AIDR 3D Iterative Reconstruction:

Integrated, Automated and Adaptive Dose Reduction

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Since the introduction of the Aquilion CT, Canon's innovation focus has been on developing methods and tools to increase dose efficiency. Dose efficiency means achieving diagnostic image quality at the lowest possible dose, and is the guiding principle behind ALARA (As Low As Reasonably Achievable). In CT, the balance between image signal and image noise, characterizes image quality. There are two methods to improve image quality, one can increase signal, or one can decrease the magnitude of image noise relative to the signal. The Aquilion CT design focuses on the second method. Rather than increase scanner power and X-ray tube output to maximize signal, Aquilion CT minimizes noise to allow for dose reduction. This was the underlying principle for the development of Adaptive Iterative Dose Reduction 3D (AIDR 3D). AIDR 3D is an iterative reconstruction algorithm designed to reduce radiation dose to the patient without burdening clinical workflow. Through the company's ongoing focus on ALARA optimization, Canon has been a leader in dose efficiency for many years[1].

ALARA imaging is made possible on Aquilion CT through innovative design of hardware and software. One of the main distinguishers of Aquilion CT is its advanced reconstruction technology. At a time when much of the CT industry was focused on increasing generator power, Canon was focusing on dose efficiency through advanced, highly efficient reconstruction techniques.

Canon's key reconstruction milestones contributing to dose reduction in CT, as illustrated in **Figure 1**, are: True Cone Beam Tomography (TCOT), windmill artifact reduction in helical cone beam reconstruction; Quantum Denoising Software (QDS), noise reduction in image space; Boost3D, projection space noise reduction; coneXact Cone Beam Reconstruction, wide volume and double slice reconstruction; Ultra-Helical VCOT, wide cone beam helical reconstruction; and Adaptive Iterative Dose Reduction (AIDR). The first two phases of iterative reconstruction, AIDR and AIDR+ involve noise reduction in image space and the latest development is AIDR 3D iterative reconstruction with noise reduction in both raw data and image space. This focus on improving image quality through innovations in reconstruction put Canon in an ideal position to release iterative reconstruction. In this paper, we will review Canon's key CT reconstruction milestones from Filtered Back Projection (FPB) to iterative reconstruction. This paper will focus on AIDR 3D, its ease of use, and the benefits of an integrated, automated and adaptive design. It will also demonstrate the image quality benefits of this reconstruction method. As will be demonstrated, implementing AIDR 3D in a clinical environment is an easy transition because the reconstruction time is fast, there are no additional steps added to scanning workflow and image quality is improved while maintaining similar spatial resolution and image texture as compared to traditional reconstruction methods. And thanks to the noise reduction and integrated nature of AIDR 3D, dose reduction can be automatically achieved with accelerated workflow.

Windmill Artifact Correction

Initially, Canon introduced a multidetector reconstruction algorithm, MUSCOT, for multidetector CT. However, the combination of wider cone beam helical MDCT and traditional reconstruction algorithms can lead to a

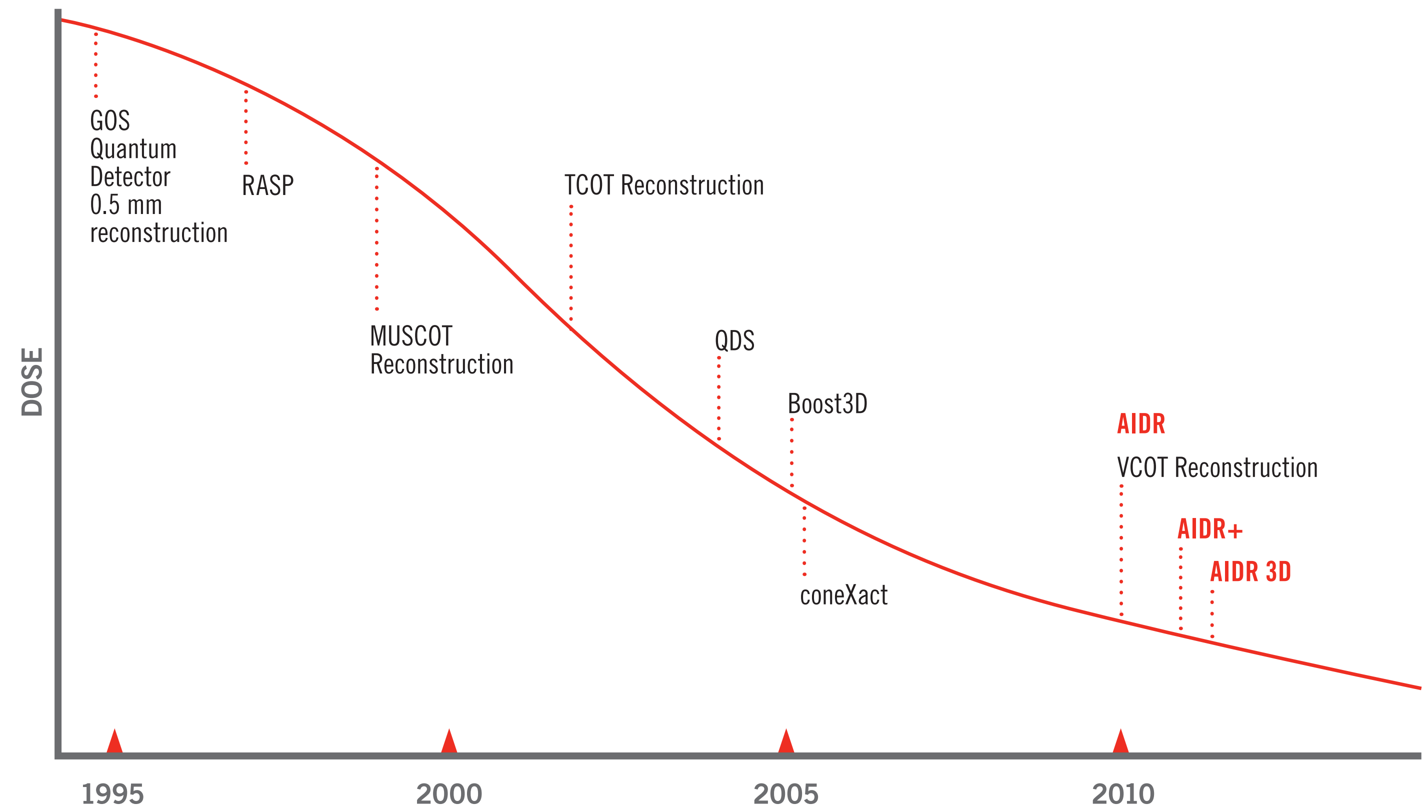

Figure 1: Canon has been leading innovation in reconstruction algorithms since the early days of multidetector CT (MDCT). This timeline represents some of Canon's key reconstruction innovations and dose-reduction technologies.

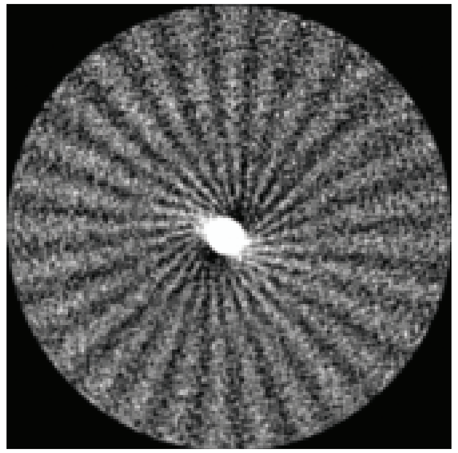

Figure 2: Windmill artifact.

windmill artifact as illustrated in **Figure 2**. Initially introduced on the Aquilion 16, Canon's patented MDCT helical reconstruction technique, TCOT, uses a modified Feldkamp algorithm, employing data from multiple projections in the z-direction to correct for the cone beam effect. TCOT reconstruction is illustrated in **Figure 3A**.

Cone Beam Reconstruction

One of the most highly regarded breakthroughs in CT innovation is the ability to reconstruct wide cone beam images with up to 16 cm of anatomical coverage per gantry rotation. This was made possible with the introduction of the Aquilion ONE 320-detector row dynamic volume CT scanner. While use of a wide cone angle offers the capability of whole organ coverage, it also presents a challenge to image reconstruction as shown in **Figure 4**. In order to successfully incorporate the wide cone angle, an advanced reconstruction technique, known as the coneXact algorithm, was developed. ConeXact enables wide cone angle imaging with up to 16 cm of coverage in volume scan mode on the Aquilion ONE. ConeXact is specifically designed for volume scan modes. However, some clinical applications call for even greater scan lengths and faster scan times. Combining helical scan modes with wide cone beam collimation would be an ideal way to cover large scan lengths quickly. But even with windmill artifact correction, typical MDCT reconstructions are inadequate for these wider collimations. To overcome this challenge, Canon developed the first cone beam reconstruction algorithm specifically for volume helical scanning. This Ultra-Helical reconstruction algorithm called VCOT reconstructs up to 8 cm of coverage per rotation[2].

QDS and Boost3D

Canon was the first CT vendor to introduce adaptive noise reduction algorithms in image space and raw data space. These noise-reduction algorithms called QDS and Boost3D are used to improve signal relative to noise, thus allowing lower dose imaging. This type of noise-reduction algorithm is often referred to as first generation noise reduction (or second generation reconstruction where simple FBP is considered the first generation of reconstruction).

QDS adaptively reduces quantum noise in the reconstructed image. In most cases, quantum noise is the predominant source of image noise, heavily influencing detectability of low-contrast objects (other types of noise include electronic and anatomic noise). QDS reduces the magnitude of quantum noise in the image and improves the signal-to-noise ratio while preserving spatial resolution and image texture. QDS allows image acquisition at a lower dose than would otherwise be possible, thus helping to optimize dose efficiency. **Figure 5** illustrates the QDS algorithm[3].

Boost3D is a noise-reduction tool that operates in the raw data domain and improves image quality by reducing both the magnitude of quantum noise and the presence of structured noise. Structured noise, unlike the random quantum noise, has a pattern, e.g. streak artifact. Boost3D adaptively targets regions of low photon count in the raw projection data and applies a correction to these portions of the raw data. Boost3D addresses photon starvation caused by high-attenuation regions such as the shoulders and helps avoid the need to increase tube current to account for high-density regions, thus enabling lower dose imaging. See **Figure 6** for a clinical example of Boost3D.

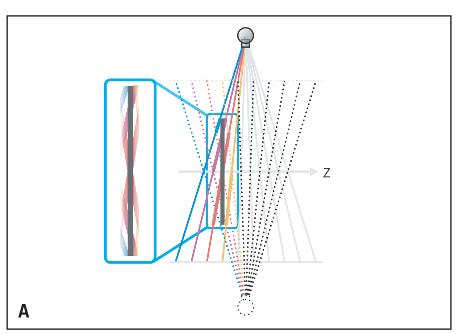

Figure 3A: TCOT Helical reconstruction.

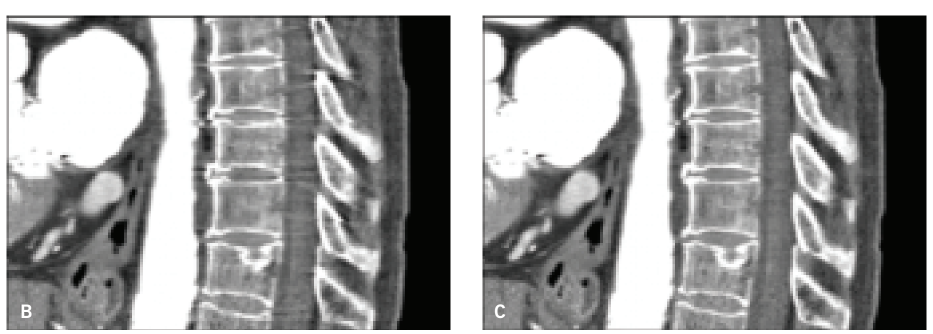

Figure 3B & C: Windmill artifact caused by MUSCOT Filtered Back Projection (FBP), **(C)** TCOT reconstruction of the same data accounts for the shape of the cone beam thus correcting for windmill artifact.

AIDR 3D* Iterative Reconstruction

AIDR 3D is Canon's latest evolution of iterative reconstruction technology; it has been fully integrated and automated into the imaging chain to improve dose reduction and image quality. It is designed to reduce dose by reducing the magnitude of image noise while preserving image detail, allowing for lower dose acquisitions. The reconstruction process incorporates raw data and image space noise optimization. During AIDR 3D reconstruction, a scanner model and a statistical noise model are taken into account to minimize the effects of photon starvation and electronic and statistical noise in projection space while an image-based anatomical model minimizes quantum noise magnitude. AIDR 3D is 3rd generation noise-reduction technology, which is also sometimes referred to as 4th generation reconstruction. The AIDR 3D process is illustrated in **Figure 7**.

To improve noise characteristics in projection space, the photon count is analyzed at each position in the raw data and an adaptive algorithm is applied based on advanced statistical and scanner modeling. The raw data space components enhance the preservation of spatial resolution while decreasing overall noise magnitude as well as the manifestation of structured noise in the image due to low photon counts, such as streaks artifacts. A voxel-based, noise-reduction component in image space adapts to feature voxel gradients, reducing the magnitude of noise with each iteration while preserving fine image details such as lines and edges. With each iteration, AIDR 3D fine-tunes these results for the particular exam, balancing the relationship between noise-magnitude reduction and spatial-resolution preservation. The original FBP image is used as an input for each iteration and is adaptively blended with the processed data to create the final image, helping to ensure the noise texture is well maintained for the viewer. AIDR 3D reconstruction can be highly effective in reducing dose to the patient as demonstrated in **Figures 8A and 8B**. And with reconstruction times up to 32 frames per second, AIDR 3D is fast (typical routine chest reconstruction times are approximately 28 frames per second). It is fully integrated, adaptive, and automated for accelerated workflow.

As demonstrated in **Figures 15–18**, AIDR 3D reconstruction can be used to achieve diagnostic image quality with doses as low as, and for some exams even lower than, the average doses that individuals living in the United States absorb yearly from natural sources (average annual background

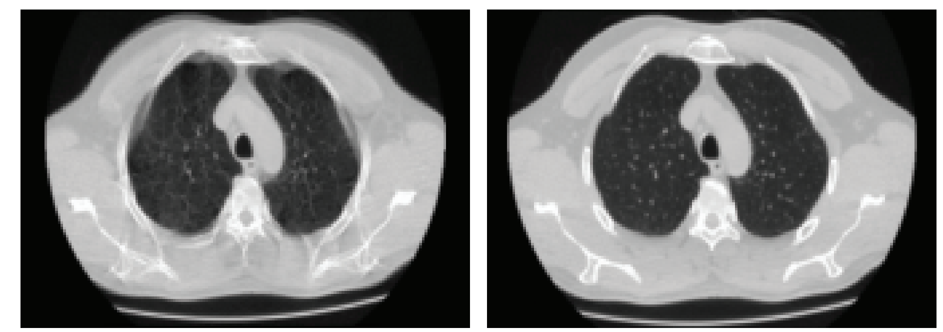

Figure 4: The image on the left demonstrates cone beam artifact with shading, ghosting, and diminished resolution. This is a result of a reconstruction algorithm that does not properly take into account the wide cone angle. The image on the right is the same dataset reconstructed with coneXact. Notice coneXact eliminates the cone beam artifact.

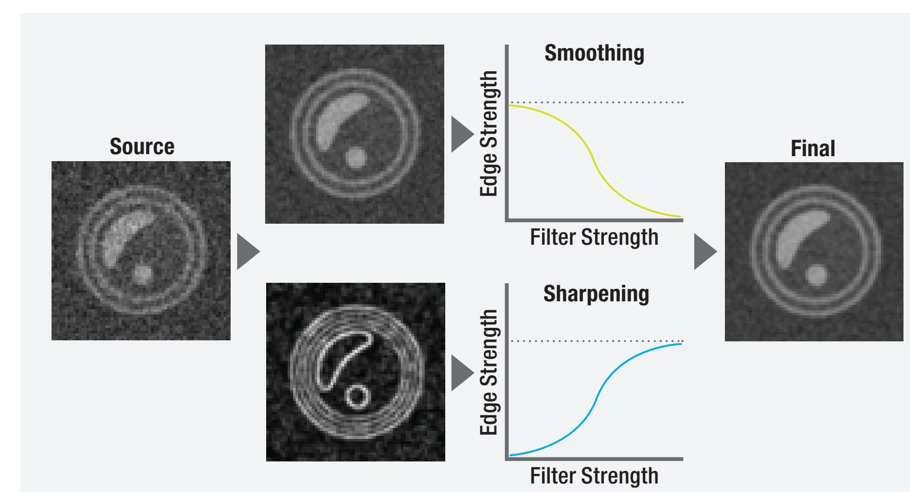

Figure 5: QDS image space noise reduction operates by determining edge strength and applying variable strength smoothing and sharpening filters in three dimensions. This reduces noise while maintaining spatial resolution.

**In clinical practice, the use of AIDR 3D may reduce CT patient dose depending on the clinical task, patient size, anatomical location, and clinical practice. A consultation with a radiologist and a physicist should be made to determine the appropriate dose to obtain diagnostic image quality for the particular clinical task.*

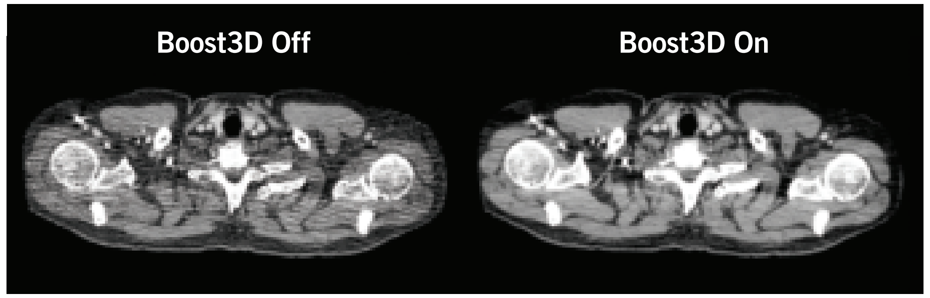

Figure 6: Boost3D reduces streak artifact off the shoulders, allowing for lower doses to be used.

exposure from non-man-made sources for US residents is estimated to be approximately 3 mSv/year[4]).

AIDR 3D is Integrated Dose Reduction

Iterative reconstruction is often thought of as simply noise reduction with the potential benefit of dose reduction. If iterative reconstruction is not integrated into the system design, dose reduction is only achieved by manually adjusting tube current settings for each protocol.

AIDR 3D reconstruction on the other hand, is integrated into system design so dose reduction can be achieved automatically for tube current modulated studies. ^{SURE}Exposure XYZ tube current modulation automatically reduces the mA based on the expected reduction in noise magnitude from AIDR 3D, eliminating the need to manually lower mA or adjust tube current modulation settings. AIDR 3D reduces noise to achieve the target image quality level (SD setting) for the imaging task and the tube current is simultaneously adjusted to lower the dose. The integrated design of AIDR 3D is demonstrated in **Figure 9**.

AIDR 3D is Automated

With the intelligent design of the AIDR 3D algorithm, there is no need to select AIDR 3D levels. AIDR 3D automatically adapts to the body region and type of exam, as well as the amount of signal in the projections, to ensure the algorithm parameters are optimized for the exam. AIDR 3D automates many internal parameters for the imaging task such as number of iterations and percent blending with FBP, automatically taking into consideration the importance of edge detail and noise sensitivity for each exam type. AIDR 3D knows the exam type for each exam based on the ^{SURE}IQ settings.

^{SURE}IQ is a workflow simplification tool. It combines imaging reconstruction parameters into a single easily selectable category for each type of imaging (e.g., Low Dose Lung). Reconstruction parameters such as the reconstruction filter are automatically selected and AIDR 3D is alerted to the imaging type so it can automatically select the optimal algorithm settings for the exam type.

Although AIDR 3D is designed to automatically select the appropriate parameters for the exam type, operators may still wish to have some manual control of the algorithm. This is why AIDR 3D is equipped with adjustable strengths. Although AIDR 3D will generally be used in the standard setting, AIDR 3D does have three strengths that can be selected: Strong, Standard, and Mild. The Standard setting is recommended for most clinical protocols, but all three settings are available for research purposes.

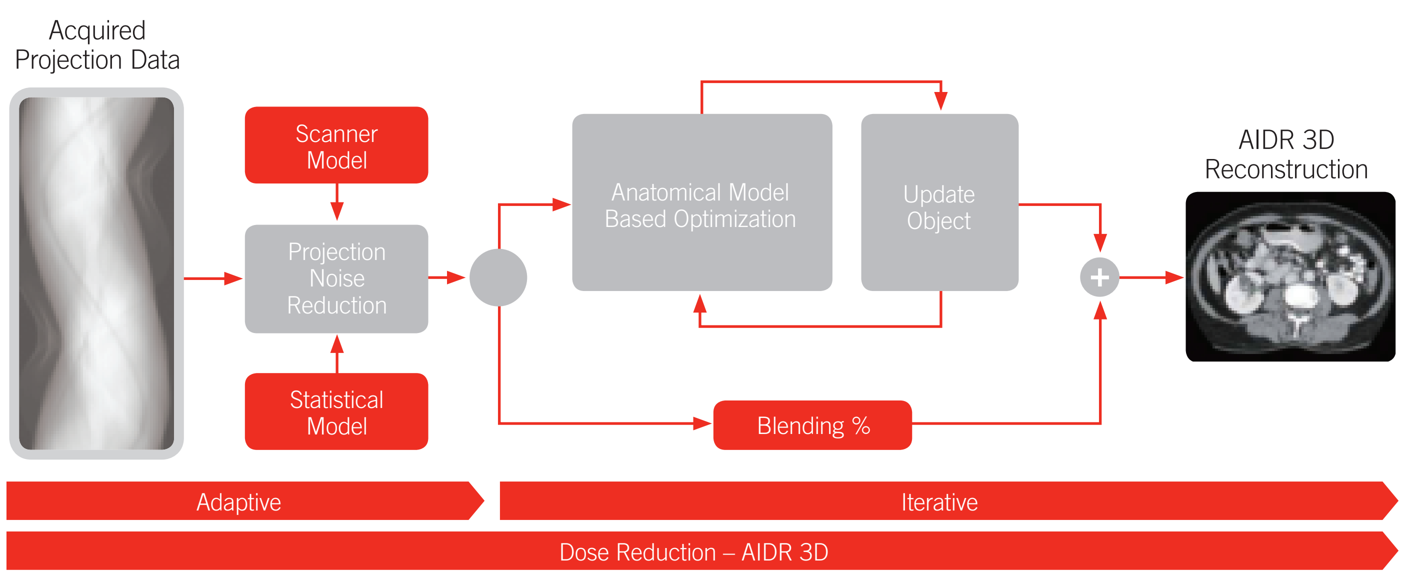

Figure 7: AIDR 3D is adaptive iterative reconstruction designed to allow for dose reduction by reducing the magnitude of image noise while preserving image detail.

AIDR 3D is Adaptive

AIDR 3D reconstruction is adaptive and can be used for all imaging tasks. It can be used for helical and volume scan modes as well as well as ECG gated acquisition scan modes. The dose reduction or image quality associated with AIDR 3D can be realized for all routine adult and pediatric head and body CT. The potential to reduce patient dose for routine CT can have a profound effect on patient safety during CT scanning.

Possibly one of the more intriguing applications of AIDR 3D reconstruction is dynamic scanning. Recently, there have been significant developments in time-resolved imaging such as brain perfusion, myocardial perfusion and body perfusion. As the clinical benefits of time-resolved imaging are further

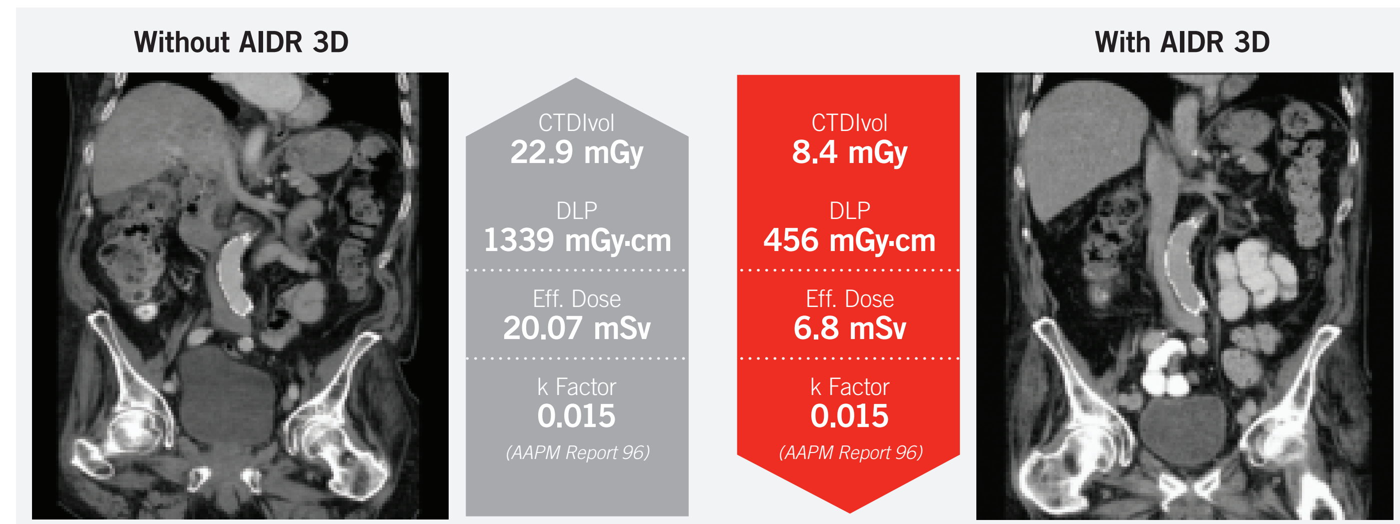

Figure 8A: Abdomen/Pelvis CT acquired without AIDR 3D with an estimated effective dose of 20 mSv (left). The same patient had another abdomen/pelvis CT about 1 month later with AIDR 3D (right). The estimated effective dose for the AIDR 3D exam was 6.8 mSv; 67% lower than the non-AIDR 3D exam.

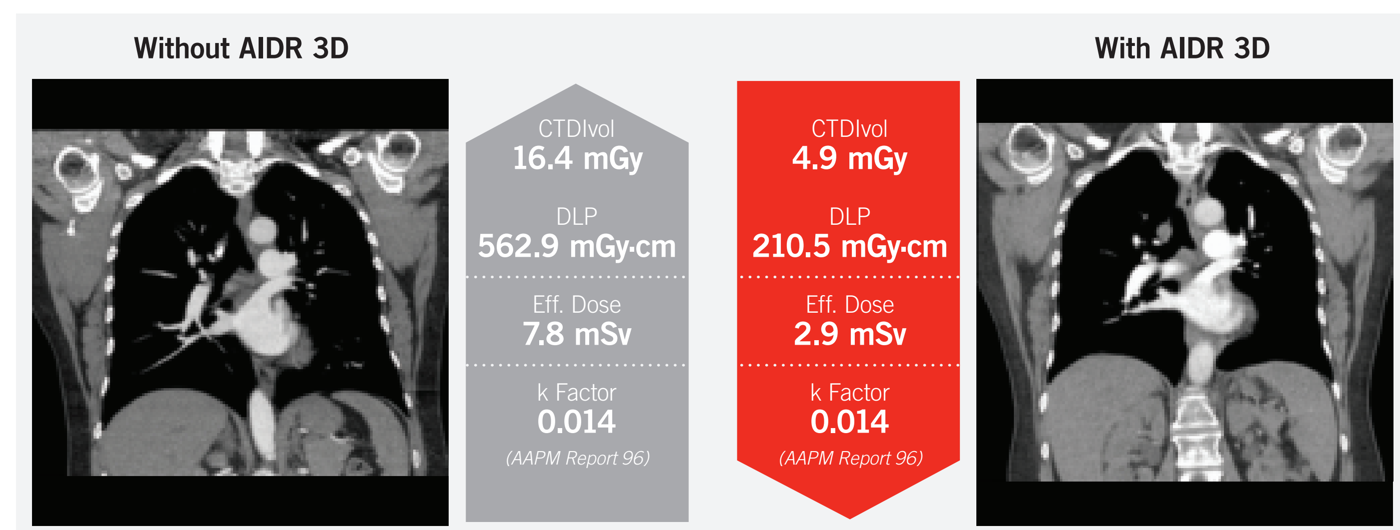

Figure 8B: A chest CT without AIDR 3D (left) and with AIDR 3D (right) for the same patient. The CTDIvol for the AIDR 3D study was 70% lower than the exam without AIDR 3D.

developed, CT is shifting from simply an anatomical imaging device to a device used for functional and anatomical analysis. AIDR 3D plays an important role in the development of functional imaging as it allows perfusion images to be acquired at lower doses than was previously considered feasible.

AIDR 3D Reduces Image Noise

Noise in a CT image obscures visibility. AIDR 3D iterative reconstruction removes noise from the raw projection data and in image space. This improves image quality and the visibility of smaller less dense objects as demonstrated in **Figure 11**. AIDR 3D automatically adapts to the amount of noise in the acquired data to achieve a low-noise image nearly independent of the tube current time product (mAs). In other words, the potential for noise reduction with AIDR 3D will vary with imaging variables such as mAs and patient size because noisier images have more noise to remove. But the final image noise will be reliably and consistently low. This non-linear mAs and noise relationship is demonstrated in **Figure 10**.

Due to the non-linear behavior of iterative reconstruction, Low Contrast Resolution (LCR) can no longer be used as a reliable metric for overall system dose efficiency. LCR is still a useful metric for assessing the dose efficiency of the base CT system prior to applying iterative reconstruction. But when assessing an image reconstructed with iterative reconstruction, more complex metrics must be used to assess image quality and the preservation of diagnostic information.

AIDR 3D Preserves Diagnostic Information

AIDR 3D reconstruction preserves diagnostic information, spatial resolution, and image texture by removing noise rather than simply smoothing it out. Even though image smoothing reduces noise, it also smooths out edge content, degrades spatial resolution, and may smooth out important diagnostic information. Smoothing can also change the image texture causing a blurry or plastic-like appearance. AIDR 3D reconstruction, on the other hand, maintains similar spatial resolution, image texture, and edge content to FBP by adapting to the image features and exam type.
As demonstrated by the Noise Power Spectrum (NPS) in **Figure 12**, AIDR 3D maintains similar image texture to FBP even at significantly lower doses. The shape of the NPS relates to image texture. Visible changes in image texture are characterized by large shifts in the NPS curve. **Figure 12** shows the NPS curves for a typical abdomen protocol acquired with 250 mAs for the FBP image and 75 mAs for the AIDR 3D image[5]. Despite applying a 70% dose reduction, the shape of the AIDR 3D curve is similar to the FBP curve demonstrating similar image texture even with significant dose reduction applied. By maintaining image texture, AIDR 3D maintains the "natural look" of FBP imaging. With less advanced iterative reconstructions, radiologists may have trouble reading images because of altered image texture, which they may describe as "plastic," "blotchy," or "Monet-like." By maintaining a similar image texture to FBP, AIDR 3D prevents radiologists from having to read through an unfamiliar image texture.

While it is important to minimize noise, noise reduction is often associated with loss of image detail or spatial resolution. AIDR 3D on the other hand maintains detail in the images. As demonstrated in **Figure 13**, spatial resolution of AIDR 3D images is maintained similar to FBP reconstruction. In a more mathematical representation of spatial resolution preservation, **Figure 14** shows the Modulation Transfer Function (MTF) of AIDR 3D reconstruction compared to FBP for the same acquisition. MTF measures a system's ability to resolve high-contrast objects of increasingly smaller sizes (smaller objects are represented by more line pairs per cm). In this example, the MTF of AIDR 3D is nearly identical to FBP, thus demonstrating that the signal is preserved and spatial resolution remains similar.

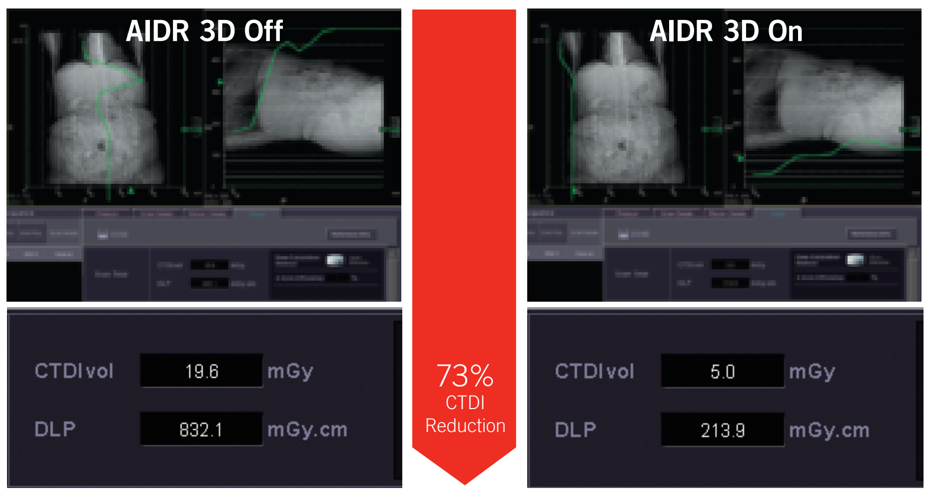

Figure 9: Example of SUREExposure integration: Prior to scan, AIDR 3D was toggled off (left) and on (right) in the protocol to demonstrate how SUREExposure automatically reduces the tube current (see green mA curve), thus lowering the dose (CTDI) automatically.

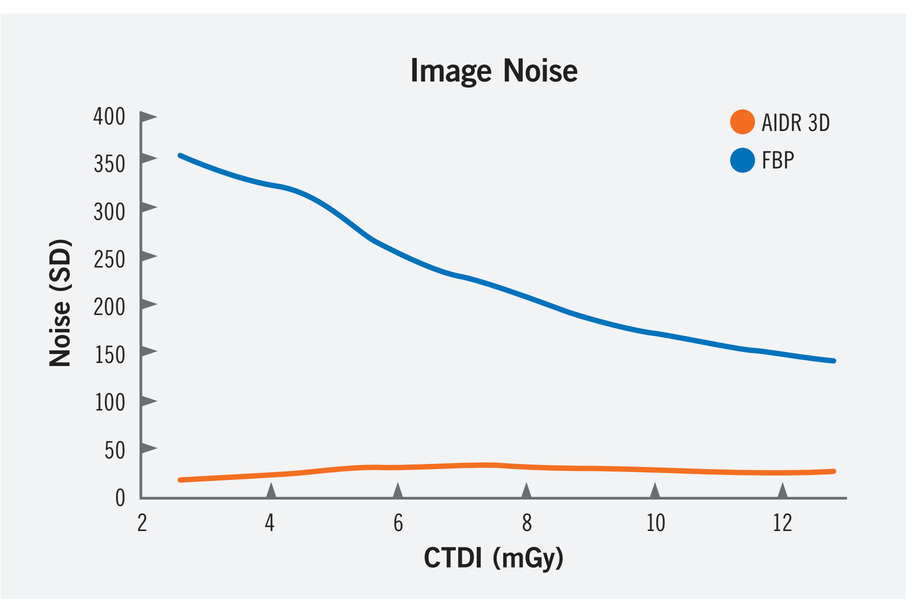

Figure 10: Noise magnitude (standard deviation) versus dose. Measured in a 40 cm water phantom.

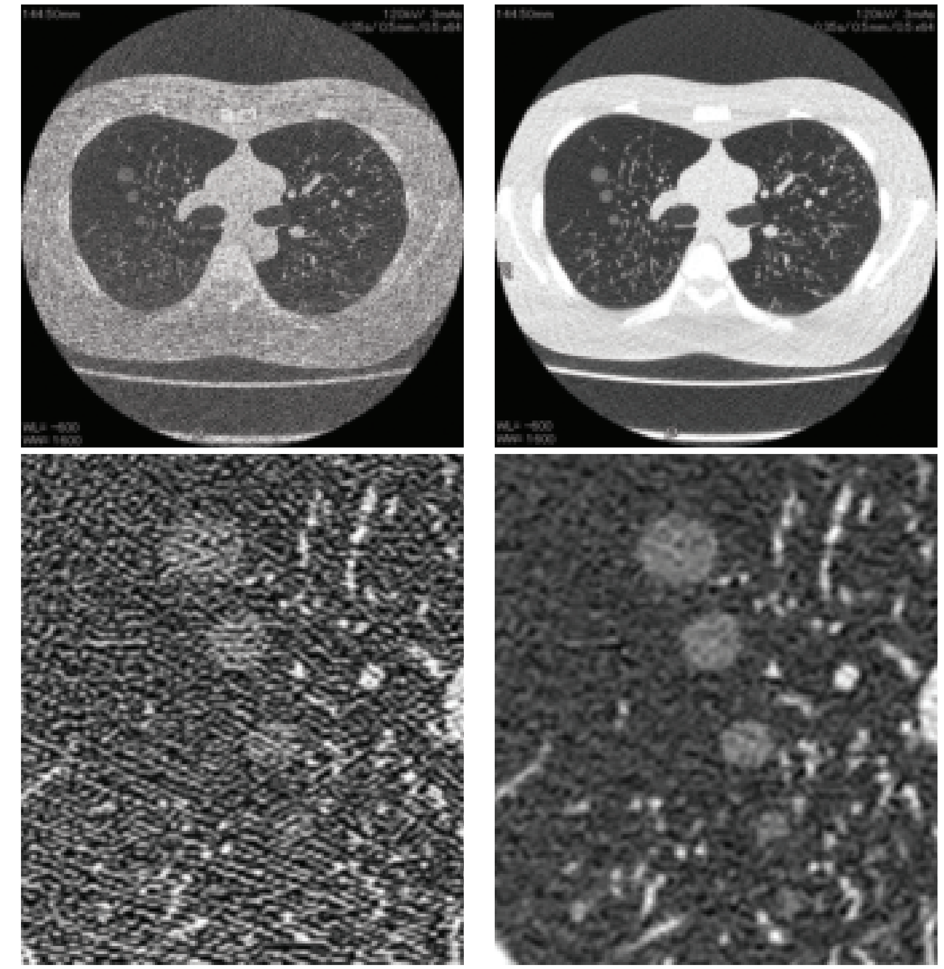

Figure 11: Images obtained with FBP reconstruction (left), and AIDR 3D reconstruction (right) of a chest phantom with low contrast objects of various sizes imaged with ultra low dose. The effective dose for this acquisition was estimated to be 0.09 mSv (k-factor = 0.014 mGy*cm*mSv-1). *Images courtesy of Keio University, Japan.*

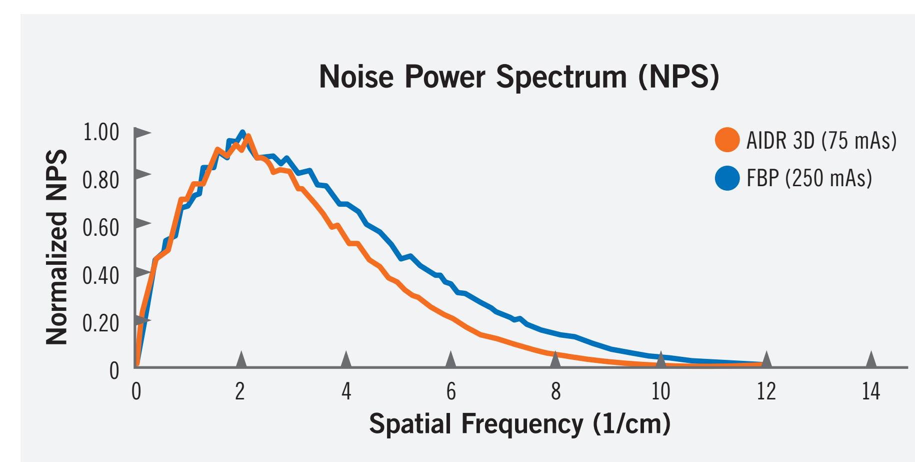

Figure 12: Noise Power Spectrum (NPS) normalized to maximum for an abdomen protocol reconstructed with FBP acquired at 250 mAs and AIDR 3D acquired at 75 mAs. The shape of the AIDR 3D curve is similar to the shape of the FBP curve signifying similar image texture despite a 70% mAs reduction for the AIDR 3D image.

Conclusion

Canon's innovations in reconstruction technology continue to push the limits of dose efficiency. With each new development, Aquilion CT achieves a new level of ALARA imaging further reducing dose for a given image quality. AIDR 3D reconstruction is advanced noise reduction, improving CT imaging and offering dose-reduction potential for patients with a wide variety of imaging needs. AIDR 3D stands apart in its implementation. It automatically adapts to the imaging task and is integrated into the imaging chain to automatically achieve dose reduction. When SUREExposure tube current modulation is used, there is no need to guess appropriate parameter or level settings for the algorithm. Thanks to the adaptive and integrated nature of this technology as well as the fast reconstruction times with accelerated workflow capabilities, implementing AIDR 3D in a clinical environment is an easy transition. The image quality improvements gained by AIDR 3D are not compromised by strange or unfamiliar image texture as the image texture is maintained similar to traditional reconstruction methods. AIDR 3D offers clinicians and patients a personalized dose management solution.

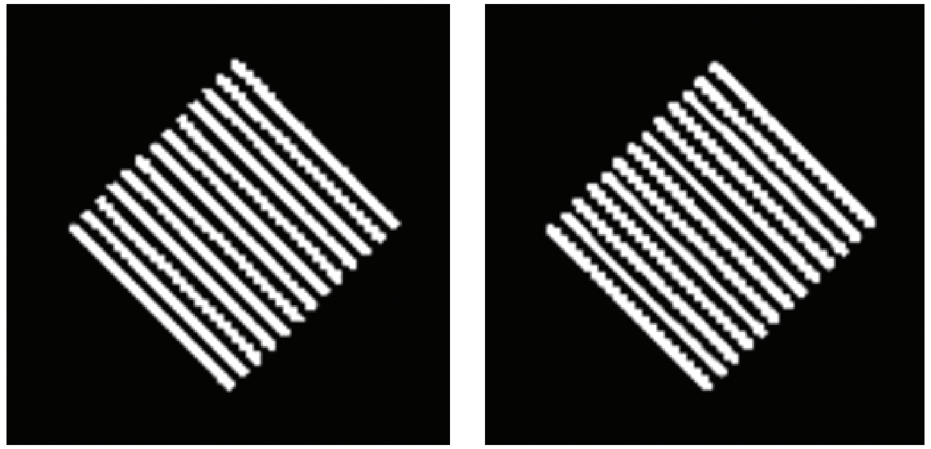

Figure 13: A single acquisition of a bar-resolution pattern of 8-line pairs/cm acquired using the ACR CT accreditation phantom (Gammex 464, Gammex). Images were reconstructed with FBP (left) and AIDR 3D iterative reconstruction (right). With the AIDR 3D reconstruction, spatial resolution is similar to FBP.

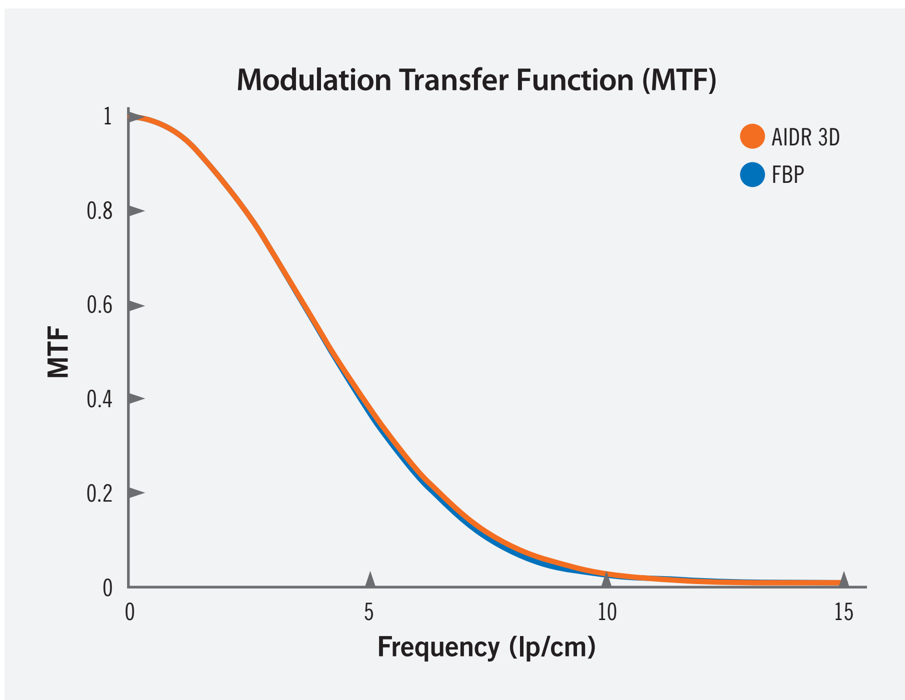

Figure 14: Modulation Transfer Function (MTF) measures a system's ability to resolve high-contrast objects of increasingly smaller sizes (smaller objects are represented by more line pairs per cm). In this example, the MTF of AIDR 3D is nearly identical to FBP thus demonstrating preservation of spatial resolution.

CTDIvol	DLP	Effective Dose	k Factor*
1.9 mGy	24 mGy·cm	0.33 mSv	0.014

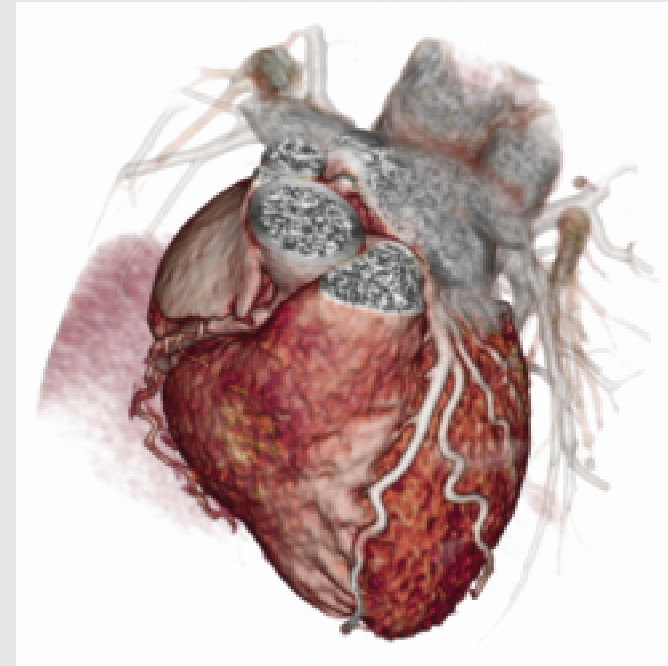

Figure 15: Ultra-Low Dose Cardiac CTA.

CTDIvol	DLP	Effective Dose	k Factor*
5.1 mGy	355.5 mGy·cm	5.1 mSv	0.0145

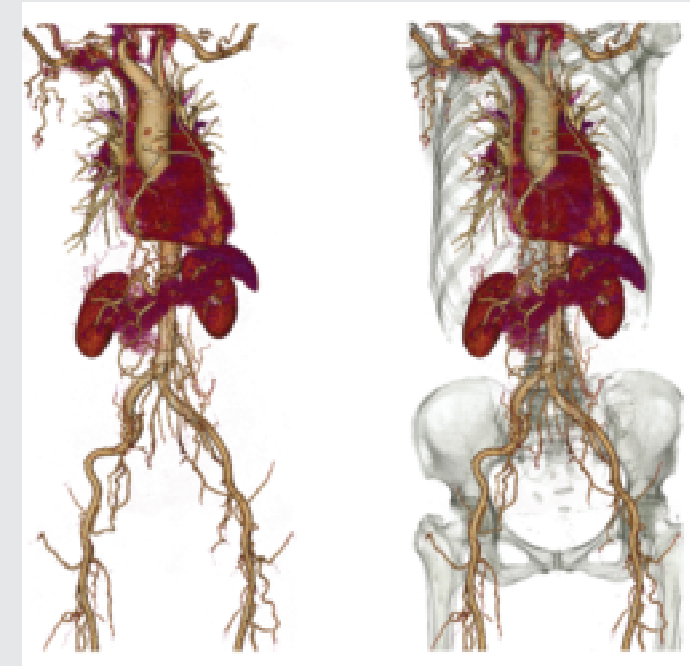

Figure 16: Ultra-Low Dose CT Aortogram.

CTDIvol	DLP	Effective Dose	k Factor*
0.3 mGy	11.6 mGy·cm	0.16 mSv	0.014

Figure 17: Ultra-Low Dose Lung Screening CT.

CTDIvol	DLP	Effective Dose	k Factor*
42 mGy	587.9 mGy·cm	1.2 mSv	0.0021

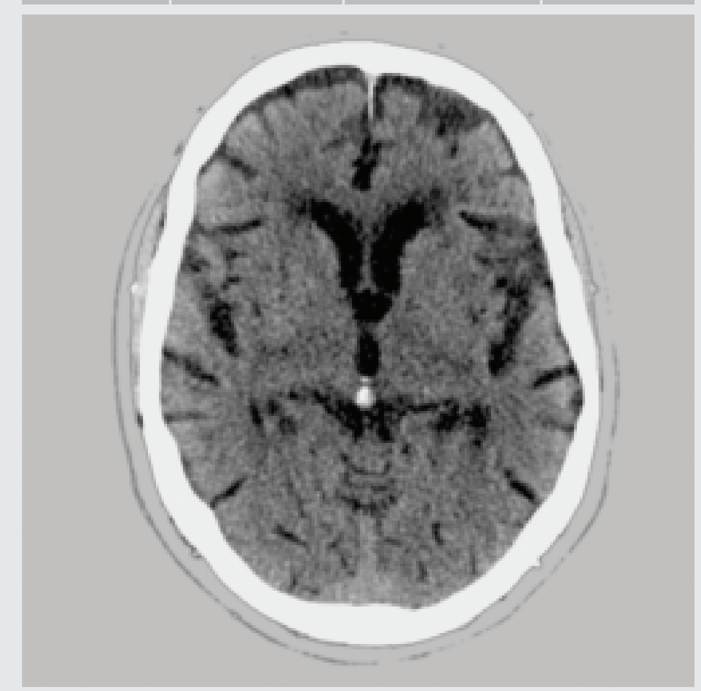

Figure 18: Head CT.

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