TOSHIBA MEDICAL

Forward projected model-based Iterative Reconstruction SoluTion "FIRST"

Raoul M.S. Joemai, PhD
Jacob Geleijns, PhD
Leiden University Medical Center,
Leiden, the Netherlands

Introduction

The reduction and management of radiation dose has been a driving force behind the technological development of Computed Tomography (CT) over the last decade. The ability to decrease radiation dose while maintaining or improving image quality has been brought to life by advancements in hardware and software at nearly every step of the imaging chain. Over the years, innovations in X-ray tube optics, detector design, and system electronics, as well as the introduction of image domain and raw data domain de-noising techniques, have advanced patient care.[1-4] Today, the realization of true model based iterative reconstruction (MBIR) represents the latest technological advancement in CT and dose reduction.

From Back Projection to Forward Projection

Model based iterative reconstruction is a complex, adaptive technique that converges on the best answer to the question, "Given a large set of individual projections through the patient, what is the optimal image that can be formed?" First proposed by Sir Godfrey Hounsfield back in the late 1960's, MBIR has long been considered the preferred reconstruction method for CT. However, early implementations of MBIR required several hours of processing time on supercomputers in order to generate CT images and it remained a prohibitively slow technique for decades. As a result, the less precise but much faster filtered back projection (FBP) reconstruction technique became the dominant reconstruction method in CT. To understand the advantages of MBIR, it is important to first understand the strengths and weaknesses of FBP.

Filtered Back Projection (FBP)

Filtered back projection is a reconstruction technique that follows a fixed procedure in which the measured projection data from each position around the patient is first mathematically filtered, in part according to a user-input reconstruction kernel, and then back projected, i.e., "smeared" back along a matrix, to form an image. Areas where the back projected data reinforce each other form structures; in general, the more projections contributing to the image, the better the final image quality.

This straightforward process, coupled with several simplifying assumptions, makes FBP fast and workflow efficient. However, the assumptions used by the FBP algorithm result in tradeoffs that can be summarized as follows:

1) The physical size of the focal spot is assumed to be infinitely small, which results in image blurring.
2) The detector size is ignored and the algorithm considers the photon interactions to occur in the geometrical center of the detector elements, further impacting spatial resolution.
3) Each of the projections is considered to be made up of mono-energetic X-rays originating from the focal spot with a fan-beam geometry without the influence of photon statistics or scatter, which can lead to artifacts and loss of contrast.

4) All projections are weighted equally, leaving the algorithm unable to cope effectively with issues such as truncated datasets.
5) When selecting a reconstruction kernel, an increase in spatial resolution is hampered by a corresponding increase in noise.

Multidetector row CT drove improvements to cone-beam correction methods and scatter modeling algorithms which evolved as detector coverage increased from 2 cm to 4 cm up to a full 16 cm as in Aquilion ONE.™ While correction factors have been successful in overcoming some of the issues, FBP remains limited in its ability to perform in low-dose conditions. Lacking the necessary computing power for forward projected MBIR, alternative solutions using iterative filtering in the image and raw data domains emerged. Sophisticated hybrid algorithms such as AIDR 3D (Adaptive Iterative Dose Reduction 3D) have become a powerful reconstruction approach for reducing the tradeoff between noise reduction and spatial resolution.

Adaptive Iterative Dose Reduction 3D (AIDR 3D)

AIDR 3D is a hybrid reconstruction algorithm incorporating raw data domain and image domain noise reduction techniques which reduce noise and artifacts while preserving a high level of spatial resolution.[5-13]

Toshiba Medical took the additional step of integrating AIDR 3D into their tube current modulation system, ensuring automated dose reduction based on patient size, a user-determined target level of image quality, and the noise reduction capabilities of AIDR 3D. This integrated and automated design helped to ensure the rapid adoption of AIDR 3D into clinical practice—a process which can otherwise be challenging to workflow for iterative-based algorithms.

While they may be effective in reducing image noise and artifacts, and therefore radiation dose, hybrid algorithms are nonetheless based on FBP reconstruction and retain some of its limitations. To overcome these, true forward projected model-based iterative reconstruction is needed.

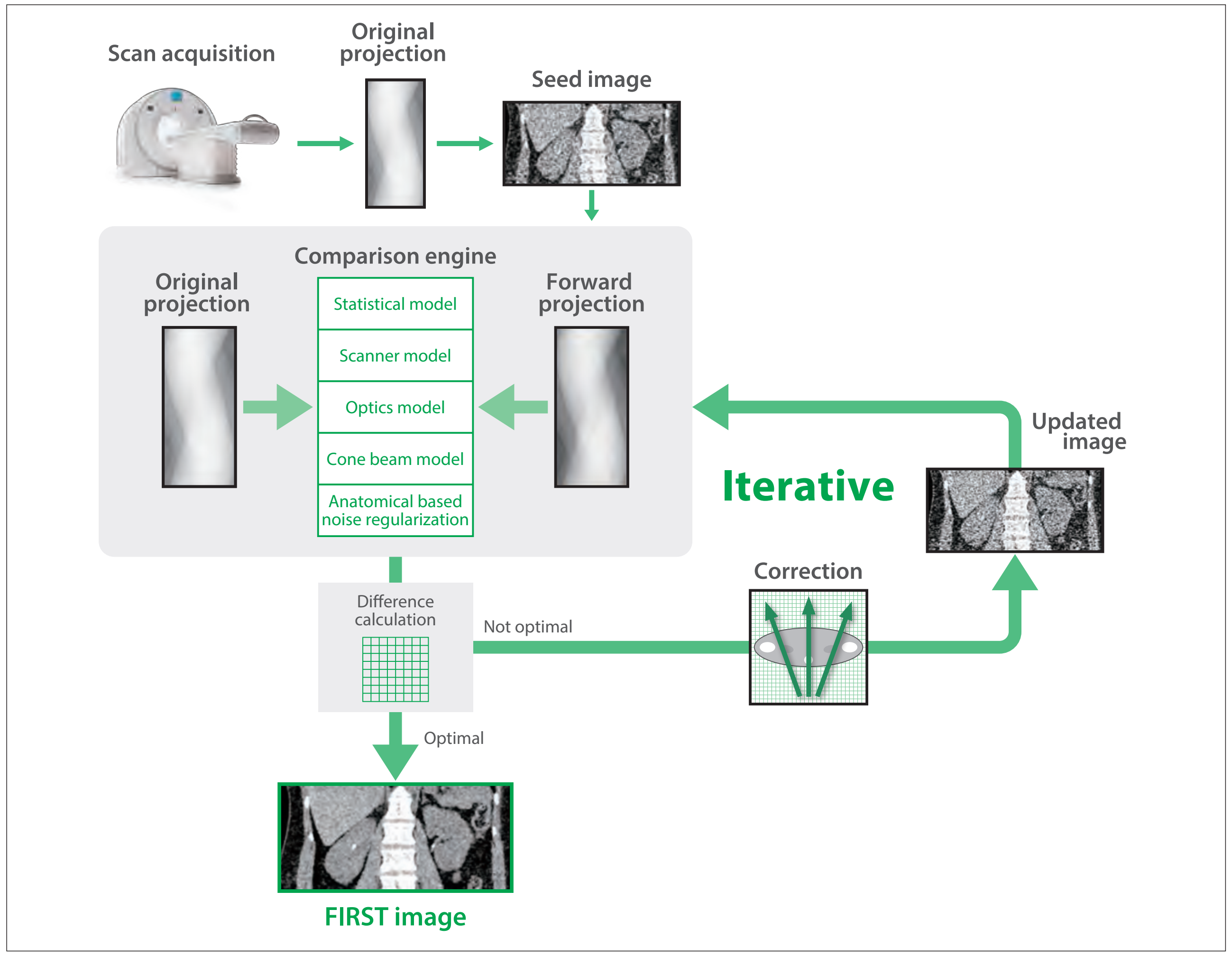


Figure 1 Reconstruction process of Forward projected model-based Iterative Reconstruction SoluTion (FIRST).

Forward projected model-based Iterative Reconstruction SoluTion (FIRST)

The forward projected model-based iterative reconstruction algorithm from Toshiba Medical (FIRST) is a true, fully implemented MBIR algorithm, meaning a forward projection step is performed for every iteration.[14-16] FIRST operates by formulating an initial "guess" at an image result based on the measured raw projection data acquired during the scan. This initial guess is called a "seed image." The seed image is then forward projected in a process that mathematically mimics the process of data acquisition to create a new set of synthesized projection data. This new set of synthesized projections is then fed into the iterative reconstruction loop, as shown in Figure 1.

The general form of an iterative reconstruction algorithm can be described by the following equation, known as an objective function.

$$\hat{x} = \arg min_{x\geq 0} \frac{1}{2} \| y - Ax \|_w^2 + \beta R(x)$$

Eqn 1: Objective function for iterative reconstruction. The term on the left is called the data fidelity term, where A is a linear operator, y is the measured projection data, and x is the synthesized projection data, while the term on the right is known as the regularization term, R(x), where β>0 is a parameter.

Once the synthesized forward projections are fed into the algorithm, they enter a mathematical comparison engine which compares the synthesized forward projection data to the original projection data to determine the differences between the synthesized and actual raw projection data. A difference calculation determines the minimum number of iterations necessary to converge on the desired image quality.

The data fidelity term in Eqn 1 (left-hand term) serves to enforce the consistency between the synthesized forward projections and the measured raw data projections throughout the iterative process. Minimizing the data fidelity term requires optimal system modeling and is responsible for improvements in spatial resolution and reductions in artifacts. The comparison engine also utilizes a statistical noise map model to incorporate the noise properties of the original projection data such that the synthesized projections are updated to more closely resemble the original measured projections with noise removed.

If one were to perform iterative reconstruction with just the data fidelity term alone, the iteration might not converge to a low-noise solution. Therefore, the regularization function (right-hand term in Eqn 1) is employed to reduce noise while preserving spatial resolution. This is accomplished by penalizing large differences in neighboring voxels. The mathematical approach used for regularization can vary significantly between MBIR algorithms. In the case of FIRST, the regularization includes both statistical edge-preserving noise reduction and anatomically-based noise reduction.

After the data fidelity and regularization terms act on the synthesized projections from the seed image, the resulting updated synthesized projections then undergo back projection to produce a new image. Starting with this new image, the process then repeats or "iterates" until it converges on the optimal solution.

It is important to realize that the measured projections contain noise and blurring and therefore the goal of iterative reconstruction is not to achieve the best match between the synthesized projections and the measured projections. Rather, the goal is to iterate until the synthesized, forward projected data suggest that the resultant image is the most accurate representation of the person or object being scanned, given what we know about the measured projections, the nature of noise, and the sources of noise and artifacts. This is achieved through the use of sophisticated models in the forward projection process which ensure that forward projected MBIR reduces image noise while improving high contrast spatial resolution. These models are described in more detail in the next section.

Modeling in FIRST

Accurate modeling of the entire imaging process is essential to achieving optimal image quality. There are four main models found in true MBIR: the statistical noise model, the scanner model, the optics model, and the cone beam model.

Statistical Noise Model

Images can be distorted by various types of noise such as random photon noise, anatomical noise, structural noise due to photon starvation, and electronic noise. Furthermore, every detector element can have unique noise characteristics. The resulting image noise from all these sources can impair the clinically vital task of identifying low contrast objects such as liver lesions. FIRST models the statistical properties of noise into the algorithm and appropriately reduces noise-induced variations in image pixel values, greatly reducing image noise and improving low contrast detectability.

The following figure (Figure 2) shows both FBP and FIRST reconstructed images of a low contrast phantom at the same dose, highlighting the improvement of low contrast detectability associated with FIRST.

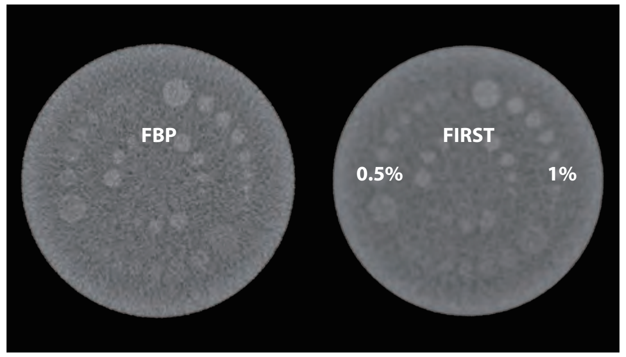


Figure 2 Low Contrast Phantom: FBP vs FIRST

The noise modeling in FIRST is also what drives its dose reduction capabilities. As mentioned previously, low contrast detectability is a vital clinical objective and an excellent benchmark of machine performance. In order to characterize the dose reduction potential of the FIRST algorithm, a statistically rigorous observer study[*1] was conducted comparing low contrast detectability in images reconstructed with a standard abdominal FBP algorithm at a baseline dose and then at reduced dose levels reconstructed with FIRST Body mode. It was found that FIRST can achieve the same low contrast detectability with up to 84.6% less dose than FBP, and even at this reduced dose level, the images still showed a 60% reduction in noise levels compared to the baseline images (Figure 3).

Scanner Model

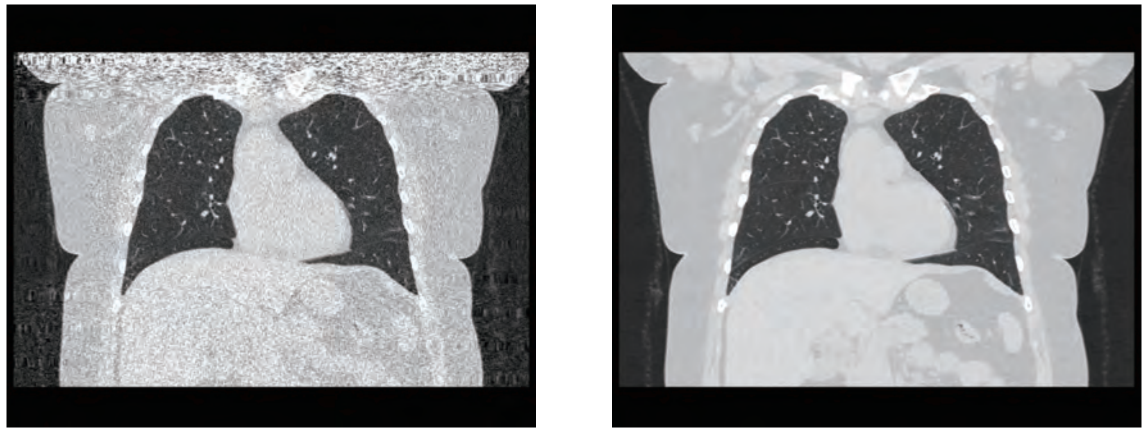
A true MBIR algorithm requires that the scanner be modeled with a high degree of detail in order to generate accurate forward projections throughout the iterative process. The more detailed the scanner and optics models, the better the spatial resolution and mitigation of artifacts. A scanner model generally consists of the scanner geometry, including bowtie filtration, collimation, source to isocenter and detector distances, and/or detector geometry.

Optics Model

The optics model simulates the path of the photons as they travel from the focal spot through the image voxels and finally to their arrival at the model's detector elements. Furthermore, the impact of blurring caused by scatter or other random variations in the X-ray photon paths are also accounted for.

The combined impact of the scanner and optics models is superior high contrast spatial resolution compared to FBP. As can be seen in the MTF curves in Figure 4, the high contrast spatial resolution of FIRST (Body mode) is superior to that of FBP, resulting in 7.7 lp/cm more resolution at 10% of the MTF.

The increased high contrast spatial resolution helps users to make a more confident and reliable diagnosis in tasks that involve small objects and fine details, such as musculoskeletal, thoracic, and cardiac applications. For example, the reduction of blooming artifacts from calcium in the coronary arteries enhances the visualization of lesions and the improvement in resolution allows superior stent imaging by providing greater detail to help determine if in-stent restenosis is present. Figure 5 demonstrates the improved visualization of fine details in a Catphan® phantom with line pair metallic objects.



FBP Reconstruction
80% Dose Reduction

FIRST Reconstruction
80% Dose Reduction

Figure 3 Chest CT at 80% dose reduction

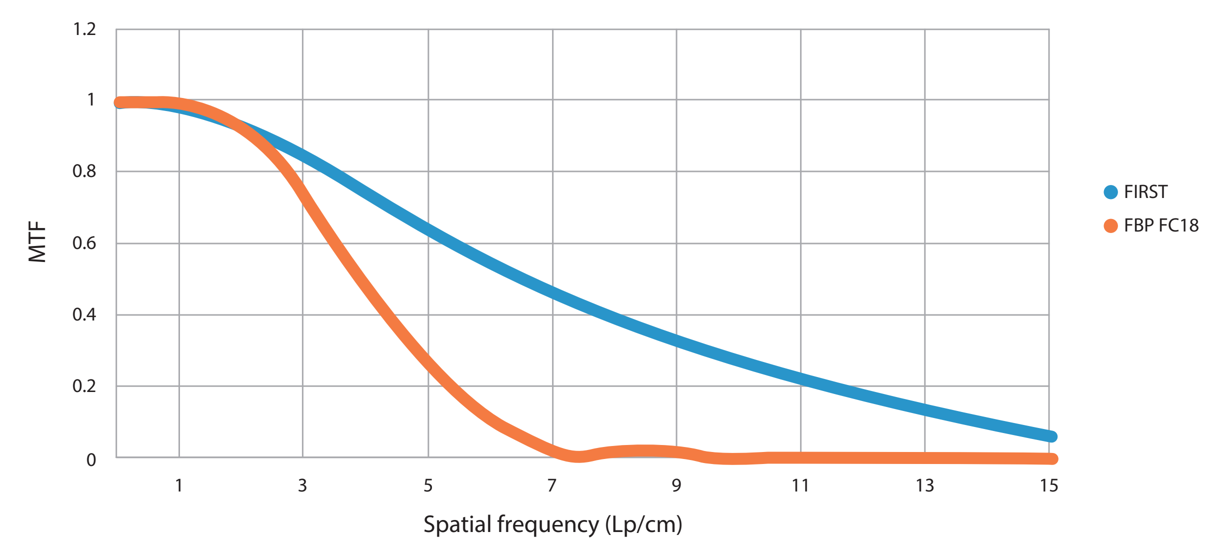


Figure 4 Modulation transfer function (MTF) for both FBP and FIRST reconstructed images

Cone Beam Model

The implementation of a wide cone beam geometry in CT has significant advantages, such as allowing dynamic imaging of whole organs, but the wide beam geometry also presents new challenges in image reconstruction. These challenges have been overcome by the development of a new reconstruction algorithm. Whole-organ volume CT was first made possible with the introduction of the coneXact™ reconstruction algorithm from Toshiba Medical.[17] The coneXact incorporates the actual cone angle of the wide beam to minimize cone beam artifacts and truncation throughout a 16 cm scan range.

Building on the methods of the coneXact algorithm, FIRST incorporates the cone beam model to achieve reliable image quality in both helical and dynamic volume scan modes.

FBP

FIRST

Figure 5 High Contrast Phantom: FBP vs FIRST

*1 A non-prewhitening model observer study was conducted, establishing dose reduction of up to 84.6% (range 71.4%-84.6%) by comparing low contrast detectability under a baseline abdominal FBP condition and reduced dose conditions reconstructed with FIRST (Body mode, Standard setting).

FIRST in Clinical Practice

There are a variety of anatomically specific FIRST modes, each optimized to ensure excellent acceptance by reading physicians. FIRST works with helical, volume, and dynamic volume scanning and is therefore applicable to the majority of examinations performed in routine clinical work (Figure 6).

Integrated

Due to the success of the AIDR 3D algorithm's integration with the tube current modulation system, FIRST was also designed to be fully integrated and automated for optimal clinical workflow.

A CT acquisition protocol including a FIRST reconstruction takes full advantage of the noise reduction capabilities of forward projected MBIR because the SUREExposure settings are automatically adjusted to reduce exposure by 80% compared to FBP based on the user-input quality setting.

In addition, the FIRST algorithm comes with six different modes that are optimized for specific anatomical regions. The user only needs to select the body region of interest when setting up the protocol. If desired, each mode is available in an easy-to-use selection of three settings (Mild, Standard, and Strong) to accommodate user preference.

Fast

The key to making MBIR realizable in clinical practice is to increase reconstruction speeds so they are fast enough for routine clinical workflow. FIRST has achieved this goal by both optimizing the design of the algorithm itself and implementing the algorithm with computation on state-of-the-art graphics processing units (GPU) rather than employing a more traditional central processing unit (CPU) configuration.

Championed by the gaming industry, GPU processing can be used to parallelize algorithms for ultra-fast processing compared with the traditional CPU configuration. The FIRST algorithm has been designed to use the special NVIDIA® programming language for parallel computing, CUDA (Compute Unified Device Architecture). This design allows the algorithm to leverage the GPU processing power with greater performance than would otherwise be achievable. The FIRST reconstruction hardware consists of 23,040 CUDA cores utilizing 8 parallel GPUs. Although the hardware itself is small (37 cm wide and 60 cm tall), its processing power is substantial.

The reconstruction speeds with the FIRST reconstruction algorithm are well suited for clinical workflow. FIRST reconstructs in minutes, not hours. A typical single-volume cardiac study reconstructs in approximately 3 minutes. When necessary, AIDR 3D reconstruction can be implemented by default for situations where traditional image reconstruction speed is necessary, with FIRST reconstruction following in parallel.

Conclusion

Over the last two decades, advances in both hardware and software technology have led to significant dose reduction and image quality improvements in CT imaging. FIRST is a fast, state-of-the-art reconstruction technique that can be applied in all acquisition modes, providing improved high contrast spatial resolution and dose reduction up to 84.6%. Integration of FIRST with automatic exposure control lets users take full advantage of the capabilities of true iterative reconstruction without any guesswork that can hamper clinical workflow. In conclusion, forward projected model-based iterative reconstruction represents an easy-to-use breakthrough in reconstruction technology.

Figure 6 Scan Protocol integration of FIRST provides automated dose reduction and reconstruction, fast enough for routine clinical workflow

References

1. Angel, E. (2009). SUREExposure™ Low Dose Diagnostic Image Quality. Tustin, CA: Toshiba America Medical Systems. medical.toshiba.com.
2. Boedeker, K. (2010). Noise Reduction Tools: Saving Dose with QDS*2 and Boost3D.™ Tustin, CA: Toshiba America Medical Systems. medical.toshiba.com.
3. Angel, E. (2012). AIDR 3D Iterative Reconstruction: Integrated, Automated and Adaptive Dose Reduction. Tustin, CA: Toshiba America Medical Systems. medical.toshiba.com.
4. Zhang, D., Ayala, R. (2014). Auto Couch Height Positioning Compensation – Making SUREExposure a Smarter Dose Reduction Tool. Tustin, CA: Toshiba America Medical Systems. medical.toshiba.com.
5. Yamada Y, Jinzaki M, Hosokawa T, et al. Dose reduction in chest CT: comparison of the adaptive iterative dose reduction 3D, adaptive iterative dose reduction, and filtered back projection reconstruction techniques. Eur J Radiol. 2012;81(12):4185-4195. doi:10.1016/j.ejrad.2012.07.013.
6. Ohno Y, Takenaka D, Kanda T, et al. Adaptive iterative dose reduction using 3D processing for reduced- and low-dose pulmonary CT: comparison with standard-dose CT for image noise reduction and radiological findings. AJR Am J Roentgenol. 2012;199(4):W477-485. doi:10.2214/AJR.11.8275.
7. Chen MY, Steigner ML, Leung SW, et al. Simulated 50 % radiation dose reduction in coronary CT angiography using adaptive iterative dose reduction in three-dimensions (AIDR3D). Int J Cardiovasc Imaging. 2013;29(5):1167-1175. doi:10.1007/s10554-013-0190-1.
8. Wallihan DB, Podberesky DJ, Sullivan J, et al. Diagnostic performance and dose comparison of filtered back projection and adaptive iterative dose reduction three-dimensional CT enterography in children and young adults. Radiology. 2015;276(1):233-242. doi:10.1148/radiol.14140468.
9. Chen C-M, Lin Y-Y, Hsu M-Y, Hung C-F, Liao Y-L, Tsai H-Y. Performance of adaptive iterative dose reduction 3D integrated with automatic tube current modulation in radiation dose and image noise reduction compared with filtered-back projection for 80-kVp abdominal CT: anthropomorphic phantom and patient study. Eur J Radiol. 2016;85(9):1666-1672. doi:10.1016/j.ejrad.2016.07.002.
10. Matsuki M, Murakami T, Juri H, Yoshikawa S, Narumi Y. Impact of adaptive iterative dose reduction (AIDR) 3D on low-dose abdominal CT: comparison with routine-dose CT using filtered back projection. Acta Radiol. 2013;54(8):869-875. doi:10.1177/0284185113488576.
11. Nishio M, Matsumoto S, Seki S, et al. Emphysema quantification on low-dose CT using percentage of low-attenuation volume and size distribution of low-attenuation lung regions: effects of adaptive iterative dose reduction using 3D processing. Eur J Radiol. 2014;83(12):2268-2276. doi:10.1016/j.ejrad.2014.09.011.
12. Ohno Y, Koyama H, Fujisawa Y, et al. Hybrid type iterative reconstruction method vs. filter back projection method: capability for radiation dose reduction and perfusion assessment on dynamic first-pass contrast-enhanced perfusion chest area-detector CT. Eur J Radiol. 2016;85(1):164-175. doi:10.1016/j.ejrad.2015.11.010.
13. Onishi H, Kockelkoren R, Kim T, et al. Low-dose pelvic computed tomography using adaptive iterative dose reduction 3-dimensional algorithm: a phantom study. J Comput Assist Tomogr. 2015;39(4):629-634. doi:10.1097/RCT.0000000000000242.
14. Nishiyama Y, Tada K, Nishiyama Y, Mori H. Effect of the forward-projected model-based iterative reconstruction solution algorithm on image quality and radiation dose in pediatric cardiac computed tomography. Pediatr Radiol. 2016. doi:10.1007/s00247-016-3676-x.
15. Ohno Y, Yaguchi A, Okazaki T, et al. Comparative evaluation of newly developed model-based and commercially available hybrid-type iterative reconstruction methods and filter back projection method in terms of accuracy of computer-aided volumetry (CADv) for low-dose CT protocols in phantom study. Eur J Radiol. 2016;85(8):1375-1382. doi:10.1016/j.ejrad.2016.05.001.
16. Yasaka K, Kamiya K, Irie R, et al. Metal artefact reduction for patients with metallic dental fillings in helical neck computed tomography: comparison of adaptive iterative dose reduction 3D (AIDR 3D), forward-projected model-based iterative reconstruction solution (FIRST) and AIDR 3D with single-energy metal artefact reduction (SEMAR™). Dentomaxillofac Radiol. 2016 Jun 22:20160114. http://dx.doi.org/10.1259/dmfr.20160114.
17. Boedeker, K. (2012). ConeXact: Wide Area Detector Reconstruction. Tustin, CA: Toshiba America Medical Systems. medical.toshiba.com.

*2 Quantum Denoising Software

TOSHIBA MEDICAL SYSTEMS CORPORATION

http://www.toshibamedicalsystems.com

MCACT0301EA 2017-02 TMSC/NS/Printed in Japan

Toshiba Medical Systems Corporation meets internationally recognized standards for Quality Management System ISO 9001, ISO 13485.
Toshiba Medical Systems Corporation Nasu Operations meets the Environmental Management System standard ISO 14001.

Made For *life*