

Systematic Review

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Does Iterative Reconstruction Improve Image Quality and Reduce Dose in Computed Tomography?

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ABSTRACT

The Filtered Back Projection (FBP) algorithm has been the standard algorithm for image reconstruction in computed tomography (CT) for many years, but it creates possible streak artifacts and a notable increase in image noise when radiation dose is reduced exceedingly. With technological advancement and increased computational capacities in workstations, iterative reconstruction (IR) algorithms have re-emerged as a potential alternative. The purpose of this review is to establish if there is a general consensus that IR algorithms faithfully reduce radiation dose and improve image quality in CT in comparison with the FBP algorithm. A systematic review of the literature from 2012 to 2015 was conducted using Ovid MEDLINE and PubMed databases, as well as various well-known journals such as the *American Journal of Roentgenology*, *European Journal of Radiology*, *Physica Medica* and the *Korean Journal of Radiology*. A total of 57 articles were categorized as either synopsis articles or performance evaluation clinical studies, where the latter was further divided into 6 sub-categories according to the type of IR algorithm examined. The results show that the use of IR algorithms reduces objective image noise, and at least preserves spatial resolution and low contrast detectability, even when dose is reduced. The findings are also applicable to specific patient groups, such as pediatrics and obese patients. In conclusion, there is a general consensus that IR algorithms can faithfully reduce radiation dose and improve image quality in CT in comparison with the FBP algorithm.

KEYWORDS: Iterative Reconstruction (IR); Computed Tomography (CT); Filtered Back Projection (FBP); Radiation dose; Image quality.

ABBREVIATIONS: FBP: Filtered Back Projection; CT: Computed Tomography; IR: Iterative Reconstruction; ASIR: Adaptive Statistical Iterative Reconstruction; MBIR: Model-Based Iterative Reconstruction; IRIS: Image Reconstruction in Image Space; SAFIRE: Sinogram Affirmed Iterative Reconstruction; AIDR: Adaptive Iterative Dose Reduction; ASiR: Adaptive Statistical Iterative Reconstruction; BMI: Body Mass Index.

INTRODUCTION

Rapid technological advancements in imaging techniques, such as the development of multi-detector computed tomography, has resulted in a substantial rise in demand for CT examinations as a key diagnostic imaging modality over the past decade.¹⁻³ While the diagnostic benefits of CT are well-documented, the associated risks of increased exposure to ionizing radiation such as radiation-induced cancer has become an area of increasing concern.⁴ Radiation exposure from CT accounts for approximately two-thirds of all medical-related radiation worldwide, and recent studies have cited associated cumulative cancer risk from CT to be as high as 1.5%.⁵ Several techniques, such as automatic tube current modulation, automatic tube voltage selection and dynamically adjustable z-axis beam collimation, have been employed to reduce CT-associated radiation dose, but the amount of dose reduction is limited if the FBP algorithm is used for image reconstruction.^{6,7} The FBP algorithm has been the standard algorithm for im-

age reconstruction in CT for many years, but it poses the limitation of producing possible streak artifacts and a notable increase in image noise level if radiation dose is reduced exceedingly.⁸

The re-emergence of IR techniques in CT recently offers a potential alternative that allows a reduction in radiation dose while preserving image quality.¹ IR algorithms were first considered for use in early CT scanning back in the 1970's, but were deemed unsuitable for clinical use due to the need for high computational capacities in workstations and long reconstruction times.⁹ However, with the advancement of computer technology and improvements in computational capacities, IR has now become a realistic option for use in CT in clinical settings, and various CT manufacturers currently offer a variety of IR algorithms. For example, while GE Healthcare offers Adaptive Statistical Iterative Reconstruction (ASIR) and Model-Based Iterative Reconstruction (MBIR), Siemens Healthcare offers Iterative Reconstruction in Image Space (IRIS) and Sinogram Affirmed Iterative Reconstruction (SAFIRE). On the other hand, other major CT manufacturers such as Philips Healthcare and Toshiba America Medical Systems, offer iDose and Adaptive Iterative Dose Reduction (AIDR) respectively.^{1,9}

Several studies done between 2012 and 2015 have shown that the use of IR algorithms do indeed aid in reducing radiation dose and improving image quality in CT examinations when compared to the FBP algorithm.^{6,10} However, there has yet to be any known review published on related studies to establish if this is a shared consensus within the medical imaging community, and whether the outcomes differ for different types of CT examinations and patients. This is especially crucial, as most of these studies often employ the use of IR algorithms from only one or two CT manufacturers, with the focus on a single specific type of CT examination.

The primary aim of this literature review is to establish if there is a general consensus that IR algorithms faithfully reduce radiation dose and improve image quality in CT in comparison with the FBP algorithm. The secondary aims are to provide an overview of the limitations of the FBP algorithm, outline the advantages of IR algorithms, as well as to explain how IR algorithms work in general and present examples of available IR algorithms from CT vendors.

MATERIAL AND METHODS

An online search was conducted for literature published from 2012 to 2015 using PubMed and Ovid MEDLINE databases. A subsequent search was also performed in various well-known journals, such as the *American Journal of Roentgenology*, *European Journal of Radiology*, *Physica Medica* and the *Korean Journal of Radiology*. Only articles that were published within the last four years were included, in view of the rapid development of technology in CT. The search strategy involved the use of three primary keywords, which were “iterative reconstruction (IR)”, “computed tomography (CT)” and “filtered back projec-

tion (FBP)”, in addition to five secondary keywords, namely “radiation dose”, “image quality”, “image noise”, “advantages” and “limitations”. Each of the searches consisted of a combination of one primary keyword and one secondary keyword. The articles that were collected provided information on the various types of IR algorithms, as well as their effects on radiation dose and image quality when used in place of the FBP algorithm in CT image reconstruction.

Articles from the initial search results were screened in detail and assessed for relevance. Studies that were included in this review were peer-reviewed and belonged to two main categories of literature, namely synopsis articles that provided general information about IR and FBP algorithms, and controlled experimental studies that measured the comparative effects of IR algorithms on radiation dose and image quality against the FBP algorithm. Literature that were not available in the English language were excluded for review, in addition to those that were physically unobtainable from library databases. Papers evaluating the use of IR algorithms in nuclear medicine were also excluded as they were considered to be beyond the scope of this literature review.

RESULTS

The initial searches performed using the two databases returned a total of 535 articles after removing duplicate results. After applying the exclusion criteria, 221 papers were considered to be clinically relevant for review. However, due to the number of similarities in the types and outcomes of relevant studies, only articles with the most informative and representative findings were included for review. As such, 57 articles were eventually analyzed in this review. Articles were categorized as either synopsis articles or clinical studies evaluating the performance of various IR algorithms. Articles that belonged to the latter were further sub-divided into 6 categories according to the types of IR algorithms used in these studies, since algorithms offered by different manufacturers may have varying extents of influence on dose and quality of images when used for image reconstruction.

Synopsis Articles

Twenty-two synopsis articles were analyzed in this review. These articles provided an insight into the image reconstruction process of FBP and IR algorithms, as well as an overview of IR algorithms available from CT vendors and the differences between each algorithm.

Limitations of the FBP Algorithm in CT Image Reconstruction

It is essential to first comprehend the image reconstruction process and limitations of the FBP algorithm, so as to recognize the advantages offered by IR algorithms. Various articles provided an overview of the basic principles behind the FBP reconstruction algorithm.^{8,9,11,12}

The FBP algorithm is described as an analytical image reconstruction method which consists of 2 main components, namely back-projection and convolution filtering. The back-projection process involves the summation of multiple back-projections of projection data obtained with the x-ray source at different angles, until the complete image is reconstructed.⁹ This however results in a blurred image, so convolution filtering using filter kernels is applied to each set of projection data before back-projection to improve spatial resolution and contrast.^{9,12} The reconstruction process of the FBP algorithm is illustrated in Figure 1.

Application of the convolution filters to obtain a sharper image however, also increases the amount of noise in images. The limitations of the FBP algorithm become even more pronounced when it is used in low-dose CT examinations, since an inverse correlation exists between radiation dose and image noise.¹² These limitations in image quality can be primarily attributed to the underlying assumptions about scanner geometry that the FBP algorithm is based on, which are mostly deviant from reality.¹¹ These assumptions include a pencil x-ray beam, the x-ray focal spot being a point source, a lack of consideration for the shape and size of detector cells and voxels, as well as neglecting the image noise resulting from Poisson statistical variations of x-ray photons.⁸ As a result, there is a need for alternative algorithms that model the CT system more accurately, in order to produce diagnostic images while maintaining a low dose in CT examinations.

Advantages of IR Algorithms and How They Work

A number of articles have also identified the ability to reduce image noise while preserving spatial resolution and image contrast, even at lower tube currents in reduced-dose examinations, as the main advantage offered by IR algorithms.^{6,12,13} In addition, IR algorithms can help reduce artifacts caused by metallic implants, as well as those resulting from photon starvation and beam-hardening effects.¹ It is therefore essential to understand

how IR algorithms work in general, since it provides the basis to comprehending why IR algorithms are able to offer these advantages.

The iterative reconstruction process can generally be divided into a few steps. Firstly, the measured projection data is acquired, before it is reconstructed using the standard FBP algorithm to produce an initial image estimate. This initial image estimate is then forward-projected to create a simulated projection data, which is subsequently compared with the measured projection data. The difference between the 2 sets of data is then determined to generate an updated image that will be back-projected on the current CT image, to keep the difference between the current CT image and the measured projection data to a minimum. This iteration process is then repeated several times in what is known as the “iterative loop”, until the difference is considered to be sufficiently minimal. The output is the resultant volumetric image after the termination of the iterative cycle.^{1,6,9} The entire iterative reconstruction process is illustrated in Figure 2. A comparison of images reconstructed using the FBP and IR algorithms is shown in Figure 3.

Examples of IR Algorithms

There are currently several IR algorithms available from the 4 major CT vendors, namely GE Healthcare, Siemens Healthcare, Philips Healthcare, and Toshiba Medical Systems. Algorithms from the respective vendors differ significantly in their approaches within the image reconstruction process, but share the common objective of improving image quality and reducing noise, especially in low-dose CT procedures. The various examples of IR image reconstruction techniques are listed in Table 1. As these algorithms are now part of standard image reconstruction for CT, only a brief overview of algorithms from GE Healthcare and Siemens Healthcare will be provided to illustrate the differences between various IR algorithms. A summary of the key differences between IR algorithms offered by various major CT vendor is presented in Table 2.

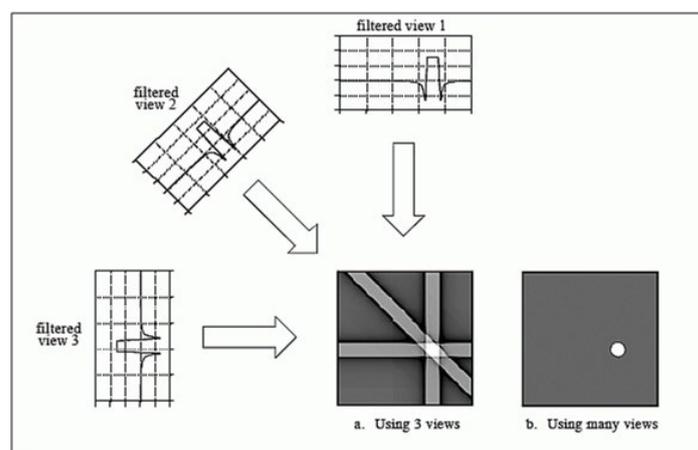


Figure 1: The image reconstruction process of the FBP algorithm. Each set of projection data, taken at different angles, undergoes convolution filtering before back-projection. This removes the blurring that would result from simple backprojection without filtering.²

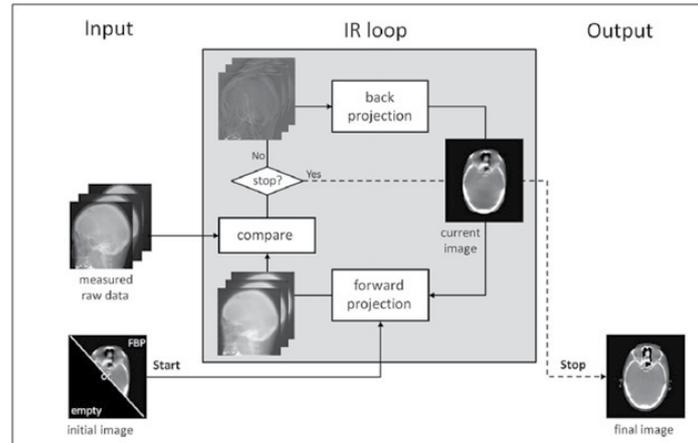


Figure 2: An illustration of the iterative reconstruction process. Forward projection of the CT image reconstructed with standard FBP algorithm creates an initial image estimate, which is then compared with the measured raw data. Comparisons generate an updated image that is back-projected to the current CT image until the difference is minimized. The final volumetric image is produced when the iterative loop terminates after multiple cycles of iteration.¹



Figure 3: Comparison of image quality of images reconstructed using FBP and IR algorithms.¹

Acronym	IR Algorithm	Vendor	Year
ASiR	Adaptive Statistical Iterative Reconstruction	GE Healthcare	2008
Veo (MBIR)	Veo Model-Based Iterative Reconstruction	GE Healthcare	2009
ASIR-v	ASIR-v	GE Healthcare	2013
IRIS	Image Reconstruction In Image Space	Siemens Healthcare	2009
SAFIRE	Sonogram-Affirmed Image Reconstruction	Siemens Healthcare	2010
ADMIRE	Advanced Modeled Oterative Reconstruction	Siemens Healthcare	2014
IDose ⁴	IDose ⁴	Philips	2009
AIDR	Adaptive Iterative Dose Reduction	Toshiba Medical System	2010
AIDR 3D	Adaptive Iterative Dose Reduction 3-Dimensional	Toshiba Medical System	2012

Table 1: Examples of IR algorithms from major CT vendors.

IR Algorithm	Key features
ASiR	1 st generation hybrid IR algorithm blended in 10% increments with traditional FBP according to user preference Based on advanced statistical noise and object modeling
Veo (MBIR)	Fully-iterative model-based IR algorithm Based on advanced modeling of system optics , in addition to statistical noise, object and physics modeling Allows for further noise reduction but involves long processing times
ASIR-V	Next generation of the ASiR algorithm Based on advanced physics modeling , in addition to statistical and object modeling Improved performance over ASiR, with shorter processing times as compared to MBIR
IRIS	1 st generation IR algorithm Iterative corrections are performed in the image space on a virtual "master image", instead of on the raw data Allows for fast processing times , but limited in removal of image artifacts
SAFIRE	Involves 2 different iterative correction loops Corrections first performed on the raw data to remove image artifacts, before noise reduction in the image space
ADMIRE	Next generation of the SAFIRE algorithm Weighted FBP is introduced into the first iteration loop for improved artifact removal, in addition to advanced statistical noise modeling
iDose ⁴	Iterative corrections performed on both projection data and in the image space Statistical noise modeling applied to denoise image in projection data, then compared to a noiseless ideal anatomical model in image space to avoid artificial appearance of images
AIDR	Iterative corrections only performed in the image domain and not on the raw projection data Fast processing times but limited in overall dose reduction
AIDR 3D	Next generation of the AIDR algorithm Iterative corrections performed in both the raw data and image domains Based on statistical noise, object and system optics modeling Weighted blending added to avoid artificial appearance of images

Table 2: Key differences between IR algorithms from major CT vendors.

Adaptive statistical iterative reconstruction (ASiR) is a hybrid IR algorithm by GE Healthcare, and was the first IR algorithm available among vendors.¹⁴ The ASiR model accounts for changes in the projection data measurements due to statistical distribution of photons, and the iterative process involves comparison of estimated pixel values and predicted ideal values until both values converge.^{15,16} ASiR is usually blended with traditional FBP in 10% increments. GE healthcare later introduced Veo, or model-based iterative reconstruction (MBIR) in 2009, which is a complex and fully iterative reconstruction algorithm.⁹ In addition to statistical noise modelling, MBIR uses a model that accounts for the system optics, in order to achieve further noise reduction.¹⁷⁻¹⁹ Increased complexity of the algorithm however means that a longer processing time is needed, hence MBIR is used less extensively in the clinical setting.²⁰ ASIR-V, known as the next generation of ASiR, was then introduced in late 2013 with comparable clinical performance to MBIR but shorter processing times.

Siemens Healthcare on the other hand, introduced image reconstruction in image space (IRIS) in 2009, a unique algorithm that does not involve forward and back projections onto the raw image data.⁹ The IRIS algorithm creates a virtual image from the raw data, and the iterative corrections to reduce image noise are performed on the virtual image itself in the image space, allowing for faster processing times.^{21,22} Eliminating the need for multiple forward and back projections however also meant that the IRIS algorithm is solely for the purpose of noise reduction, and not for the removal of potential image artifacts.²³

Siemens Healthcare later introduced sinogram affirmed iterative reconstruction (SAFIRE) in 2010, and it differs from IRIS in that the iterative corrections are performed on the raw data, before conversion into the image space.²⁴ This allows for noise reduction, artifact removal and reduced processing time.²⁵ Advanced modeled iterative reconstruction (ADMIRE), the third-generation of IR technique by Siemens Healthcare, was

finally approved for use in 2014 with additional algorithm processing steps such as the use of weighted FBP in the iterative loop, allowing for improved artifact removal in produced images.⁹

Clinical Studies Evaluating the Performance of IR Algorithms

These studies were performed with the use of either phantom or patient models, and examined the performance of IR algorithms in terms of noise reduction, dose reduction and improvement in image quality when compared with the FBP algorithm. Thirty-five articles were reviewed, and the results are discussed in 6 sub-sections according to the type of IR algorithm that was used. A summary of the performance of various IR algorithms is listed in Table 3.

Performance of ASiR and ASiR-V Algorithms

Various studies comparing the ASiR and FBP algorithms demonstrated significant reductions in radiation dose and preservation of image quality with the use of the ASiR algorithm. Two of such studies compared the use of the FBP protocol against 40% ASiR protocols at similar and lower tube potentials.^{26,27} The first study showed a 33.8% (3.21 mSv *versus* 4.85 mSv)

reduction in effective dose at similar tube voltages of 120 kV, in chest CT angiography examinations of patients with pulmonary embolism.²⁷ Meanwhile, the latter study found no notable differences in overall image quality between FBP and 40% ASiR images with reduced dose, although significant improvement was noted in the subjective assessment of noise level.²⁶ Image quality was both subjectively and objectively measured based on various indicators, such as image sharpness, noise, artefacts, signal-to-noise ratio (SNR), contrast-to-noise ratio (CNR), visibility of small structures and overall diagnostic confidence.

Similar results were reported in specific patient groups such as pediatrics and obese patients. A pediatric study for children under the age of 12 found that the use of a 30% ASiR algorithm led to a dose reduction of 46.4% (3.7 mGy *versus* 6.9 mGy) for chest CT and 38.2% (5.0 mGy *versus* 8.1 mGy) in abdominal CT examinations.²⁸ Another study was conducted on obese patients weighing 91 kg and above, and reported an average dose reduction of 31.5% (13.5 *versus* 19.7) with the use of a 30% ASiR algorithm.²⁹ Both subjective and objective image noise were significantly lower with ASiR in both studies, while diagnostic acceptability and image sharpness of ASiR images were comparable to FBP images. A visual comparison of the image quality of FBP and ASiR images is shown in Figure 4,

IR Algorithm	Performance of algorithms
ASiR	30% and 40% blended ASiR algorithms were most commonly used Dose reductions of up to 46.4% reported in CT examinations of the chest or abdomen Both subjective and objective image noise were lower with the use of ASiR , with comparable diagnostic acceptability and image sharpness to FBP images Results are also similar in both pediatrics and obese patients Use of a high blend (>50%) can result in smoothed appearance which decreases visibility of small structures
Veo (MBIR)	Reported better dose reduction and image quality improvement than older-generation IR algorithms such as ASiR Not used extensively in clinical settings due to long processing times Use of MBIR can result in pixelated blotchy appearance and smoothed appearance , resulting in suboptimal resolution of thin bone structures
ASiR-V	50% blended ASiR-V algorithm reported to be the preferred blending weightage to obtain best spatial resolution Significantly superior to ASiR and FBP in noise reduction (up to 61.3%) and improvement in contrast-to-noise ratio.
IRIS	Variable results reported on the effects of IRIS on image quality and dose reduction Use of the IRIS algorithm definitively improved or preserved objective image noise , but subjective image quality reported to deteriorate with use of IRIS in 3 studies Poorer subjective image quality attributed to poorer image contrast and sharpness One study suggested the use of IRIS only allows approximately up to 20.4% dose reduction
SAFIRE	Use of SAFIRE at lower doses generally resulted in superior or similar image quality to full-dose FBP images Amount of improvement in image quality with the use of SAFIRE is lesser in patients of heavier weights (>75kg) or obese patients
ADMIRE	Use of ADMIRE improved or at least preserved low-contrast detectability in images, with significant dose reduction of up to 80% when compared to FBP images
iDose ⁴	Superior image quality reported in iDose ⁴ images when compared to FBP images when performed at the same dose level Variable results reported in terms of subjective quality when comparing iDose ⁴ images acquired at lower doses to standard-dose FBP images
AIDR	Reported noise reduction of up to 31% and estimated dose reduction of 52%
AIDR 3D	Superior noise reduction of up to 37.5% in abdominal examinations, with increased noise reduction with increased size of patients

Table 3: Performances of IR algorithms from major CT vendors.

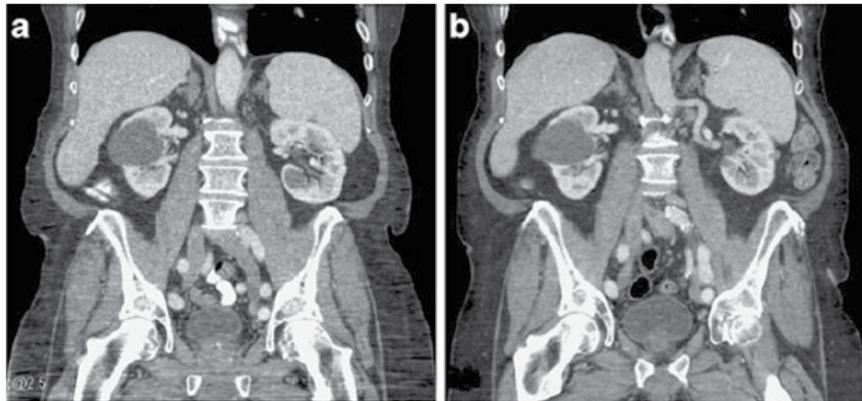


Figure 4: A comparison of image quality of coronal images reconstructed with FBP (a) and ASiR (b) algorithms in the imaging of a right renal cyst. The image reconstructed using the ASiR algorithm at reduced radiation dose (21.4% dose reduction) shows comparable image quality to the image reconstructed with FBP, with lower image noise.²⁹

comparing coronal images of a patient with a right renal cyst. The lesion was well visualized on both images with comparable image quality, however the image reconstructed using ASiR was significantly less noisy and required a lower radiation dose to obtain.

Certain studies did however show that using an excessive blend of ASiR in the algorithm can result in a deterioration in the quality of images.^{14,30,31} One study conducted on a CT phantom reported that a blend of 50% ASiR or higher can result in a smoothed image texture that radiologists are uncomfortable with.³⁰ A smoothed appearance can result in a deterioration of subjective image quality, as shown in 2 studies performed in abdominal and soft tissue neck CT scans, where significant decreases in the visibility of small structures due to the smoothing effect were noted in ASiR images even at a blend of 40% ASiR.^{14,31}

Finally, one study evaluated the performance of ASIR-V, which is the latest generation of the ASiR algorithm.²⁰ Image noise, CNR and spatial resolution were compared between FBP and 3 levels (30%, 50% and 70%) of ASiR and ASIR-V algorithms, at 5 different tube currents with the use of a body phantom. The 50% ASIR-V algorithm was found to produce the best spatial resolution in images, and the ASIR-V algorithms in general demonstrated significantly superior decreases in noise levels and increases in CNR. The use of a 50% ASIR-V algorithm yielded a maximum noise reduction of 61.3%, in addition to an increase in CNR of 248.4% when performed at the lowest tube current of 30 mA.

Performance of Veo (MBIR)

Results from various studies showed that Veo may potentially offer better dose reduction and image quality improvement than older-generation IR algorithms such as ASiR when compared to FBP. One phantom study compared the impact of MBIR to FBP and 50% ASiR algorithms on dose reduction in abdominal CT imaging at various levels of tube current.³² The results revealed

that while the ASiR algorithm was able to provide up to a 35.9% reduction in dose, the use of MBIR allowed for a greater dose reduction of 59.9% when both algorithms were compared to FBP. Using the exact three algorithms, a separate study by Katsura et al³³ evaluated the effect of MBIR on the image quality in the CT imaging of the cervicothoracic region, and found that MBIR images had notably lower objective image noise when compared to ASiR and FBP images (8.88 *versus* 18.63 *versus* 26.52 Hounsfield units respectively). The outcomes of both studies are similar to another phantom study, which reported significant lower noise in MBIR images when compared to FBP images at all radiation dose levels in CT scans of the liver.³⁴ Significant improvements were also noted in both spatial resolution and low-contrast detectability when MBIR was used over FBP.

Despite its advantages, the use of MBIR can result in a pixelated blotchy appearance in images, as noted in the study by Katsura et al.³³ Similar findings were reported in another study performed in pediatric chest CT examinations, where a blotchy pixelated appearance of the central bronchi and lung vessels was seen in minimum-dose MBIR images.³⁵ The smoothing effect resulting from the use of MBIR was also found to result in sub-optimal resolution of bone structures in a separate study on low-dose CT examinations of the paranasal sinuses.³⁶

Studies in specific populations such as pediatrics also reported significant improvements in overall image quality with the use of the MBIR algorithm, specifically with reduced image noise and improved SNR. Two studies in pediatric chest CT examinations in particular noted an improved visualization of small structures, such as subpleural vessels and lung fissures, in reduced-dose CT examinations with the use of the MBIR algorithm.^{35,37}

Performance of the IRIS Algorithm

Studies evaluating the performance of IRIS in CT examinations generally reported that the use of IRIS preserved or improved image quality when compared to the FBP algorithm in reduced-

dose scans. Significantly reduced noise (23.3 versus 33.5 Hounsfield Units, p -value=0.001) and improved subjective image quality scores (3.2 versus 3.0, p -value=0.038) were noted when IRIS was used over FBP in coronary CT angiography examinations.³⁸ Another study meanwhile found no notable differences in both objective image noise and subjective image quality between reduced-dose IRIS images and standard-dose FBP images in CT examinations of the chest, abdomen and pelvis, despite a dose reduction of 44.4% (6.7 mSv versus 12.0 mSv).³⁹ On the other hand, no significant differences in subjective image quality (4.37 versus 4.31, p -value=0.72) were noted between IRIS and FBP images in reduced-dose CT examinations of the paranasal sinuses when radiation dose was reduced by up to 60% (0.11 mSv versus 0.28 mSv), while significant improvement in mean image quality score (4.81 versus 4.37, p -value=0.004) was achieved when radiation dose was reduced by only 20% (0.23 mSv versus 0.28 mSv).⁴⁰

Three other studies however suggested much lower thresholds for dose reduction in order for the use of IRIS to preserve image quality. One study comparing with the use of FBP and IRIS algorithms in chest CT examinations at both 100% and 50% doses found that while objective image noise was considerably lower in half-dose IRIS images than in full-dose FBP images, the subjective image quality score was significantly lower (p -value<0.0001) for half-dose IRIS images than for full-dose FBP images.²¹ The decrease in image quality scores was largely due to poorer image contrast and sharpness of mediastinal structures. Similarly, in a study of patients undergoing liver CT scans for hepatocellular carcinoma (HCC), overall subjective image quality was lower (2.27 versus 2.87, p -value<0.05) in IRIS images at 80 kV than FBP images at 120 kV.⁴¹ Head CT images reconstructed using IRIS at 30% reduced dose were also found to have considerable poorer subjective image quality when compared to standard-dose FBP images in a study by Korn et al,²³ and a linear regression analysis of CNR against tube current performed in the study suggested that the use of IRIS only preserves image quality up to an approximate 20.4% reduction in radiation dose.

Performance of SAFIRE and ADMIRE Algorithms

Studies that evaluated the performance of the SAFIRE algorithm in general also reported superior or similar image quality in reduced-dose SAFIRE images, in comparison to standard-dose FBP images. Improvements in subjective assessment of noise and image quality scores were noted in SAFIRE images at 20% reduced dose level (1.3 versus 1.6 and 1.3 versus 1.7 respectively), in a study assessing the performance of SAFIRE in head CT examinations.⁴² The results are supplemented by findings in a study that compared half-dose SAFIRE images to full-dose FBP images in chest CT examinations, reporting lower objective noise and improved SNR (p -value<0.001) in SAFIRE lung images, while no considerable differences were noted in subjective image quality on both lung and mediastinal images.⁴³ Additionally, 1 phantom study indicated improved low-contrast detect-

ability with the use of SAFIRE for all radiation dose levels and lesion sizes, with no statistically significant changes in spatial resolution.⁴⁴

Certain studies showed that other factors, such as patient body weight and anatomy of interest, can affect the performance of SAFIRE in improving image quality. While SNR and CNR improved in SAFIRE images of patients weighing 75 kg and below, no improvements were noted in patients that were heavier than 75 kg, in a study which evaluated the performance of SAFIRE in coronary CT angiography.⁴⁵ The results are in line with a separate study by Wang et al⁴⁶ on obese patients with a body mass index (BMI) larger than 30 kg/m². Another study investigating the use of SAFIRE in cervical spine CT examinations meanwhile noted that while increasing the iteration strength level of the SAFIRE algorithm improved visualization of the intervertebral discs and ligaments, the use of a higher-strength SAFIRE algorithm resulted in poorer visualization of soft tissues and trabecular bone.⁴⁷

One study assessed the effect of ADMIRE on low-contrast detectability in a contrast-detail phantom, when compared to the FBP algorithm.⁴⁸ The results demonstrated an average increase of 5.2% (p -value<0.001) in detection accuracy with the use of ADMIRE, and low contrast detectability increased with increasing object contrast, size, dose index and strength of ADMIRE. The use of the ADMIRE algorithm allowed a significant reduction in dose that ranged from 56% to 60% and 4% to 80% in 2 reading sessions, while preserving low-contrast detectability.

Performance of the iDose⁴ Algorithm

Comparison of the performance of the iDose⁴ algorithm to the FBP algorithm generally demonstrated lower image noise, increased CNR and improved overall image quality with the use of iDose⁴, when reconstructed images were acquired at the same level of radiation dose. One such study assessed the performance of the iDose⁴ algorithm in CT perfusion scans of the pancreas, and reported a noise reduction of 36.8% (10.6 versus 16.9 Hounsfield Units) when comparing iDose⁴ images to FBP images at 80 kV.⁴⁹ Similarly, subjective image quality scores were markedly higher in iDose⁴ images, when compared to FBP images in another study involving low-dose CT scans of the brain (2.91 versus 2.72, p -value<0.0055).⁵⁰ In addition, no changes in spatial resolution were noted with the use of the iDose⁴ algorithm in another study which investigated the performance of FBP and iDose⁴ algorithms at different acquisition parameter settings with the use of a Catphan phantom.⁵¹ The study also reported improvement in low-contrast resolution with the use of iDose⁴ in low-dose scans of less than 5 mGy.

Differences do however exist between these studies when comparing the image quality of iDose⁴ images at reduced dose to FBP images acquired at standard dose. While the study on CT perfusion scans of the pancreas reported no notable dif-

ferences in subjective image quality and mean CNR values between reduced-dose (10.81 mSv) iDose⁴ images and standard-dose (23.37 mSv) FBP images, improvements in both objective and subjective image quality in iDose⁴ images were noted in another study performed in chest-abdomen-pelvis CT scans, with an effective dose reduction of 46.5% (7.1 mSv *versus* 12.9 mSv).^{49,52} Interestingly, reduced-dose iDose⁴ images were given poorer subjective image quality scores by radiologists when compared to standard-dose FBP images in the study involving low-dose CT scans of the brain, despite lower objective noise levels in the iDose⁴ images.⁵⁰

Performance of AIDR and AIDR 3D Algorithms

One study assessed the influence of AIDR on dose reduction and image quality, while four others compared the newer AIDR 3D algorithm with the FBP algorithm. In a study which assessed the impact of the AIDR algorithm in both a phantom study and a patient-based study in lumbar spine CT examinations, it was reported that lower image noise and improved SNR was achieved with the use of AIDR without altering spatial resolution.⁵³ Results of the patient-based study showed a mean image noise reduction of 31% (15.6 *versus* 22.5 Hounsfield units) and an improvement of SNR from 2.36 to 3.50 with AIDR, despite an estimated dose reduction of 52%.

Studies assessing the performance of AIDR 3D algorithms generally reported significant image noise reduction and CNR improvement when AIDR 3D was used over the FBP algorithm. In a study by Kim et al⁵⁴ which assessed the effectiveness of AIDR 3D on noise reduction according to body habitus by using phantoms of different sizes, the use of AIDR 3D significantly reduced image noise and improved CNR and SNR values (p -values=0.001), with increasing noise reduction as the size of the phantom increased. Similar findings are reported in another study by Schindera et al,⁵⁵ where objective noise was reduced by 14.5 to 37.5% in abdominal CT examinations of obese patients through the use of a liver phantom.

However, the results vary when discussing its effect on low-contrast detectability. The study by Schindera et al⁵⁶ noted no significant improvement in low-contrast detectability, when AIDR 3D was used for scans on obese patients. Yet, a separate liver phantom study conducted by the same authors evaluating the use of AIDR 3D in general abdominal scans, reported that the use of AIDR 3D failed to preserve low-contrast detectability when the radiation dose level was reduced by 80%. In the latter study, sensitivity for detection of low-contrast liver tumors was found to be significantly lower (p -value=0.019) in AIDR 3D images acquired at 20% dose, when compared to both FBP and AIDR 3D images acquired at the full radiation dose level.

DISCUSSION

Increasing demand for CT examinations has led to rising concerns over the amount of exposure to ionizing radiation in medi-

cal imaging.⁴ Together with the rapid advancements in computer technology, IR algorithms have recently re-emerged as an alternative to the FBP algorithm in CT image reconstruction for dose reduction while preserving image quality.¹ This systematic review evaluated the relevant literature from 2012 to 2015 to establish if there is a general consensus that IR algorithms faithfully reduce dose and improve image quality in CT when compared to the FBP algorithm.

Review of the literature in clinical performance studies of different IR algorithms showed that the use of IR algorithms definitively reduced objective image noise regardless of the type of IR algorithm used.^{28,29,31,33-35,37,38,43,49,54,55} The extent of the noise reduction achieved however varies and depends on various factors, such as the type of IR algorithm used, the acquisition parameter settings, patient size and the type of CT examination performed. Newer generations of IR algorithms, such as MBIR and ASIR-V, allow for significantly increased noise reduction when compared to older algorithms such as ASiR, as demonstrated in the studies by Lim et al²⁰ and Ning et al.³²

It is however insufficient to draw conclusions on the performance of IR algorithms based on objective image noise alone. The subjective image quality with the use of IR algorithms also needs to be considered, so as to evaluate their effects on spatial resolution, low-contrast detectability and diagnostic acceptability.⁹ Most studies reported no changes in spatial resolution with the use of IR algorithms, while low-contrast detectability were preserved or improved despite IR images being acquired at a lower dose level.^{29,34,44,51,57}

Results from the literature suggest that the preservation of subjective image quality with the use of IR algorithms only holds true up to a certain threshold in dose reduction. When the radiation dose level is reduced excessively, the use of IR algorithms is unable to preserve image quality, as seen in studies by Hwang et al²¹ and Hur et al,⁴¹ where subjective image scores of IRIS images acquired at 50% and 70% dose respectively were considerably poorer than standard-dose FBP images. Similar findings were reported in two other studies by Love et al⁵⁰ and Schindera et al,⁵⁶ which assessed the performance of the iDose⁴ and AIDR 3D algorithms respectively. It is difficult to quantify the optimal amount of dose reduction that IR algorithms are able to provide without compromising on image quality, since it is dependent on various factors such as the type of IR algorithm used and the anatomy of interest that is examined, although one study by Korn et al²³ suggested that the use of an IRIS algorithm preserves image quality up to a 20.4% reduction in dose level.

The use of IR algorithms in CT examinations of specific patient populations, such as pediatrics and obese patients, have also shown to preserve or improve overall image quality in low-dose scans.^{28,29,35,37,46,54} In particular, the amount of noise reduction was noted to increase as the size of the body habitus increased in the studies of obese patients.⁵⁴ This is a noteworthy finding with important implications, since radiation dose is par-

ticularly of huge concern in these patient groups. Pediatrics are generally more sensitive to ionizing radiation than adults, while patients of larger body habitus receive higher radiation doses due to higher exposure settings required to obtain diagnostically acceptable images.

In the use of hybrid IR algorithms such as ASiR and iDose⁴, the percentage blend of IR algorithm to FBP can impact the influence of IR algorithms on the image quality of produced images. Using an excessively high iteration level of these algorithms can produce a smoothing effect on images that may reduce visibility of small structures and consequently deteriorate subjective image quality.^{14,31,33} Artifacts were also noted with the use of the MBIR algorithm, where a blotchy pixelated appearance of the central bronchi and lung vessels was noted in a study performed in chest CT examinations.³³ It should however be noted that the changes in image appearance did not affect the diagnostic acceptability of images.

Finally, whether the use of IR algorithms improves image quality also depends on the anatomy of interest that is examined. Visualization of soft tissues and trabecular bone was noted to be poorer with increased strengths of SAFIRE algorithm in cervical spine CT examinations, while bone structure visualization was also poorer with the use of the MBIR algorithm in CT examinations of the paranasal sinuses.^{36,47} A possible conclusion that may be drawn from these findings is that the use of IR algorithms are unable to correct for poor image detail in denser structures as bone, although further studies are needed to validate this observation.

A limitation of the current review is that there were very few studies performed on the newest generations of IR algorithms, such as ASiR-V and ADMIRE. This is likely due to the fact that the algorithms were only introduced in late 2013 and 2014 respectively, resulting in limited availability of these algorithms for clinical use. Although results from the only studies evaluating these algorithms appear promising, further research is needed in clinical trials to affirm these results.

With the continuous research in place to develop newer generations of IR algorithms and rapid improvement in computer technology, it is likely that more advanced IR algorithms will be developed in the near future. The use of these algorithms will likely be able to further reduce radiation dose in CT examinations while preserving image quality, therefore a probable gradual shift away from traditional analytical methods for image reconstruction should be expected in the foreseeable future.

CONCLUSION

In conclusion, the results of the literature from 2012 to 2015 share the general consensus that IR algorithms do faithfully reduce radiation dose and improve image quality in CT examinations, when compared with the FBP algorithm. The use of IR algorithms definitively reduces objective image noise even at

reduced radiation dose levels, while subjective image quality, in terms of spatial resolution and low contrast detectability, is improved or preserved with the use of IR algorithms as long as the radiation dose is not reduced excessively. However, the use of IR algorithms of excessively high iteration levels should be avoided, as the produced smoothing effect can negatively impact the subjective image quality. The use of IR algorithms may also be unable to preserve image detail in denser structures such as bone, although further research may be needed to validate this observation. With the rapid improvement in technology, IR algorithms will likely become the preferred CT image reconstruction method in the foreseeable future.

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CONFLICTS OF INTEREST

The authors do not have any conflicts of interest to disclose.

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