatial resolution improvements enabled by iDose[4] combined with higher-resolution acquisition/reconstruction while maintaining the noise. Impact of dose reduction.
Spatial resolution, Noise	Head (Ultra-high Res)	Maintaining spatial resolution independent of the iDose[4] aggressiveness.
Low-contrast detectability, Noise	Cardiac CTA (Std Res)	Contrast/noise improvements with iDose[4]. Impact of dose reduction.

Spatial resolution tests:

CT acquisitions of the CATPHAN phantom (Catphan 600, The Phantom Laboratory) were performed on the Ingenuity CT scanner. Reference acquisitions were performed using a routine-dose Chest/Abdomen/Pelvis protocol (64 x 0.625, 300 mAs, 120 kVp, rotation time: 0.5 s, pitch: 0.6, FOV: 250 mm, slice thickness: 1 mm) and were reconstructed using standard FBP. Additional high-resolution acquisitions were performed at multiple dose reduction levels (0%: 300 mAs, 50%: 150 mAs & 80%: 60 mAs, dose reduction relative to reference) with all other acquisition parameters maintained. iDose[4] reconstructions were performed on the high-resolution acquisitions taking into account the increase in noise from the lower dose acquisition and increased spatial resolution acquisitions/kernels, such that the noise was matched between the reference routine dose FBP and iDose[4] recons. The spatial resolution was assessed from the modulation transfer function at 50% ($MTF_{50\%}$) of the bead in the high-resolution module of the phantom. Note that while $MTF_{cut\text{-}off}$ is frequently reported, it is less deterministic of the spatial resolution that is visually appreciated in an image. Image noise was measured for all reconstructions in a 100 mm^2 region-of-interest (ROI).

	Routine Dose		50% Dose reduction		80% Dose reduction	
mAs (CTDIvol)	300 mAs (17.7 mGy)	300mAs (17.7 mGy)	300mAs (17.7 mGy)	150mAs (8.8 mGy)	300mAs (17.7 mGy)	60mAs (3.5 mGy)
Resolution Matrix	Std 512^2	High 768^2	Std 512^2	High 512^2	Std 512^2	High 512^2
Recon	FBP	iDose[4] L7	FBP	iDose[4] L7	FBP	iDose[4] L7
Filter	C	C, IE 0.25	C	C	C	B
Noise	10.4	10.2	10.4	10.4	10.4	11.1
$MTF_{50\%}$	3.1	5.2	3.1	4.2	3.1	3.6
Conclusion	68% spatial resolution (@50% MTF) improvement on iDose[4] recon without noise increase		35% spatial resolution improvement on iDose[4] recon without noise increase		16% spatial resolution improvement on iDose[4] recon with small noise increase	

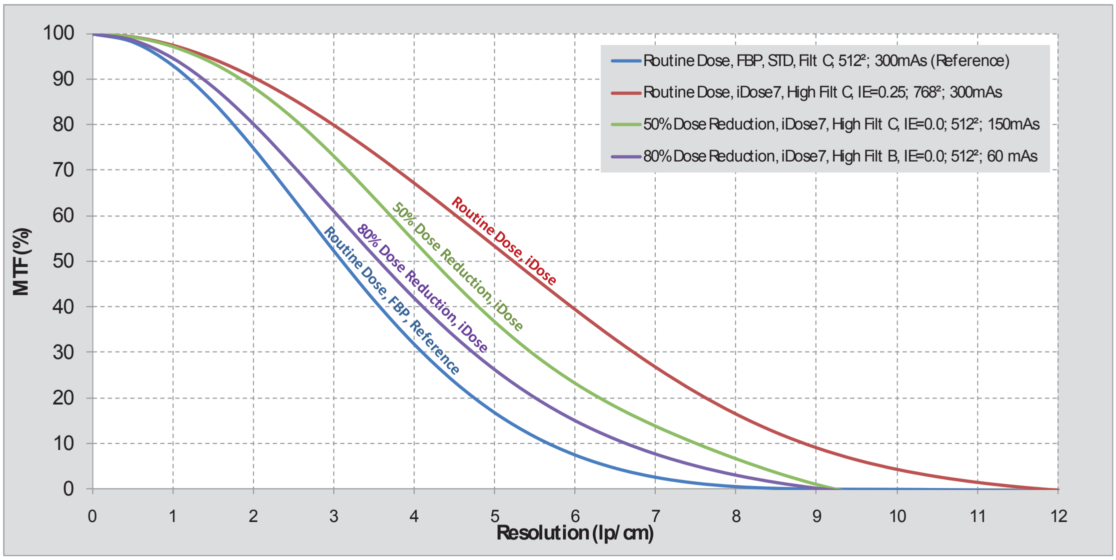


Figure 19: MTF plots demonstrating (a) 68% spatial resolution improvements at routine dose (b) 35% spatial resolution improvements at 50% dose (c) 16% spatial resolution improvements at 20% dose.

A key component of the iDose⁴ algorithm is that spatial resolution is preserved among the different strengths (levels) of iDose⁴. The CATPHAN phantom was scanned using an ultra-high-resolution head protocol at 800 mAs (120 kVp: 64x0.625 mm, pitch: 0.6, rotation time: 0.5 s, YF kernel) on a Brilliance 64-channel with Essence technology. The data was reconstructed using FBP, iDose⁴ level 1. Qualitative MTF assessments were performed on the line-pair section by two independent readers blinded to the reconstruction technique. Quantitative MTF measurements for $MTF_{50\%}$ and $MTF_{10\%}$ were performed on the tungsten bead in the high-resolution section of the phantom. As can be observed, $MTF_{50\%}$ and $MTF_{10\%}$ were maintained independently of the iDose⁴ aggressiveness. These results agreed with those observed from the qualitative assessments.

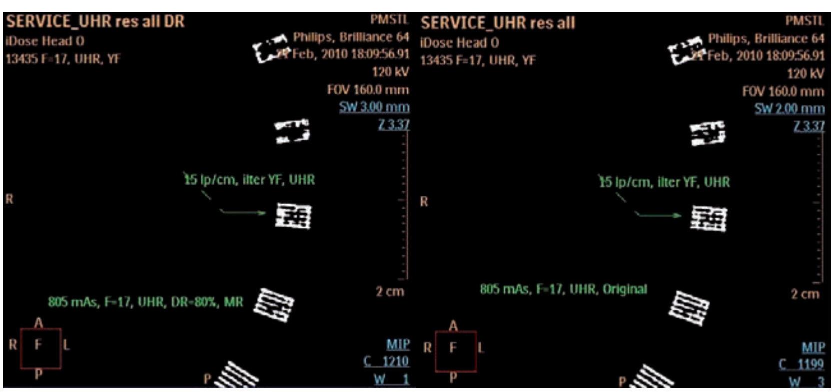


Figure 20: Line-pair phantom demonstrating equivalent spatial-resolution independent of iDose⁴ level.

Reconstruction technique	$MTF_{50\%}$	$MTF_{10\%}$	Cutoff
iDose⁴ Level1	11	15	17
iDose⁴ Level4	11	15	17
iDose⁴ Level7	11	14.5	16.5

Low-contrast resolution tests:

CT acquisitions of the CATPHAN phantom were performed on a Brilliance 64-channel with Essence technology. Acquisitions were performed using a routine-dose cardiac CTA protocol (600 mAs, 120 kVp, rotation time: 0.4 s, pitch: 0.2, FOV: 220 mm) and multiple lower doses (30% and 50% dose reduction). Objective assessments of low-contrast resolution were performed on 10 mm slices. Image noise and CT numbers were measured in all reconstructions in a region-of interest placed in the 15 mm 1% contrast pin and the background. The contrast-to-noise (CNR) was computed as:

$$CNR = \frac{HU(contrast\ pin) - HU(background)}{[Noise(contrast\ pin) + Noise\ (background)]\ /2}$$

	Clinical Goal					
	Routine Dose with IQ improvements		30% Dose reduction with IQ improvements		Up to 50% Dose reduction with no loss in IQ	
Dose	600mAs	600mAs	600mAs	420mAs	600mAs	300mAs
Recon	FBP	iDose⁴ L7	FBP	iDose⁴ L7	FBP	iDose⁴ L4
Kernel	CA	CA	CA	CA	CA	CA
Noise	1.6	0.7	1.6	0.9	1.6	1.6
CNR	5.1	10.4	5.1	9.1	5.1	5.2
Conclusion	Routine dose FBP has 51% lower CNR than routine dose iDose⁴		Routine dose FBP has 44% lower CNR than 30% lower dose iDose⁴		Routine dose FBP has equivalent CNR as 50% lower dose iDose⁴	

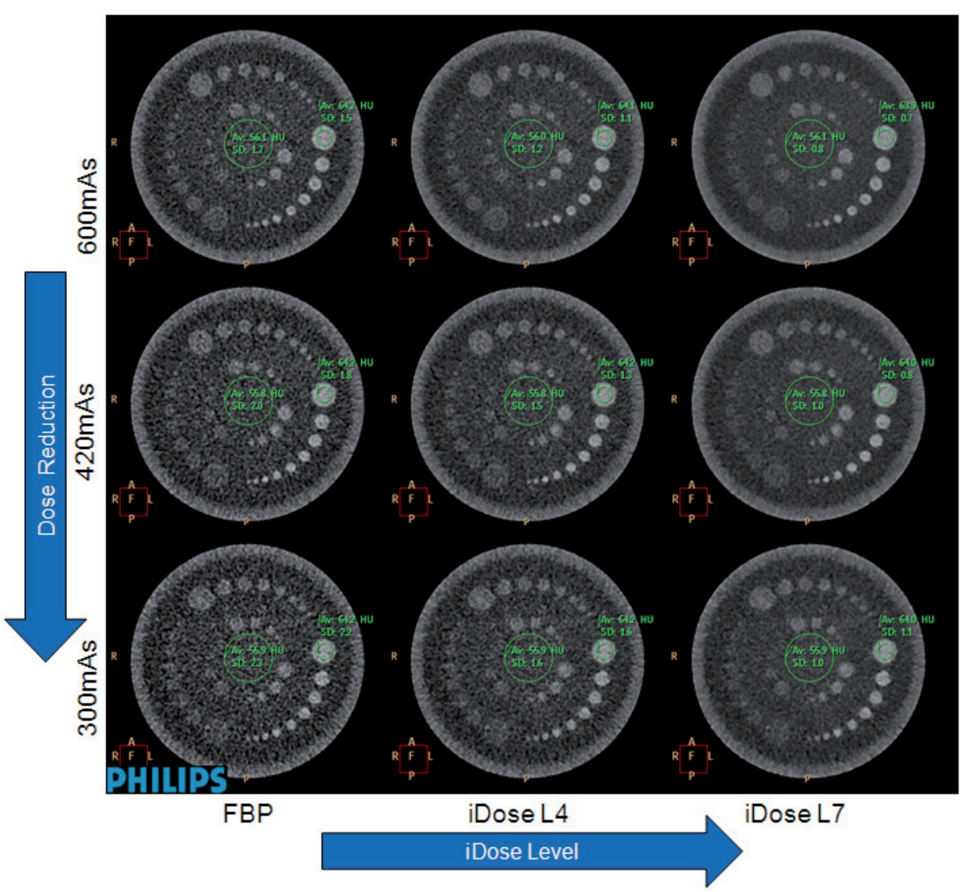


Figure 21: Contrast/Noise Measurements as a fucntion of dose reduction and iDose⁴ levels.

iDose[4] dose reduction support

The plot in Figure 21 is from a set of graphs that indicate the potential for dose reduction when using iDose[4]. These graphs may be used in conjunction with other clinical criteria and when working closely with a physicist or application support personnel. The graphs are based on rigorous phantom studies performed using the CATPHAN phantom. Expansion rings and mathematical techniques were used to account for variations in patient size & anatomy (adult head, adult body, pediatric head, and pediatric body). Image quality was assessed at 40 different tube current-time-products (25 – 1500 mAs) for each scan type. For a given mAs setting (x-axis) used with FBP, the y-value of the curve represents a bound for mAs reduction with iDose[4], that maintains image quality on a CATPHAN relative to a full-mAs scan with FBP, according to the following acceptance criteria. Decrease in low-contrast resolution less than 1 mm, change in noise less than 10%, and decrease in spatial resolution is less than 10% at $MTF_{50\%}$ and $MTF_{10\%}$.

The graph in Figure 22 is for an average-size adult (70 kg, average water equivalent diameter of 30.5 cm) and simulates a routine abdominal scan. Two additional curves are shown to illustrate the process of decreasing mAs in incremental steps. For example, if 200 mAs was the starting tube current-time-product, an incremental dose reduction strategy on the CATPHAN (vertical arrow) with iDose[4] could be to lower the mAs to 185 (Conservative), then to 145 (Moderate), with a lower bound of 115 mAs (Aggressive). The range of mAs settings from 200 to 115 indicates a range of mAs settings that are hypothesized to maintain image quality according to the aforementioned acceptance criteria.

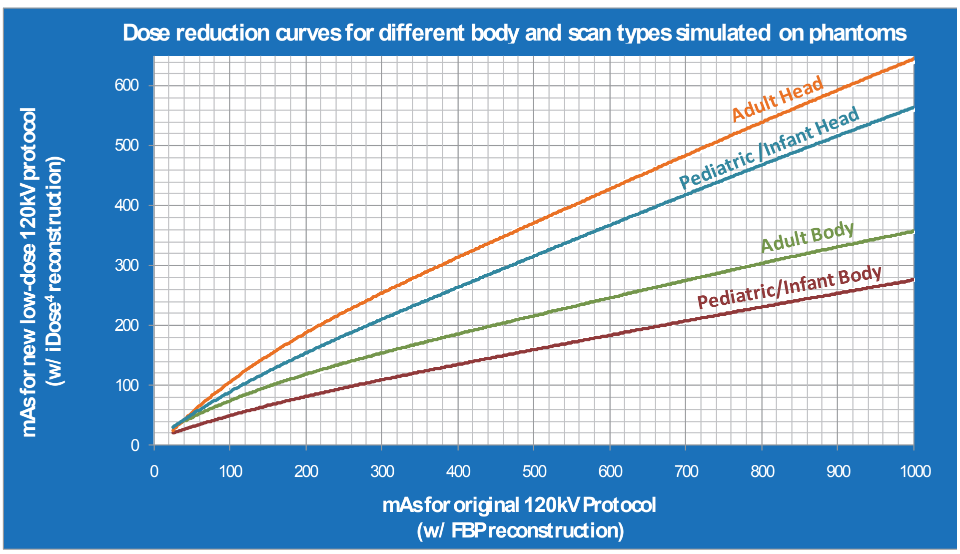


Figure 21: Dose (tube current) reduction curves for different scan types.

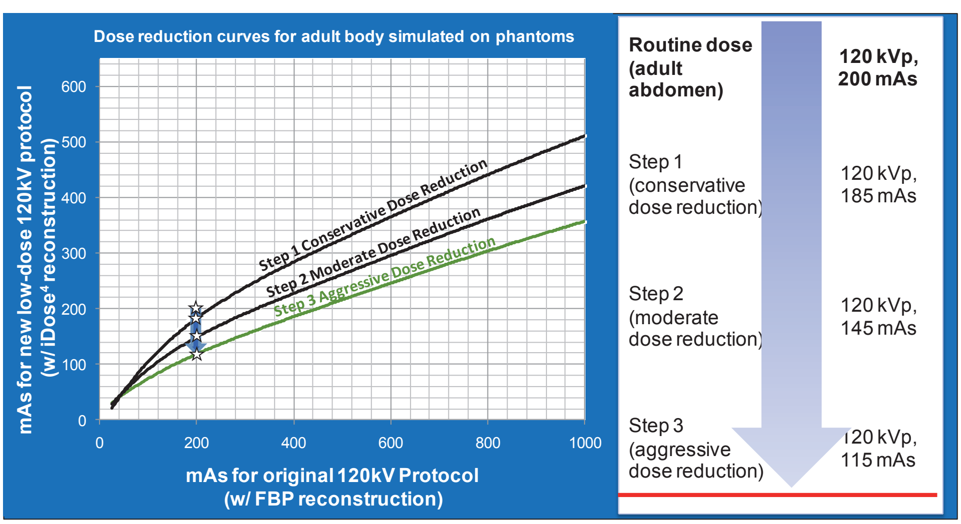


Figure 22: Incremental dose (tube current) reduction steps (for adult phantom using body protocol).

Workflow

iDose^4 reconstruction is triggered by changing the reconstruction type from "standard" (FBP) to "iDose". iDose^4 reconstruction can be either selected prospectively (before the scan) or performed retrospectively on datasets for which the projection (raw) data is still available on the scanner. Scan protocols may utilize iDose^4 by default.

An additional parameter - iDose^4 level (scale: 1-7) is used to define the strength of the iterative reconstruction technique in reducing image quantum mottle noise (range 11% -55% noise reduction relative to a corresponding FBP reconstruction). The level can be defined independent of the radiation dose with which an acquisition is performed. This allows targeting the application of iDose^4 to a clinical target (dose reduction, IQ improvement, or combined dose-reduction with IQ improvement).

Figure 23 summarizes the net change in image quality (quantum mottle noise) as a function of dose reduction and/or iDose^4 level combinations. The relevant multiplication factor from the table may be applied to the noise obtained from an acquisition to estimate the change if dose reduction and/or a certain iDose^4 level is applied. The vertical axis defines the change in image noise as a function of the dose reduction, relative to the higher dose acquisition with FBP. For example, if a 30% dose (mAs) reduction is planned with no change to the reconstruction technique, the increase in noise can be estimated by multiplying 1.2 (20% increase) to the image noise obtained if no dose reduction is applied. The horizontal axis defines the change in noise as a function of the iDose^4 level, relative to noise obtained from FBP reconstruction of the same acquisition. For example, if an iDose^4 level 2 is applied with no change in dose, then the noise can be estimated by multiplying 0.84x (16% decrease) to the image noise obtained if reconstructed with FBP. Increasing levels of iDose^4 indicate a greater strength of noise removal (level 1=11%, 2=16%, 3=23%, 4=29%, 5=37%, 6=45%, 7=55%). The choice of the appropriate iDose^4 level depends on the clinical goal; dose reduction, IQ improvement, or a combination of both. iDose^4 can be used to lower the radiation dose while maintaining approximately the average image noise levels. These setting are represented along the diagonal where each cell has a net noise factor of 1.0. A dose reduction of 50% without iDose^4 would result in a noise increase by a factor of 1.41; however, when used with an iDose level of 4 (on the diagonal), noise would be reduced by a compensatory factor of 0.71 (=1/1.41). This net noise factor of 1.0 implies approximate noise level equivalency between the low-dose iDose images and the routine, higher dose FBP results. Using iDose^4 levels higher than required to compensate for the relevant noise increase from dose reduction (if any) can be used for imaging parameter improvements. This can be realized either through the additional noise reduction which

	iDose level	0	1	2	3	4	5	6	7
Dose Change %	noise decrease with iDose (mult. factor): / noise increase w/ dose reduction as mult.factor	1.0	.89	.84	.78	.71	.63	.55	.45
		change with iDose relative to noise in lower dose FBP; Net Change in Noise (mult. factor) change relative to noise at higher dose FBP							
-0	1.00	**1.0**	.89	.84	.78	.71	.63	.55	.45
-20	1.12 (=1/.89)	1.12	**1.0**	.93	.87	.79	.71	.61	.50
-30	1.20 (=1/.84) change relative to noise at higher, original dose FBP	1.20	1.07	**1.0**	.93	.84	.76	.65	.53
-40	1.29 (=1/.78)	1.29	1.15	1.08	**1.0**	.91	.82	.71	.58
-50	1.41 (=1/.71)	1.41	1.25	1.18	1.10	**1.0**	.89	.77	.63
-60	1.58 (=1/.63)	1.58	1.41	1.33	1.23	1.12	**1.0**	.87	.71
-70	1.83 (=1/.55)	1.83	1.63	1.54	1.43	1.30	1.15	**1.0**	.82
-80	2.24 (=1/.45)	2.24	1.99	1.88	1.75	1.59	1.41	1.23	**1.0**

Figure 23: Net change in noise as a function of dose reduction and/or iDose^4 level.

translates to increased CNR. Alternatively, this additional noise reduction can open up opportunities for use of sharper acquisition/ reconstruction techniques. Since artifact prevention occurs before image creation, the extent of artifact prevention is uniform across all levels. The net change in noise outlined in the table does not take into account changes resulting from artifact removal.

Figure 24 shows a clinical example of how iDose^4 can help reduce dose and/or reduce image noise. The baseline acquisition (fig. 24a) performed at 175mAs and reconstructed with FBP, had an average image noise of 20.4 (measured in the bladder). When the same patient was scanned at 87mAs (50% dose reduction) using FBP, the noise is expected to increase by a factor of about 1.41 (fig. 23) relative to the baseline acquisition. This yields an estimated noise level of 20.4 x 1.41=28.8 HU. By comparison, the noise measured with an ROI was 27.8 HU (fig. 24e).

When applying an iDose^4 level 4 to the low-dose acquisition, the net noise is expected to change by a factor of 1.0, i.e. level 4 compensates for the noise increase associated with a 50% dose reduction. Thus, the expected noise level is 20.4 x 1 = 20.4 HU, and the measured noise (fig. 24f) was 19 HU.
Noise levels can be reduced further by using an iDose^4 level higher than that required to compensate for the noise increase associated with a given dose reduction. For example, when applying iDose^4 level 6 (instead of level 4), the estimated net noise factor is 0.77 - resulting in an estimated noise of 20.4 x 0.77 = 15.7 HU. The measured noise (fig. 24g) was 14.6 HU. This additional noise reduction provides an estimated 29.9% improvement in the contrast-to-noise ratio. Alternatively, it can enable increased spatial resolution (fig. 24h) through the use of higher spatial resolution techniques (e.g., filters, matrix, focal spot size, etc.) while maintaining image noise approximately the same as that present in the baseline acquisition [noise(baseline-dose + FBP) = 20.4 HU , noise(low-dose + iDose^4 level6 + sharp-filter) = 19 HU]. iDose^4 may be used for improvement in CNR (fig 24a, 24c) or spatial resolution (fig 24d) even when dose reduction is not performed. This may be particularly useful

in inherently noisy acquisitions, such as imaging obese patients. The table below summarizes the use of the net noise change multiplication factor (from fig. 24).

Dose (mAs)	Reconstruction	Estimated Noise Per Table (HU)	Measured Noise from Images (HU)
175mAs	FBP	N/A	20.4
175mAs	iDose[4] Level4	(0.71 x 20.4) = 14.5	14.2
175mAs	iDose[4] Level6	(0.55 x 20.4) = 11.2	10.9
87mAs	FBP	(1.41 x 20.4) = 28.8	27.8
87mAs	iDose[4] Level4	(1.00 x 20.4) = 20.4	19
87mAs	iDose[4] Level6	(0.77 x 20.4) = 15.7	14.6

The dose-reduction / image quality benefits for the clinical example in Figure 24 can be summarized as below:

	Conventional scan	Dose Saving with CNR equivalent to conventional scan	CNR boosting with no dose reduction	Dose Saving + CNR improvement
Dose	120 kVp 175 mAs	120 kVp, 87 mAs 50% dose reduction	120 kVp, 175 mAs	120 kVp, 87 mAs 50% dose reduction
Image Quality	Conventional	Conventional	Improved CNR Increase = 81.8% OR Spatial resolution improvement	Improved CNR Increase = 29.9% OR Spatial resolution improvement
Recon	FBP	iDose[4] level 4	iDose[4] level 6	iDose[4] level 6

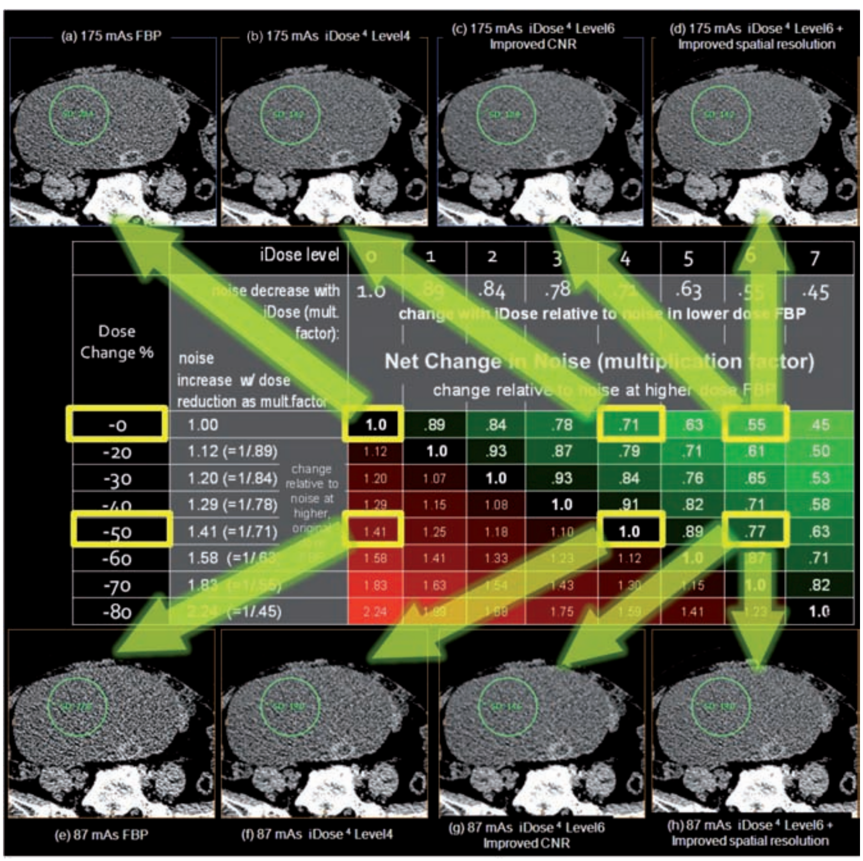


Figure 24: Example illustrating the use of iDose[4] for dose reduction and/or image quality improvements.

Reconstructor Hardware Performance

iDose[4] is a sophisticated and complex reconstruction algorithm that demands enormous computational power. The interaction of information between the projection and image domains requires the support of elegant software and hardware architectures. Running iDose[4] on the prior generation of reconstruction hardware (RapidView) would result in clinically unacceptable reconstruction times.

The RapidView IR reconstruction engine was designed from the ground up to benefit from not only higher performance computational cores but also the number of cores. The architecture is highly parallel and the design enables the reconstructor to scale with the latest multiple-core processors and state-of-the-art massively parallel, high-density computing devices. The high-density computing device on RapidView IR processes and transfers huge amounts of data. The latest-generation PCI express bus offers substantially higher I/O bandwidth, and Intel 6-core processors are utilized to address the additional computing requirements. As a result, the new Philips RapidView IR reconstructor is able to deliver exceptional reconstruction performance with iDose[4], thus providing reconstruction speeds similar to those previously achievable with FBP on conventional reconstructors. An additional benefit of the RapidView IR is that FBP reconstruction speeds on this enhanced hardware are significantly higher than previously achievable. The chart below provides a comparison of reconstruction speeds for FBP and iDose[4] on each hardware platform.

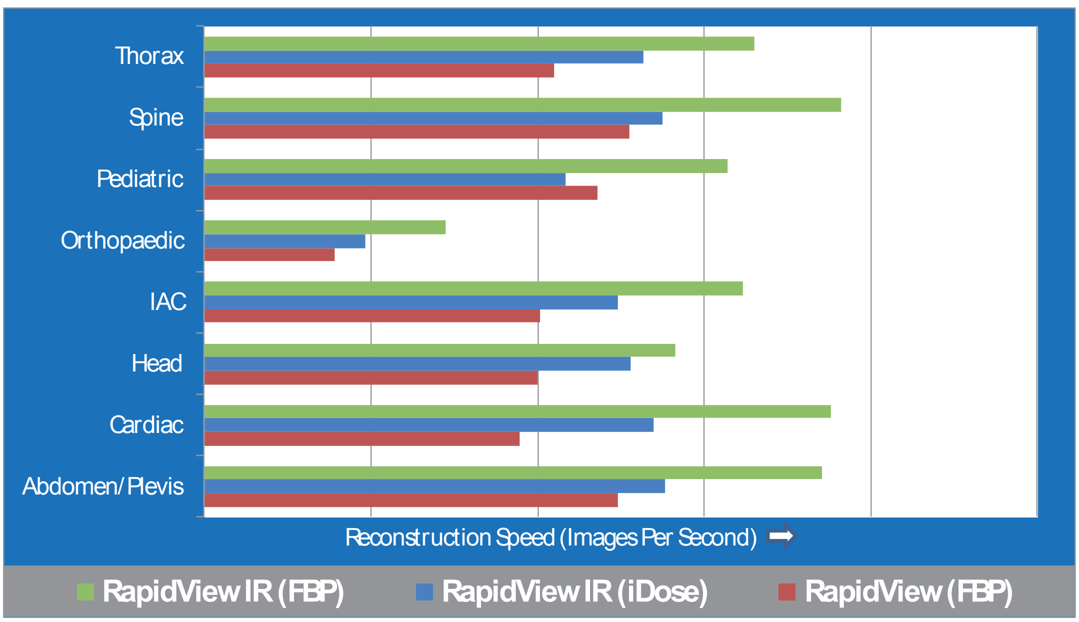


Figure 25: Reconstruction speeds of FBP and iDose[4] on conventional (Rapidview) and enhanced (RapidView IR) reconstructors.

Clinical Evaluation

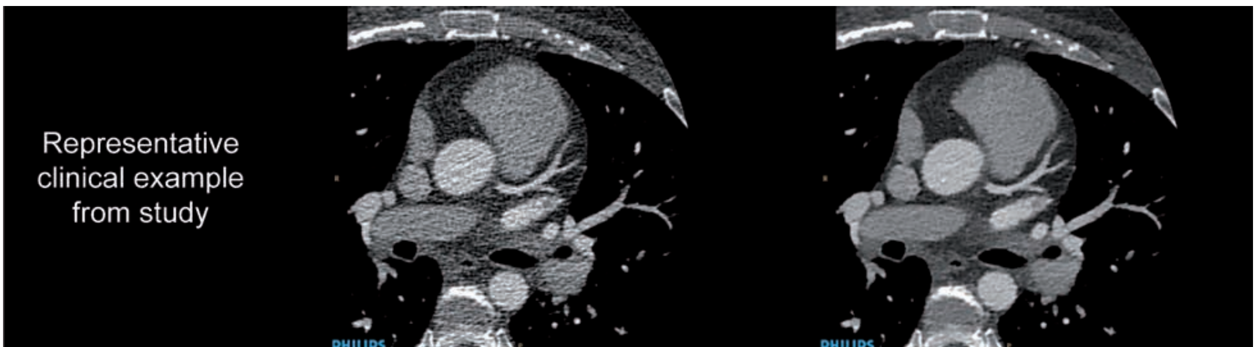
iDose^{4} target	Dose reduction		Low-dose and improved image CNR		Improved image quality
	Non-contrast Brain (Phantom + Cadaver) 50% DR Shenjing Univ Study F.1 (pg 32)				
	Non-contrast Brain 50% DR Huashan Hospital Study F.2 (pg 32)	Head & Neck CTA 60% DR Huashan Hospital Study F.3 (pg 33)			
	Chest CTA (dual) 80% DR AsahiKawa Hospital Study B.12(pg 26)		Aortic CTA Low Dose Artifacts reduced, Diag conf inc CCF Study B.1 (pg 26)		
	Cardiac CTA (Phantom) 70% DR Shengjing Univ Study A.6 (pg 24)	Pediatric Cardiac CTA 70% DR Gd General Hospital Study A.1 (pg 22)	Cardiac CTA IQ improved on low-dose NEUSS Study A.3 (pg 23)	80kV Cardiac CTA CNR improved Kumamoto Univ Study A.4 (pg 23)	Bariatric Cardiac CTA IQ improved, diag conf inc OHSU Study A.1 (pg 22)
	Cardiac CTA 70% DR Shengjing Univ Study A.5 (pg 24)		Pediatric Cardiac CTA IQ improved, potential for DR OHSU Study H.1 (pg 35)		Cardiac CTA IQ improved, TJUH Study A.2(pg 22)
					Cardiac CTA IQ improved for calcium blooming Lenox Hill Study A.7 (pg 25)
		Routine Chest Low Dose IQ improved, diag conf inc Lyon Study C.2 (pg 27)			
			Routine Chest Low Dose IQ improved, diag conf inc La Pitie Study C.1 (pg 27)		
	80kV 4-phase Liver 80% DR Asahikawa Study E.4 (pg 31)	Contrast Abdomen 50% DR Shengjing Univ Study E.1 (pg 30)	Routine Abdomen (phantom) 50% DR AsahiKawa Hospital Study D.2 (pg 28)		Pediatric contrast abdomen IQ Improve Oakland Children Study H.2 (pg 35)
	Routine C/A/P 66% DR UMMC Study D.1 (pg 28)	Contrast Abdomen (dual) 50% DR Shengjing Univ Study E.2 (pg 30)	Routine Abdomen 50% DR Shengjing Univ Study D.3 (pg 29)		
	Routine Abdomen 50% DR AsahiKawa Hospital Study D.4 (pg 29)	Contrast Abdomen 50% DR Technical Univ of Munich Study E.3 (pg 31)			80kV DVT CNR improved Kumamoto Univ Study G.1 (pg 34)

Clinical Area A- Cardiac CTA

Study A.1: Evaluation of Noise-Reducing Iterative Reconstruction Technique in 256-Slice Coronary CT Angiography (CCTA) of Pre-Operative Bariatric Surgery Candidates				
Collaborator	Clinical Target	Clinical Area	Clinical Indication	iDose[4] Benefit
Oregon Health & Science University, USA	Routine Dose IQ Improvement	Cardiac CTA on bariatric patients	Coronary assessment	Improved overall image noise

Study Design: Study included cardiac CTA datasets from 30 patients (BMI 38.9 ± 7.1). All acquisitions were performed using prospectively triggered CCTA (Step & Shoot Cardiac) on the 256-slice Brilliance iCT using routine scan protocols (120 kVp, 200 - 340 mAs, avg. effective dose 6.3 mSv) and were reconstructed using FBP and iDose[4]. Image quality of both approaches was subjectively analyzed by two blinded readers.

Findings: The study shows that iDose[4] facilitates noise reduction while maintaining diagnostic image quality in prospectively-gated coronary CTA scans performed on morbidly obese patients for preoperative assessment prior to bariatric surgery.

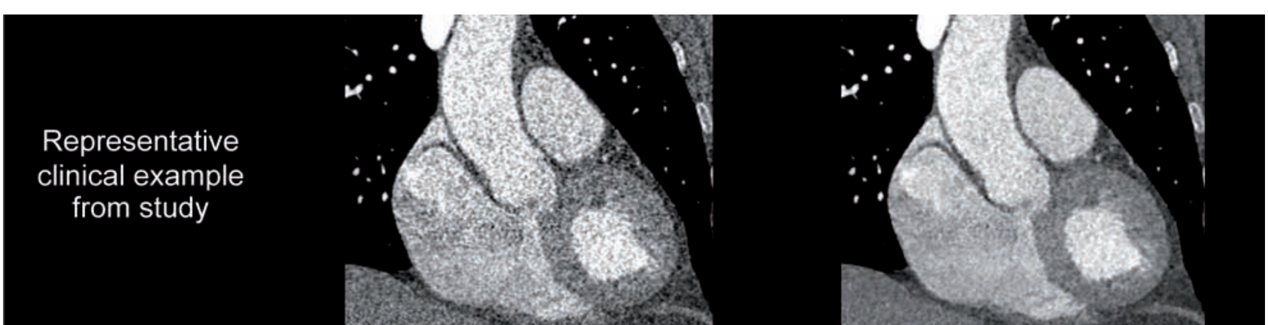


	FBP	iDose[4]
Reconstruction Acquisition Protocol	120 kVp, 360 mAs, 0.27 s rotation time, Step & Shoot Cardiac	120 kVp, 360 mAs, 0.27 s rotation time, Step & Shoot Cardiac
iDose[4] Benefits		Improved overall CNR

Study A.2: Iterative Reconstruction Technique Provides Noise Reduction and Improved Image Quality for Coronary CT Angiography				
Collaborator	Clinical Target	Clinical Area	Clinical Indication	iDose[4] Benefit
Thomas Jefferson University Hospital, USA	Routine Dose CNR Improvement	Cardiac CTA	Coronary assessment	Improved overall image noise

Study Design: Data from 28 patients who underwent CCTA on 256-slice Brilliance iCT were reconstructed with standard FBP and iDose[4]. iDose[4] was applied at three aggressiveness levels (2, 4 and 6). The four resulting image sets were reviewed in random order by two independent observers blinded to the reconstruction technique.

Findings: iDose[4] improves the image by improving homogeneity of the vascular lumen in CCTA without loss of sharp edge definition. The weighting of the iterative reconstruction technique with iDose[4] should be adjusted to achieve a standard deviation of pixel intensity of 30-40 HU in the left atrium



	FBP	iDose[4]
Reconstruction Acquisition Protocol	120 kVp, 800 mAs, 0.33 s rotation time, 0.18 pitch	120 kVp, 800 mAs, 0.33 s rotation time, 0.18 pitch
Clinical Benefits		Improved overall CNR

Study A.3: New iterative reconstruction technique: image quality in 256-slice Computed Tomography				
Collaborator	Clinical Target	Clinical Area	Clinical Indication	iDose^4 Benefit
NEUSS, Germany	Routine dose CNR improvement	Cardiac CTA	Coronary assessment	Improved image noise for low-dose cardiac CTA

Study Design: 29 patients were examined on the 256-slice Brilliance iCT to exclude significant coronary artery disease with coronary CT angiography. Seven of 29 patients were examined in helical mode (effective dose 13.1 mSv (+/- 4.0)), 22 patients examined with Step & Shoot Cardiac (effective dose 1.3 mSv +/- 0.5). All examinations were performed with standard protocols and individually adapted dose parameters. Images acquired on a routine protocol basis were reconstructed with FBP and with iDose^4.

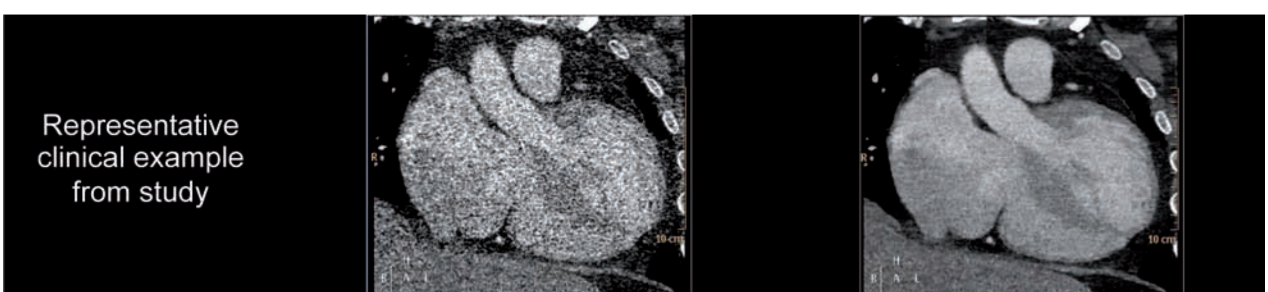
Findings: iDose^4 significantly improved image noise with no artifacts induced. A potential dose reduction of up to 50% may be possible.

Reconstruction	FBP	iDose^4
Acquisition Protocol	100 kVp, 150 mAs, 0.27s rotation time, Step & Shoot Cardiac	100 kVp, 150 mAs, 0.27 s rotation time, Step & Shoot Cardiac
Clinical Benefits		Improved overall image noise

Study A.4: Improved Image Quality with iDose^4: Evaluation of Low-kilovoltage CT Coronary Angiography				
Collaborator	Clinical Target	Clinical Area	Clinical Indication	iDose^4 Benefit
Kumamoto University, Japan	Low Dose CNR Improvement	Cardiac CTA	Coronary assessment	Improved CNR for low-kV cardiac CTA

Study Design: Ten patients (7 men, 3 women; mean age 60 years) underwent cardiac CTA on the Brilliance 64 using low-kVp technique (80 kVp, CTDIvol = 25.1 mGy). CT images were reconstructed using FBP and 3 levels of iDose^4 (2, 4, 6). Four different reconstructions were reviewed by two observers. Quantitative image quality parameters (HU of coronary arteries, and contrast-to-noise ratio) were measured.

Findings: The overall image & objective CNR scores were significantly better with iDose^4 relative to FBP. Visual scores were best for iDose^4 level 6. No statistically significant difference in arterial CT attenuation between different reconstructions.



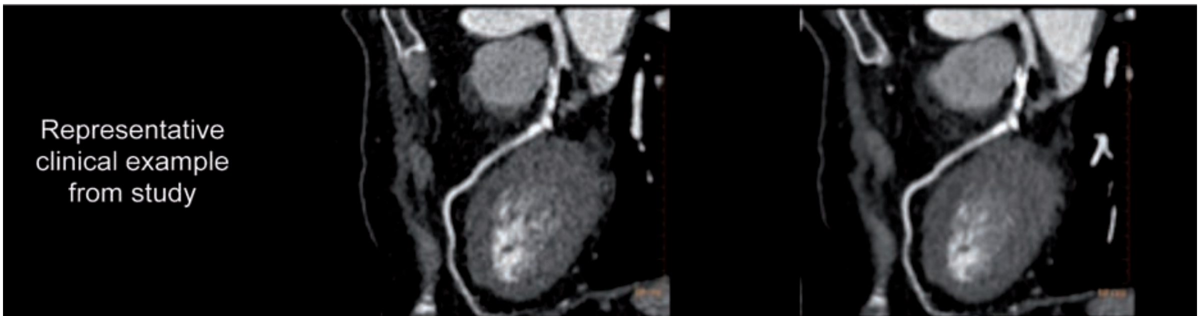
Reconstruction	FBP	iDose^4
Acquisition Protocol	120 kVp, 1000 mAs	120 kVp, 1000 mAs
Clinical Benefits		Significantly improved CNR with low-kVp + iDose^4 combined

Study A.5: Evaluation of an iterative reconstruction technique for reducing body radiation dose in Cardiac CTA

Collaborator	Clinical Target	Clinical Area	Clinical Indication	iDose^4 Benefit
Shengjing Hospital of China Medical University, China	Dose Reduction	Cardiac CTA	Coronary assessment	70% dose reduction while maintaining diagnostic image quality

126 patients (avg. BMI: 25.48, m:77, f:49) referred for Cardiac CTA were enrolled in the study. Patients were randomly divided into 0%, 30%, 40%, 50%, 60%, and 70% radiation dose reduction groups (1000 mAs - 13.5 mSv; 700 mAs - 9.7 mSv; 600 mAs - 8.1 mSv; 500 mAs - 6.9 mSv; 600 mAs - 5.8 mSv & 300 mAs - 4.3 mSv, respectively). Images were reconstructed with FBP and iDose^4. Qualitative ranking on per-vessel basis was performed.

Findings: Images were considered diagnostic for up to 70% dose reduction. Beyond 50% dose reduction iDose^4 level 4 was considered to be optimal.



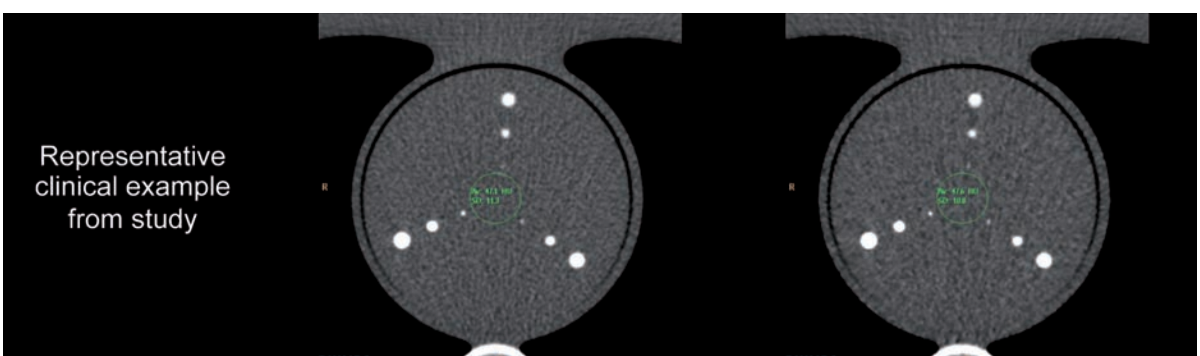
Reconstruction	FBP	iDose^4
Acquisition Protocol	120 kVp, 300 mAs	120 kVp, 90 mAs
Clinical Benefits		70% dose reduction while maintaining diagnostic image quality

Study A.6: Low-dose 256-slice coronary CTA with an iterative reconstruction algorithm: Cardiac phantom feasibility study

Collaborator	Clinical Target	Clinical Area	Clinical Indication	iDose^4 Benefit
Shengjing Hospital of China Medical University, China	Dose Reduction	Cardiac CTA	Coronary assessment	70% dose reduction while maintaining qualitative and quantitative scores

Study Design: A cardiac coronary phantom was scanned using prospective ECG-triggered CCTA (Step & Shoot Cardiac) protocols at standard dose (D1: 120 kVp, 200 mAs) and 3 levels of radiation dose reduction (140 mAs; 100 mAs; 60 mAs) on the 256-slice Brilliance iCT. The routine dose scan was reconstructed using filtered back projection (FBP) and the low-dose scans with iDose^4. Two radiologists blinded to acquisition technique evaluated images for contrast, sharpness, image noise, and overall Image quality. Quantitative noise measurements were performed.

Findings: iDose^4 enabled CCTA acquisitions with up to 70% less dose compared to a standard scan protocol with no significant difference in image quality, and objective image noise. In addition, the algorithm may improve contrast resolution.



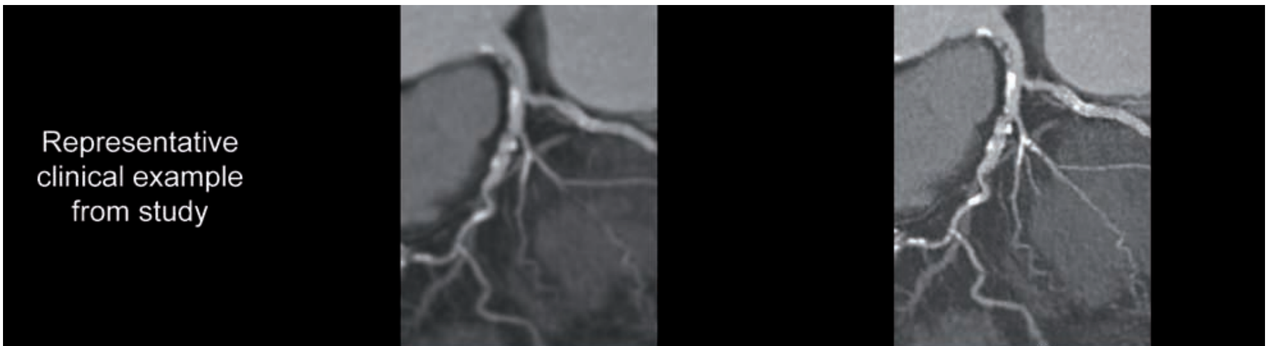
Reconstruction	FBP	iDose^4
Acquisition Protocol	120 kVp, 80 mAs, 0.33 s rotation time, Step & Shoot Cardiac	120 kVp, 24 mAs, 0.33 s rotation time, Step & Shoot Cardiac
Clinical Benefits		70% dose reduction while maintaining qualitative and quantitative scores.

Study A.7: Improvements in calcium blooming reduction and in-stent visualization using iterative reconstruction techniques

Collaborator	Clinical Target	Clinical Area	Clinical Indication	iDose^4 Benefit
Lenox Hill Hospital, USA	Image quality improvements	Cardiac CTA	Coronary assessment	Improved image quality through reduction of calcium blooming artifact

Study Design: Ten patients with significant coronary calcification referred for Cardiac CTA were examined on the 256-slice Brilliance iCT at routine dose. Reconstructions were performed with FBP and iDose^4. iDose^4 reconstructions were performed in high resolution mode while keeping the image noise at the same level as the FBP reconstruction. Extent of calcium blooming was objectively assessed. Quantitative image noise was measured.

Findings: Qualitative assessment indicated that blooming artifact was reduced on the iDose^4 reconstructions compared to FBP reconstruction. Objective noise was not significantly different between reconstructions. Potential benefit could include improvement in in-stent visualization.



Reconstruction	FBP	iDose^4
Acquisition Protocol	120 kVp, 600mAs, 0.27 s rotation time, 0.16 pitch	120 kVp, 600mAs, 0.27 s rotation time, 0.16 pitch
Clinical Benefits		Improved image quality through reduction of calcium blooming artifact

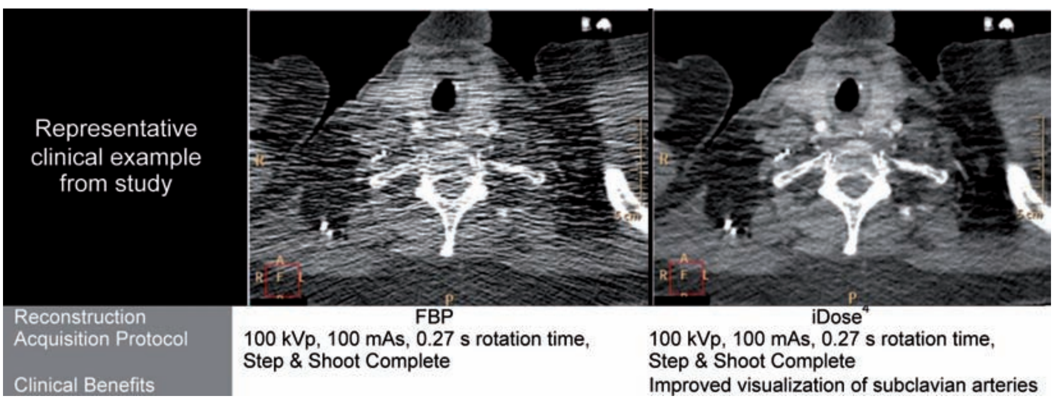
Clinical Area B – Aortic/Chest CTA

Study B.1: Iterative Reconstruction technique Reduces Shoulder Artifact in Low-Dose, Prospective ECG-triggered Axial CT Scans of the Thoracic Aorta

Collaborator	Clinical Target	Clinical Area	Clinical Indication	iDose[4] Benefit
Cleveland Clinic, USA	Low Dose IQ Improvement	Aortic CTA	Thoracic aorta assessment	Reduced streak artifacts for low-dose imaging. Improved diagnostic confidence.

Study Design: Thoracic aorta CTAs of 50 patients were acquired using low-dose, ECG-triggered axial techniques (Step & Shoot Complete) on the 256-slice Brilliance iCT (100 or 120 kVp, 60-145 mAs for 100 kVp or 70-300 mAs for 120 kVp, beam collimation=96,112, or 128 x 0.625 mm, 270 ms rotation time). Average scan length was 280±25 mm. Mean patient BMI was 28.1±5.3 kg/m2 and the majority of patients (70%) were imaged with a tube voltage of 100 kVp. Overall image quality and extent of shoulder artifact were graded for both reconstructions.

Findings: Low dose imaging of the thoracic aorta with filtered back projection reconstruction provides sufficient image quality and noise in the aorta but limits evaluation of arch branch vessels at the level of the shoulders. iDose[4] reduces shoulder artifact in prospective ECG-triggered axial CT imaging of the thoracic aorta; permitting low dose acquisitions.

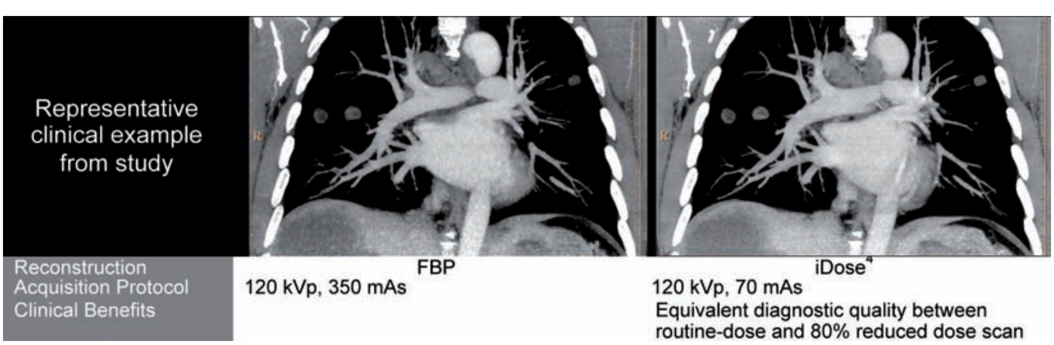


Study B.2: Iterative Algorithm for Reducing Dose While Maintaining Image Quality: Pilot Clinical Study

Collaborator	Clinical Target	Clinical Area	Clinical Indication	iDose[4] Benefit
AsahiKawa Hospital, Japan	Dose Reduction	Chest CTA	Oncology follow-up	Up to 80% dose reduction while maintaining diagnostic image quality

Study Design: Twelve patients presenting for tumor follow-up were recruited for the study. Patients were randomly divided into 50% (7 patients) & 80% (5 patients) radiation dose reduction groups. All acquisitions were performed on Brilliance 64. Routine- and low-dose CT scans were acquired sequentially. Routine dose data was reconstructed with FBP, and low-dose data reconstructed with iDose[4]. Qualitative ranking of diagnostic confidence was performed on each dose reduction acquisition (w/ iDose[4]) relative to the routine-dose FBP acquisition.

Findings: Both 50% & 80% dose reduction groups were not significantly different relative to the full-dose FBP acquisitions.



Clinical Area C – Routine Chest

Study C.1: First experience with a hybrid iterative reconstruction technique for low dose chest CT				
Collaborator	Clinical Target	Clinical Area	Clinical Indication	iDose[4] Benefit
La Pitié Salpêtrière, Paris, France	Low Dose IQ Improvement	Routine Chest	N/A	Overall improved image quality and reduced artifacts for low-dose imaging.

Study Design: Twelve consecutive low dose chest CT - Average BMI/CTDI/DLP: 24.2 kg.m-2/3.2 mGy/135.3 mGy.cm (19.4-35.8 kg.m-2/0.4 – 8.0 mGy/15.8 – 341.1 mGy.cm) - were reconstructed with iDose[4] and FBP. For each acquisition, 3 different iDose[4] aggressiveness levels (2, 4 and 6) and the FBP images, were individually evaluated and compared for lung reconstruction and soft tissue reconstruction.

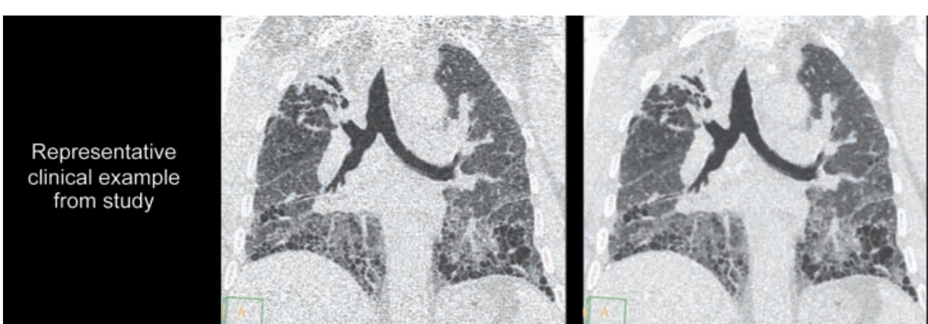
Findings: For all lung reconstructions, the original FBP images were classified as lowest image quality for diagnosis and the higher iDose[4] level (6) was preferred for all but one dataset. For soft tissue reconstructions, the lower and medium iDose[4] levels (2 and 4) were preferred in all cases. iDose[4] level needs to be adjusted according to clinical application. Larger scale studies are needed to validate this technique.

Reconstruction / Acquisition Protocol / Clinical Benefits	FBP (2.5 mm MIP)	iDose[4] (2.5 mm MIP)
	100 kVp, 30 mAs, 1.2 mGy, 38.9 mGy.cm	100 kVp, 30 mAs, 1.2 mGy, 38.9 mGy.cm Good image quality even at upper lung level with very low dose protocol

Study C.2: First experience with a hybrid iterative reconstruction technique for low dose chest CT				
Collaborator	Clinical Target	Clinical Area	Clinical Indication	iDose[4] Benefit
Hôpital Louis Pradel, Lyon, France	Low Dose CNR Improvement	Low dose Chest follow up	N/A	Overall improved image noise and reduced artifacts for low-dose imaging.

Study Design: 110 consecutive unenhanced low dose chest CT - Average BMI/CTDI/DLP: 23.9 kg×m2 / 3.1 mGy / 126.1 mGy.cm - were reconstructed with iDose[4] (Level 4, 6) and FBP. These were individually evaluated and compared for lung reconstruction and soft tissue reconstruction. Quantitative noise measurements were performed.

Findings: For the soft tissue reconstruction, noise level is significantly decreased with iDose[4] Level6 in comparison with iDose[4] Level 4 and original FBP reconstruction. Similarly, for the lung reconstructions, iDose[4] Level 6 had a significantly improved image than the other reconstruction. iDose[4] provides significant improvement in image noise in low dose chest CT in comparison to FBP.



Reconstruction / Acquisition Protocol / Clinical Benefits	FBP	iDose[4]
	120 kVp, 47 mAs (ACS+ZDOM), 2.8 mGy, 105 mGy.cm, 1.47 mSv	120 kVp, 47 mAs (ACS+ZDOM), 2.8 mGy, 105 mGy.cm, 1.47 mSv Improved image noise for low dose follow up

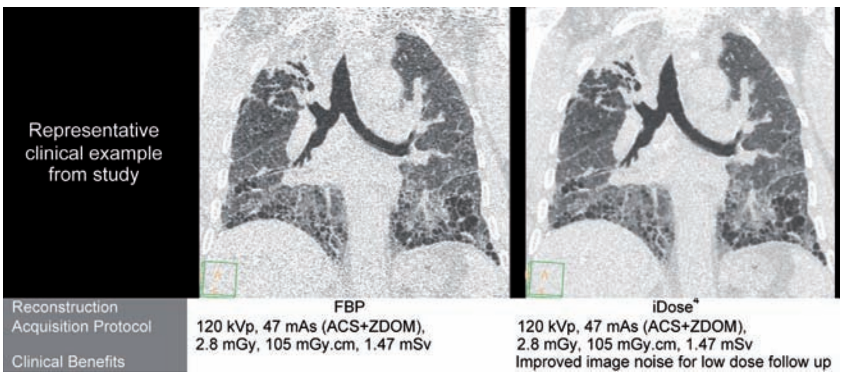
Clinical Area D – Routine Abdomen-Pelvis

Study D.1: Investigation of a Hybrid Iterative Reconstruction Technique for Radiation Dose Reduction with Preservation of Diagnostic Quality in Cadaveric Models

Collaborator	Clinical Target	Clinical Area	Clinical Indication	iDose[4] Benefit
University of Maryland, USA	Dose Reduction	Routine Body	N/A	58-66% dose reduction while maintaining diagnostic image quality

Study Design: Three human cadavers were scanned on a Brilliance 64 at standard dose based on body habitus & weights of 80, 140, 205 lbs (164, 252, 387 mAs, respectively) and subsequently at multiple reduced mAs levels. Sample images with subtle anatomic findings, focal pathology and/or artifacts in the mediastinum, lungs, liver, pelvis, and bone were reconstructed with filtered back projection and iDose[4]. Both image quality and artifact presence were blindly scored by 3 experienced radiologists.

Findings: Subjective reader evaluations and quantitative noise measurements confirm that iDose[4] can provide diagnostic CT studies of equivalent quality, with a 58%-66% (80 lbs-58%, 140, 205 lbs-66%) reduction in radiation dose compared with standard-dose studies using FBP reconstruction.

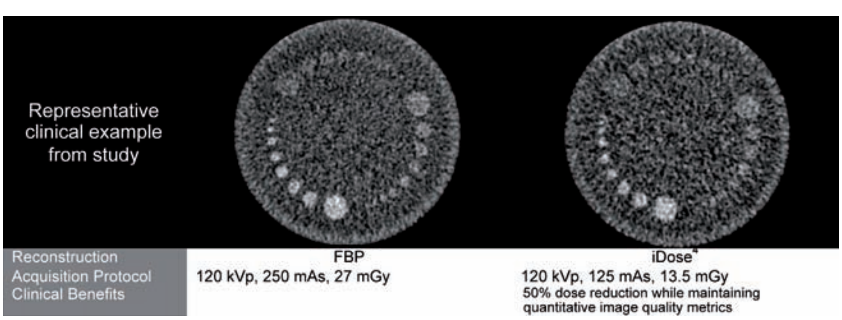


Study D.2: Evaluation of an iterative reconstruction algorithm for radiation dose reduction in CT: Phantom Study

Collaborator	Clinical Target	Clinical Area	Clinical Indication	iDose[4] Benefit
AsahiKawa Hospital, Japan	Dose Reduction	Routine Abdomen		50% dose reduction while maintaining quantitative image quality metrics

Study Design: CT acquisitions of the CATPHAN phantom were performed on the Brilliance 64 scanner. Acquisition parameters were similar to a standard abdomen protocol – 120 kVp, 250 mAs, standard filter, CTDI of 27 mGy at surface of the phantom. Acquisitions were repeated at one-half the radiation dose (i.e., 125 mAs) (13.5 mGy). The routine dose (27 mGy) data was reconstructed using FBP and half dose (13.5 mGy) data reconstructed using iDose[4]. Image SNR and qualitative comparisons of the low-contrast detectability were performed.

Findings: Image SNR for acrylic rod on routine dose FBP and half dose iDose[4] images were 60.2 and 62.5, respectively. Qualitative assessment of low-contrast resolution indicated 4mm objects at 0.3% contrast were discernible on both datasets. There was no significant difference in low-contrast detectability, between routine dose FBP and half dose iDose[4].

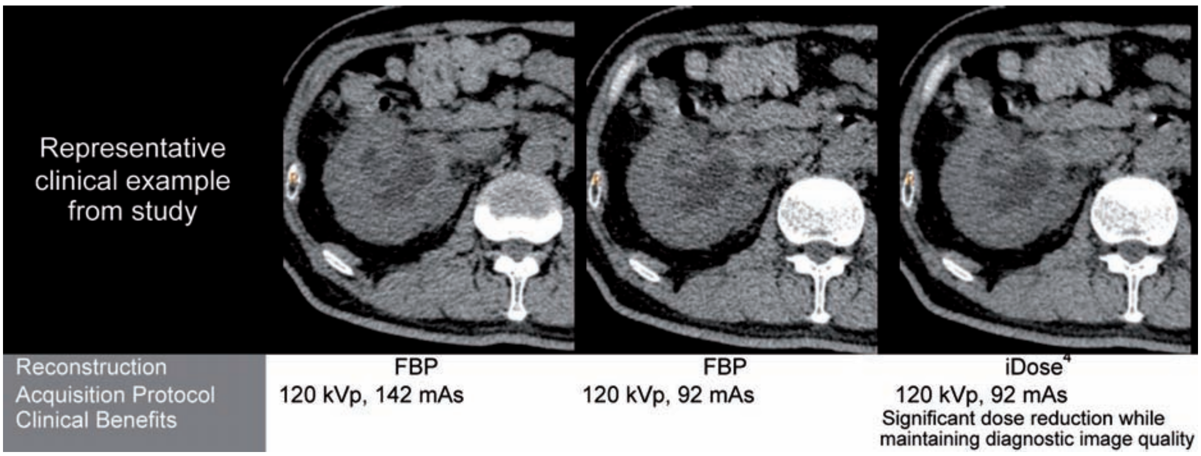


Study D.3: Evaluation of an iterative reconstruction technique for reducing body radiation dose in routine non-contrast abdominal imaging

Collaborator	Clinical Target	Clinical Area	Clinical Indication	iDose[4] Benefit
Shengjing Hospital of China Medical University, China	Dose Reduction	Non-contrast abdomen		50% dose reduction while maintaining diagnostic image quality

Study Design: Twenty five routine non-contrast acquisitions were performed on the Brilliance iCT. Patients were randomly divided into 35% & 50% radiation dose reduction groups. Routine- and low-dose CT scans were acquired sequentially. Routine dose data was reconstructed using FBP, and low-dose data reconstructed with iDose[4] & FBP. Qualitative ranking of low-contrast, sharpness and overall image quality were graded by six physicians relative to the FBP.

Findings: The overall image quality scores were significantly higher for low-dose iDose[4] compared to low-dose FBP. The 35% and 50% acquisitions with iDose[4] reconstructions were diagnostically equivalent to the routine dose FBP acquisitions.

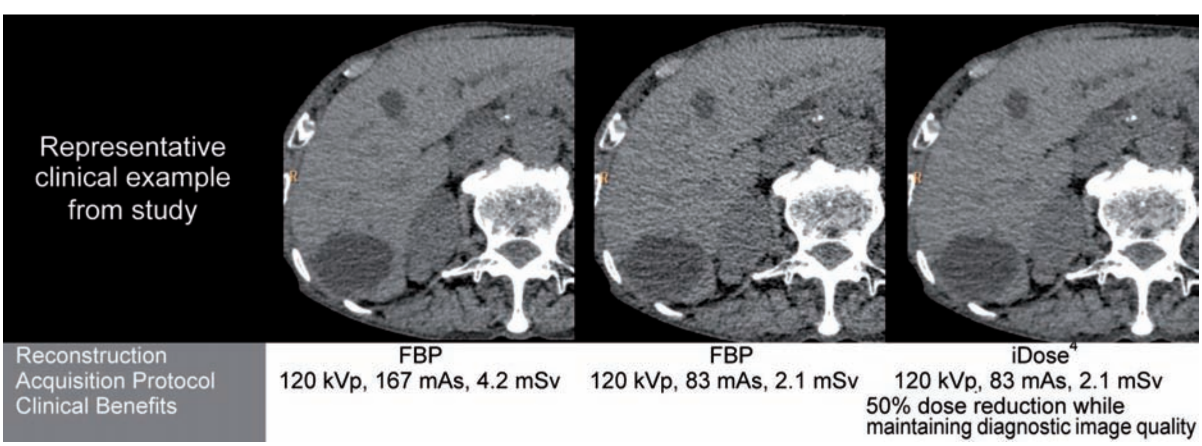


Study D.4: Iterative Algorithm for Reducing Dose While Maintaining Image Quality: Pilot Clinical Study

Collaborator	Clinical Target	Clinical Area	Clinical Indication	iDose[4] Benefit
AsahiKawa Hospital, Japan	Dose Reduction	Routine abdomen		50% dose reduction while maintaining diagnostic image quality

Study Design: CT acquisitions on patients were performed with 50% radiation dose reduction relative to that used on the original routine dose CT acquisitions. Acquisitions were performed sequentially. Six patients were scanned on the Brilliance 64, generating a total of 12 acquisitions (6 routine dose baseline studies, 6 half-dose follow-up). Routine dose data was reconstructed with FBP, and low-dose data reconstructed with iDose[4]. Evaluations were performed by a radiologist blinded to the dose and reconstruction algorithm.

Findings: There was no significant difference in diagnostic image quality between the routine dose (w/FBP) and low-dose (w/iDose[4]) acquisitions.



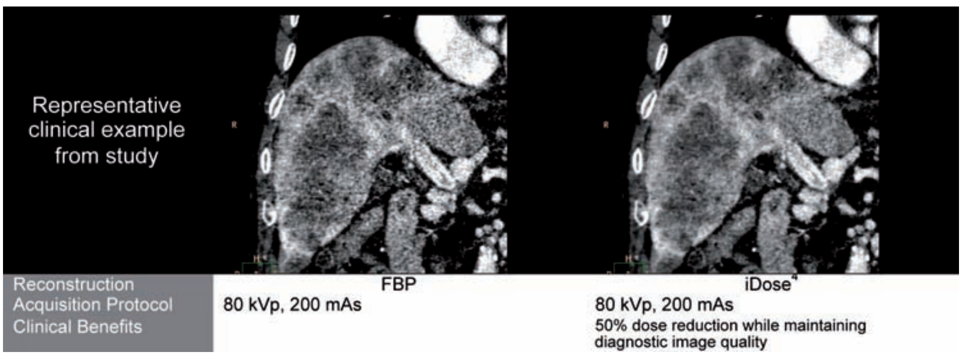
Clinical Area E – Contrast Abdomen

Study E.1: Evaluation of an iterative reconstruction technique for reducing body radiation dose in CT imaging of liver tumors

Collaborator	Clinical Target	Clinical Area	Clinical Indication	iDose[4] Benefit
Shengjing Hospital of China Medical University, China	Dose Reduction	Contrast Abdomen	Oncology follow-up	50% dose reduction while maintaining diagnostic image quality

Study Design: One hundred and thirty eight patients with clinical diagnosis of liver tumors were scanned on the Brilliance iCT. Patients were randomly divided into 30%, 50% and 70% radiation dose reduction groups. Images were reconstructed with standard FBP and iDose[4]. Qualitative ranking of sharpness of tumors, contrast between tumors and normal liver tissue, and image quality were graded relative to the FBP.

Findings: This study indicates that 50% is the maximum radiation dose reduction clinically feasible with iterative reconstruction techniques for hepatic enhanced CT.

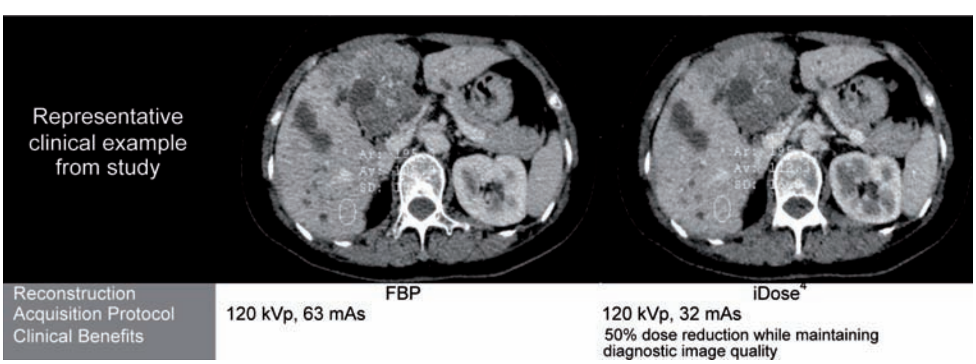


Study E.2: Evaluation of an iterative reconstruction technique for reducing body radiation dose in CT imaging of liver tumors

Collaborator	Clinical Target	Clinical Area	Clinical Indication	iDose[4] Benefit
Shengjing Hospital of China Medical University, China	Dose Reduction	Contrast Abdomen	Oncology follow-up	50% dose reduction while maintaining diagnostic image quality

Study Design: Forty eight patients with clinical diagnosis of liver tumors were scanned on the Brilliance iCT. Routine- and low-dose CT scans were acquired sequentially during the hepatic portal venous phase of contrast enhancement. The CT dose index (CTDI) of low-dose acquisition was 50% (45-58%) lower than routine-dose acquisition. Images were reconstructed with standard FBP and iDose[4] (Routine-dose: FBP; low-dose: FBP, iDose[4]). Qualitative ranking of sharpness of tumors, contrast between tumors and normal liver tissue, and image quality were graded relative to the FBP.

Findings: iDose[4] iterative reconstruction technique enabled 50% radiation dose reduction in CT imaging of liver tumors while maintain the diagnostic quality of routine dose CT.

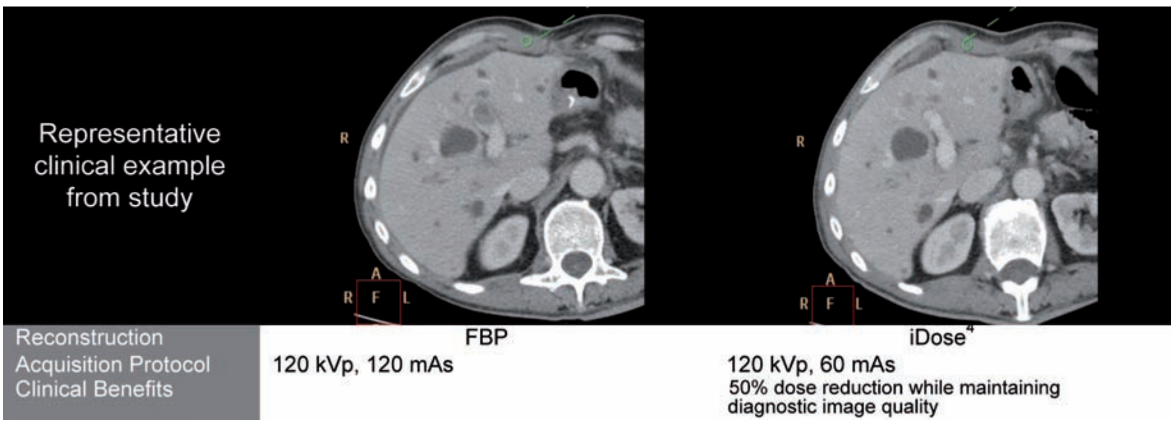


Study E.3: Evaluation of an iterative reconstruction algorithm for dose reduction in abdominal tumor staging

Collaborator	Clinical Target	Clinical Area	Clinical Indication	iDose[4] Benefit
Technical University of Munich,Germany	Dose Reduction	Contrast Abdomen	Tumor Staging	50% dose reduction while maintaining diagnostic image quality

Study Design: Twenty two patients (M-7, F-14; BMI 18-38, Avg. Age-34) with malignant disease referred for follow-up CT of tumors were recruited for the study. Existing baseline acquisitions at routine dose (120 kVp, 120-250 mAs; dependant on body habitus) were available for all patients. The follow-up acquisitions were performed with 50% lower radiation dose (120 kVp, 60-110 mAs) relative to the baseline acquisition. All acquisitions were performed on the Brilliance iCT. The low-dose acquisitions were reconstructed with FBP and iDose[4] (Level 1, 4, 7). Two readers blinded to reconstruction technique evaluated diagnostic image quality and presence of artifacts. Objective noise measurements were performed.

Findings: iDose[4] image quality was preferred over FBP. iDose[4] level 1 was sufficient in cases where artifacts were the primary limitation in FBP. All anatomical structures were visible even at the most aggressive iDose[4] level (7). 50% dose reduction provides diagnostic image quality and can be used routinely. In case of high contrast clinical targets such as lung, bones, CTA dose reduction of up to 80% may be possible.

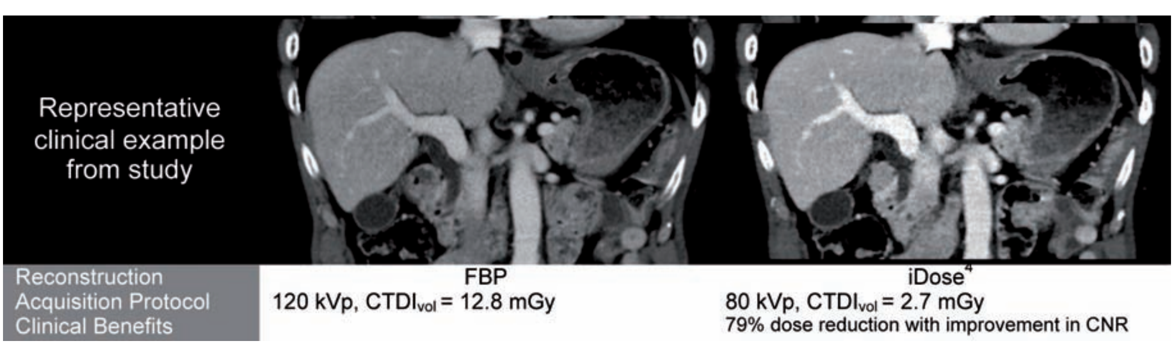


Study E.4: Evaluation of an iterative reconstruction algorithm for dose reduction in portal and late phase of a four-phase liver CT on follow-up candidates for assessment of hepatic carcinoma

Collaborator	Clinical Target	Clinical Area	Clinical Indication	iDose[4] Benefit
AsahiKawa Hospital, Japan	Dose Reduction	Contrast Abdomen	Oncology follow-up	80% dose reduction with improvement in CNR

Study Design: Twenty patients presenting for follow-up of hepatic carcinoma referred for four-phase liver CT protocols were recruited for the study. The acquisitions were performed such that the arterial phase was performed using 120 kVp protocols and portal-venous phase was performed using 80 kVp protocols at 80% lower dose (CTDI) than the 120 kVp protocols. All acquisitions were performed on a Brilliance 64. The 120 kVp examinations were reconstructed with FBP and the 80kVp examinations reconstructed with iDose[4]. A blinded review was performed which evaluated the overall diagnostic image quality.

Findings: The study shows that in portal phase of four-phase liver CT scans performed on hepatic carcinoma follow-up patients the contrast-to-noise ratio can be improved while simultaneously reducing the applied dose by 80% over routine levels.

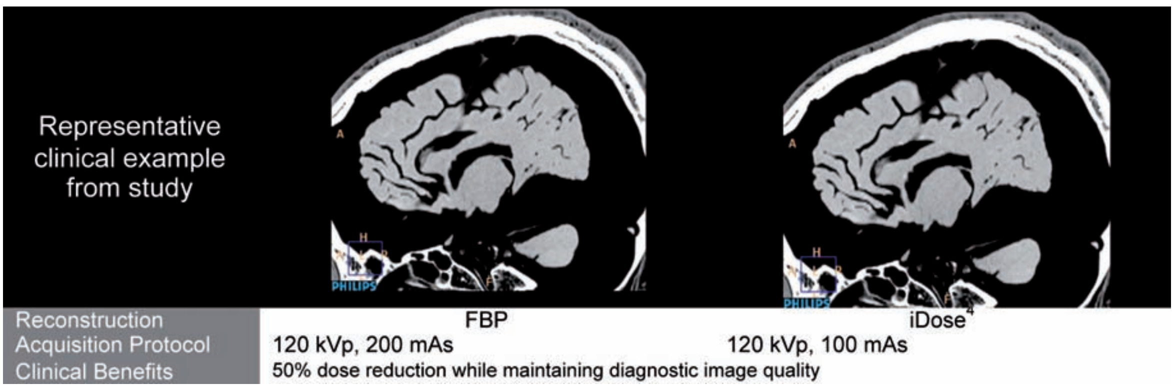


Clinical Area F – Head & Neck

Study F.1: Evaluation of an iterative reconstruction algorithm for radiation dose reduction in CT: Phantom & Cadaver Study				
Collaborator	Clinical Target	Clinical Area	Clinical Indication	iDose⁴ Benefit
Shengjing Hospital of China Medical University, China	Dose Reduction	Non-contrast brain		50% dose reduction while maintaining diagnostic image quality

Study Design: CT acquisitions of the CATPHAN phantom (CATPHAN 500, The Phantom Laboratory), anthropomorphic body phantom with calibration inserts (IBA Dosimetry, Germany), and 3 cadaver heads were performed on a 256-slice MDCT (Brilliance iCT, Philips). Acquisitions were performed using weight-based, routine-dose head protocols and multiple lower dose levels (range: 20% – 80% of routine dose, in increments of 10%). Data was reconstructed with standard FBP and iDose⁴.

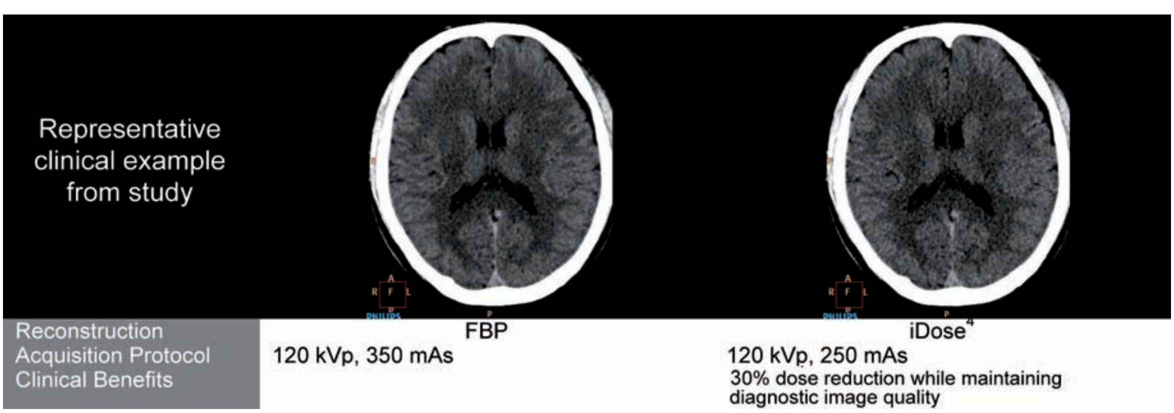
Findings: iDose⁴ demonstrated improved low-contrast resolution in routine dose acquisitions. The image quality metrics were maintained for up to 50% dose reduction. Evaluation of cadaver head images were in agreement with the phantom data findings.



Study F.2: Radiation dose reduction in routine brain CT with iterative reconstruction techniques				
Collaborator	Clinical Target	Clinical Area	Clinical Indication	iDose⁴ Benefit
Huashan Hospital of Fudan University, China	Dose Reduction	Non-contrast brain		30% dose reduction while maintaining diagnostic image quality

Study Design: Twenty five routine non-contrast brain acquisitions were performed on the Brilliance iCT. Patients were randomly divided into 30% (245 mAs) and 50% (175 mAs) radiation dose reduction groups. Data was reconstructed with FBP and iDose⁴. Differentiation of grey-white matter, noise texture and overall image quality were graded by eight readers.

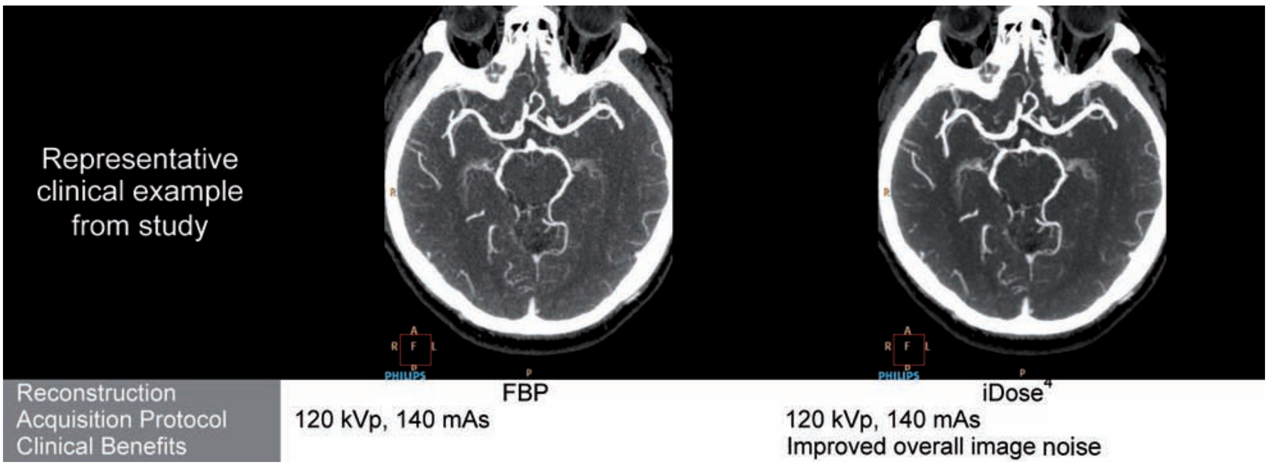
Findings: It was possible to achieve a maximum dose reduction of 30% while still maintaining diagnostic quality on the FBP & iDose⁴ reconstructions.



Study F.3: Radiation dose reduction in Neck CTA with iterative reconstruction techniques				
Collaborator	Clinical Target	Clinical Area	Clinical Indication	iDose[4] Benefit
Huashan Hospital of Fudan University, China	Dose Reduction	Head & Neck CTA		60% dose reduction while maintaining diagnostic image quality

Study Design: Five Head & Neck CTAs were performed on the Brilliance iCT. Patients were randomly divided into 30% & 60% radiation dose reduction groups relative to routine dose examinations (120 kVp, 350 mAs). Data was reconstructed with FBP and iDose[4]. Image quality was evaluated by eight radiologists blinded to the dose reduction and reconstruction technique.

Findings: It was possible to obtain 60% dose reduction while maintaining the diagnostic image quality.

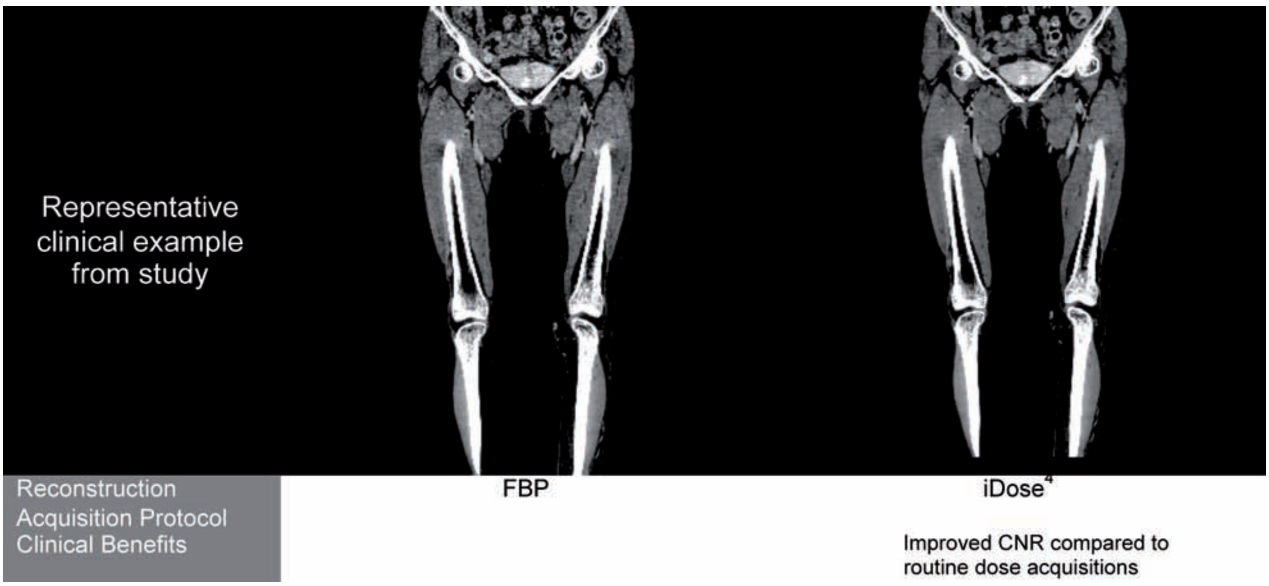


Clinical Area G – Peripheral CTA

Study G.1: Evaluation of an iterative reconstruction technique for low-kVp DVT assessment				
Collaborator	Clinical Target	Clinical Area	Clinical Indication	iDose[4] Benefit
Amakusa Medical Hospital, Japan	Image quality improvement	Peripheral CTA	DVT	Improved CNR compared to routine dose acquisitions

Study Design: Six patients referred to CT for DVT assessment were recruited for the study. The CT acquisitions were performed using 80 kVp protocols. All acquisitions were performed on the Brilliance iCT. Acquisitions from previously existing 120 kVp studies were used for defining the baselines image quality. A blinded review was performed which evaluated the overall diagnostic image quality.

Findings: The study shows that with 80 kVp acquisitions combined with iDose[4] the contrast-to-noise ratio can be significantly improved relative to 120 kVp protocols.

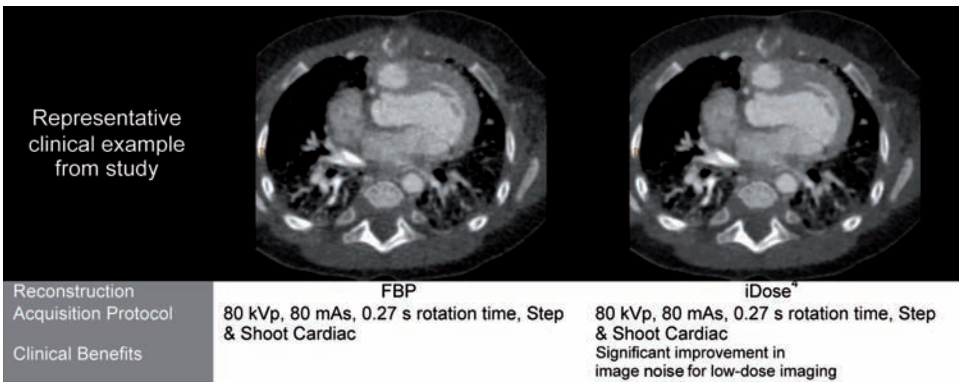


Clinical Area H – Pediatric Imaging

Study H.1: Evaluation of Iterative Reconstruction Techniques in Ultra Low Radiation Exposure Pediatric CTA: A New Tool for Pediatric Dose Management				
Collaborator	Clinical Target	Clinical Area	Clinical Indication	iDose⁴ Benefit
Oregon Health & Science University, USA	Routine Dose IQ Improvement	Cardiac CTA on pediatrics	Congenital Heart Disease	Significant improvement in image quality for low-dose imagining

Study Design: Cardiac CTA was performed on five pediatric patients. All acquisitions were performed using prospectively triggered ECG-gated acquisitions for congenital heart disease indications on a 256- or 64-slice MDCT scanner (Brilliance 64, iCT) using 80 kVp, 80 - 120 mAs (avg. eff. Dose: 1.1 mSv). The projection data was reconstructed using filtered back projection (FBP) and iDose⁴. IQ of both techniques was subjectively analyzed by two blinded readers.

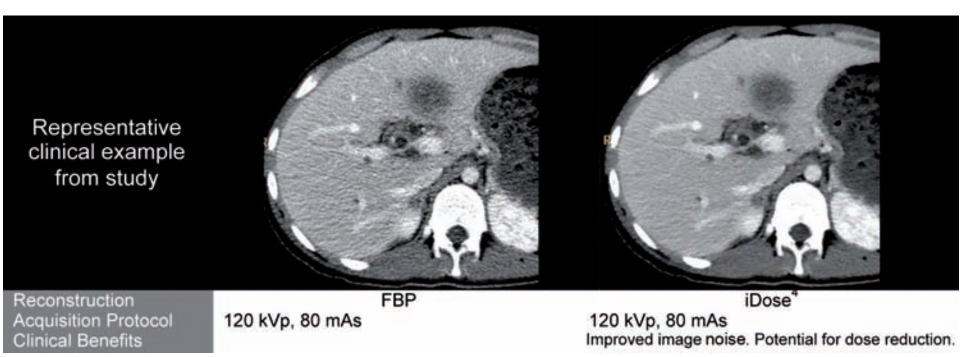
Findings: Preliminary results indicate that iterative reconstruction techniques can maintain the diagnostic IQ while providing a significant improvement in SNR in pediatric CTA, thereby enabling further potential reductions in radiation dose.



Study H.2: Evaluation of an Iterative Noise-Reducing Reconstruction Technique for Low Radiation Dose MDCT: Application to Pediatric Abdominal Examinations				
Collaborator	Clinical Target	Clinical Area	Clinical Indication	iDose⁴ Benefit
Oakland Children's Hospital, USA	Low Dose CNR Improvement	Abdominal CTA		Improved image noise. Potential for dose reduction.

Study Design: Eleven helical data sets (M 5, F 6) were acquired with weight-based abdominal scan protocols (N=5: 11-40 kg, 3: 41-60 kg, 2: 61-80 kg, 1: 81-100 kg). The scan parameters were 120 kVp, pitch 0.88, average mAs= 87, and average CTDIvol= 4.2 mGy (CTDI32). Filtered back projection (FBP) with a standard kernel ("C") and a slice thickness of 4 mm was used as the baseline image reconstruction method. iDose⁴, was applied to each projection (raw) data (levels 2, 4, 6) and compared with FBP.

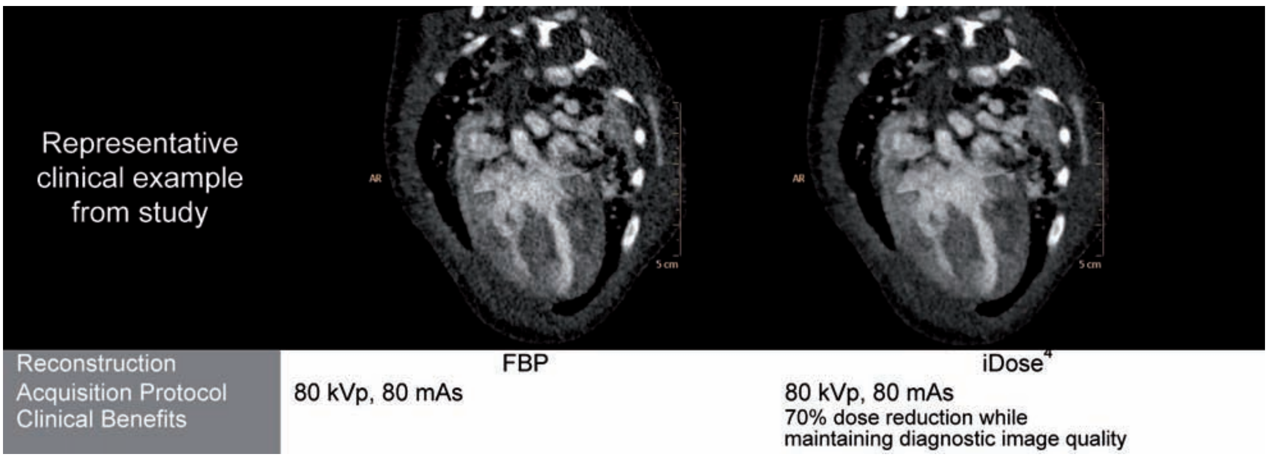
Findings: The iterative reconstruction technique can significantly reduce image noise and may allow for significant dose reduction without loss of image quality in pediatric abdominal MDCT examinations.



Study H.3: Evaluation of iterative reconstruction technique for dose reduction on pediatric cardiac CTA				
Collaborator	Clinical Target	Clinical Area	Clinical Indication	iDose[4] Benefit
Guangdong General Hospital, China	Dose Reduction	Pediatric Cardiac CTA		70% dose reduction while maintaining diagnostic image quality

Study Design: Twenty pediatric patients (avg. wt 7.2+/- 4.4 kg, avg. age 1 +/- 1.6 yrs) referred for cardiac CTA were scanned on the Brilliance iCT. Patients were randomly divided into three dose reduction groups – 30% (1), 50% (14) and 70% (5), relative to the reference dose based on weight-based protocols. Images were reconstructed with standard FBP and iDose[4]. Qualitative ranking of diagnostic confidence and overall image quality were assessed, blinded to the reconstruction technique.

Findings: All three radiation dose reduction groups were found to be diagnostic. The overall image quality was ranked better on iDose[4] reconstructions compared to FBP reconstructions.



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APPENDIX A – Noise power spectrum (NPS) benchmarking test

The goal of this test was to measure the similarity of image texture resulting from various reconstruction algorithms, using filtered back projection from routine-dose acquisitions as the gold standard. A comparison of images using different iterative reconstruction techniques has revealed that not all algorithms are equal in the resultant image quality. A metric is defined to indicate how closely the noise spectrum (NPS) produced by each algorithm resembles that of a conventional (FBP) reconstruction.

Method:

Noise Power Spectrum (NPS) measurements are best achieved using a large homogenous region. This ensures that measured frequency variations are due to noise properties from the system acquisition and the impact of the reconstruction algorithm without influence from variations due to physical object texture arising from anatomy or pathology. The homogeneous section of the CATPHAN 500 (The Phantom Laboratories) was scanned using a routine abdominal protocol at 120 kVp, 0.42 second rotation time, and 0.39 pitch using a 64x0.625 mm collimation to produce 0.9 mm thick image slices at 250 mm field of view using a smooth (A) filter. A scan was performed at a dose of 600 mAs and was reconstructed using FBP. A second scan was performed at 80% dose reduction (120 mAs) and all slices through the volume were processed using two iterative reconstruction approaches. All 3 methods produced images with a similar noise level, as defined by the standard deviation of a central region of interest with width equal to half the phantom diameter.

The NPS was measured using a centered box with width equal to half the diameter of the homogeneous phantom region, and was calculated using the 2D Fourier Transform averaged radially in the frequency domain to provide a 1-dimensional representation of the frequency distribution. The NPS was calculated for FBP and both iterative reconstruction methods.

Finally, the metric for similarity in texture to FBP was defined as the ratio of the NPS for the low-dose iterative technique (NPS_{IR}) divided by the NPS for routine-dose FBP (NPS_{FBP}) as a function of frequency. The resulting NPS ratio would have a value of one in the case when the iterative technique NPS matched the FBP NPS. The deviation from the FBP NPS was characterized by the average magnitude of shift in the ratio from unity. The resulting spectral change metric, represented as a percentage shift from unity, provides a measure that quantifies the image texture, with an image having a "plastic look" having a larger spectral change than an image with a "natural texture":

$$spectral\ change = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{NPS_{IR}(i)}{NPS_{FBP}(i)} - 1\right| * 100\%,$$

where the N samples of the NPS curves represent the noise spectrum range of interest up to 7 lp/cm. For the smooth standard spatial resolution reconstruction shown, the MTF rolls off above 7 line pairs. A smooth reconstruction was used to emphasize the difference in response at the lower frequencies which are related to a "blotchy," "plastic" image texture.

Findings:

Two iterative reconstruction methods were evaluated. The first approach represented a 3rd-generation reconstruction technique, arbitrarily named "3rd-Gen". The 3rd-Gen IR image exhibited noise texture problems that have been reported in the literature and have been associated with some scanner models. In contrast, Philips' iDose4 iterative reconstruction technique includes a dynamic frequency noise removal technique that lowers overall noise while closely preserving the desired frequency spectrum characteristic of a corresponding routine-dose FBP image.

The NPS curves are shown for the FBP reconstruction as well as the two iterative algorithms in Figure 9a. For purposes of an equal comparison with the metric, small differences in the total noise were removed by normalization (scaling the spectrum by the integrated area under the curve). Note that a shift to lower spatial frequencies is clearly evident for the 3rd-Gen IR approach. Next, the ratio of the NPS to the NPS FBP is calculated, where an algorithm that exactly reproduces the spatial response of FBP will have a uniform value of one at all frequencies. This metric was calculated for 82 slices through the volume of the CATPHAN phantom, and the results were then averaged to provide a measure representative of the volume. This ratio is shown in Figure 9b.

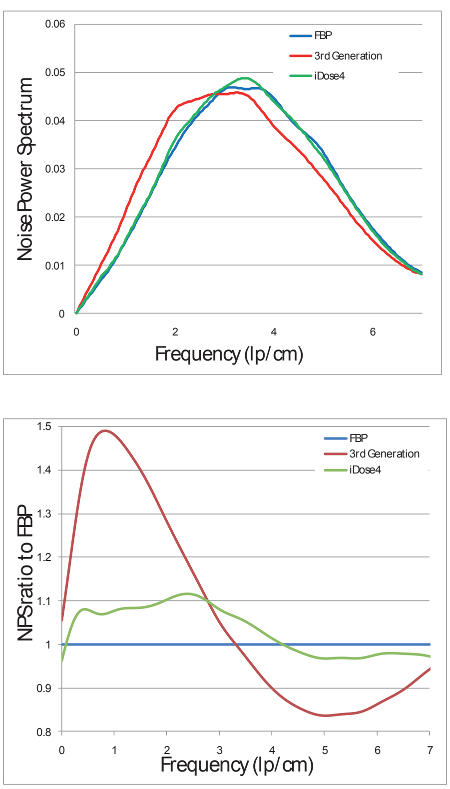

Figure 9: NPS of different reconstruction techniques used for benchmarking (a) original NPS curves (b) NPS ratio to FBP NPS.

Visually, it is quite apparent that the iDose4 NPS to FBP NPS ratio stays much closer to the gold-standard value of one. This can be quantified using the spectral change metric defined earlier. The ratio of the 3rd-Gen IR to gold standard is 19.4% change, whereas the ratio of iDose4 to the gold standard is 5.3%.

Algorithm	Spectral Change (%)
3rd-Gen	19.4
iDose4	5.3

Conclusion

Some iterative reconstruction techniques can change the texture of the reconstructed image. This can be quantified as a change in the distribution of spatial frequency content in the image. Philips' iDose4 algorithm leverages dynamic frequency noise removal to retain the desirable look and feel of gold–standard FBP reconstruction while providing a dramatic dose reduction.

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