CT Dose Reduction Applications: Available Tools on the Latest Generation of CT Scanners

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Increasing concerns about radiation dose have led CT manufacturers to further develop radiation dose reduction tools in the latest generation of CT scanners. These tools include automated tube current modulation, automated tube potential selection, and iterative reconstruction. This review details the principles underlying each of these 3 dose reduction utilities and their different permutations on each of the major vendors' equipment. If available on the user's equipment, all 3 of these tools should be used in conjunction to enable maximum radiation dose savings.

Key Words: CT, automated tube current modulation, automated tube potential selection, iterative reconstruction

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INTRODUCTION

The growth in the volume of CT studies performed in the United States over much of the past 2 decades has been enormous [1]. This growth in volume, combined with the increasing use of CT in radiation-sensitive populations (ie, children, young adults, and pregnant female patients), has been an impetus for CT manufacturers to develop a number of radiation dose reduction tools. Furthermore, there has been a realization among radiologists that image quality should not be the only parameter considered when imaging a patient and that every study should be performed at the lowest possible radiation dose.

However, although there has been a rapid proliferation of dose reduction tools on all of the most recent CT scanners, these dose reduction applications are still underused, largely because of confusion on the part of users as to the purpose and utilization of each tool. In this review, we detail 3 radiation dose reduction methods, found on the most recent generation of CT scanners, that should be used in every practice: (1) automated tube current modulation, (2) automated tube potential selection, and (3) iterative reconstruction. Clearly, most of these tools are available in a number of different forms on each of the major vendors' newest equipment. However, given our institution's recent experience with the latest Siemens Somatom Flash scanners (Siemens Healthcare, Forchheim, Germany), we use the Siemens software as an example for each of these entities.

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AUTOMATIC TUBE CURRENT MODULATION

Automatic tube current modulation (or automatic exposure control [AEC]), referred to by a number of different names on each of the major vendors' equipment (Table 1), is a tool designed to modulate the imparted radiation dose (via changes in tube current-time product [mAs]) on the basis of patient size and attenuation [2,3]. In other words, the mAs is increased in those parts of the body with the greatest attenuation (such as through the shoulders or hips) and diminished as the soft tissue attenuation decreases (such as through the abdomen and thorax), resulting in an overall radiation dose reduction for the patient. Without AEC, noise (and dose) in an image would be primarily determined by those parts of the body with the highest soft tissue attenuation, and the overall dose to the patient would be substantially higher. Although there is some variation in the dose reduction seen with each of the vendors' systems, AEC software can reduce radiation dose by up to 40% to 50% [2,3].

Four distinct types of AEC can be found on modern CT scanners, at least 2 of which are found in every system: (1) Patient-size AEC entails an overarching adjustment in mAs on the basis of the overall size of the patient as determined by a topographic image. (2) Z-axis AEC adjusts the mAs along the length of the patient on

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Table 1. AEC systems available from each of the major manufacturers [3]

Vendor	AEC System Name	Operator-Controlled Parameter	Parameter Explanation	Principles	Z-Axis Modulation	Angular (X-Axis, Y-Axis) Modulation?
Siemens	CAREDose4D	Image quality reference mAs	mAs that would be used for an average-sized patient	Angular modulation of tube current in the x, y, and z axes on the basis of patient size relative to the mAs specified by the user for a standard-sized reference patient	Yes	Yes
Phillips	Dose Right	Reference image	Image quality expressed in terms of noise level of an existing optimal clinical image	Modulation of tube current on the basis of patient size to achieve the same image noise level as in a previously defined reference image	Yes	Yes
Toshiba	Sure Exposure 3D	Target image quality level	Standard deviation of pixel values in an image (higher standard deviation = higher noise)	User prespecifies image quality on the basis of a patient-equivalent water phantom, and mAs is modulated on the basis of patient size to maintain image quality	Yes	Yes
GE	Auto mA	Noise index	Measure of image quality/ noise level defined relative to uniform water phantom	Modulation of tube current only in the longitudinal direction to maintain a constant noise index	Yes	No
GE	Smart mA	Noise index	Measure of image quality/ noise level defined relative to uniform water phantom	Modulation of tube current in the x, y, and z axes to maintain a constant noise index	Yes	Yes

Note: mAs = tube current-time product.

the basis of the topographic image to equalize the image quality throughout a series. For example, when performing thoracoabdominal CT, the image quality (or noise) in the thorax and abdomen should be identical, despite attenuation differences. (3) Angular AEC modulates radiation dose as the x-ray tube rotates 360° around the patient, given that soft tissue attenuation in the x-y plane can vary from different projections. For example, this system accounts for substantially increased soft tissue attenuation as the x-ray beam travels laterally through the shoulder or pelvis [3,4]. (4) X-axis, y-axis, and z-axis AEC combines the angular and z-axis modulation throughout the length of the scan range.

Automatic tube current modulation is relatively similar on most manufacturers' equipment, although the strength of the modulation algorithm (clinical performance) varies across vendors, as does the definition of how the user specifies a minimum acceptable image quality. Depending on the system, the user can specify the standard variation of pixel values in an image (Toshiba Corporation, Tokyo, Japan), enter a noise index value that must be maintained on every image (GE Healthcare, Milwaukee, Wisconsin), provide an image quality reference mAs that would be used on an average-sized patient (Siemens), or instruct the system to replicate the image quality of an "ideal reference image" (Philips Medical Systems, Andover, Massachusetts) (Table 1). Using the parameters entered by the user, the software then modulates the tube current for the system specific axis after estimating the patient's attenuation characteristics on the basis of the topographic image [5].

AUTOMATED TUBE POTENTIAL SELECTION

Decreasing tube voltage (kVp) can be an extremely effective means of reducing radiation exposure, as the radiation dose changes with roughly the square of the tube potential [6]. With a constant tube current, decreasing the tube potential from 120 to 100 kVp can result in a dose reduction of roughly 33%, and decreasing the tube potential from 120 to 80 kVp can result in up to a 65% reduction in dose [7,8]. Moreover, as the kVp is decreased, the attenuation of iodine increases because of the increased influence of the photoelectric effect, even without a change in the dose of contrast administered, improving the tissue contrast in an image. At the same time, however, if all other factors are constant, decreasing the tube potential can markedly increase image noise in a nonlinear fashion (as a result of decreased tissue penetration by photons), resulting in a decrease in the contrast to noise ratio. As a result, mAs must typically be increased to preserve image quality when a lower tube potential is used [6].

Overall, despite the resultant increase in image noise, a number of studies over the past 2 years have shown that images acquired at a lower tube potential (100 or 80 kVp) with an appropriately adjusted mAs can still be of high diagnostic quality (particularly in thin patients) but at a substantially lower radiation dose. These studies have evaluated a wide variety of different CT examinations, including carotid CT angiography (CTA), coronary CTA, pulmonary CTA, and conventional thoracoabdominal CT [7,9-14]. However, in practice, changing the kVp is a rarely used option because technologists and radiologists must take the time to individually appraise each patient's body habitus, the region to be scanned, and the importance of iodine contrast in the examination to determine if a low-kVp protocol is appropriate. Moreover, although it is generally the case that a compensatory increase in mAs is required to reduce image noise, there are no clear clinical guidelines to determine this increase, and there have been very few guidelines in the literature or from CT manufacturers regarding the best means by which to make this manual adjustment [4,8].

Automated tube potential selection, a tool currently available on only the Definition line of Siemens scanners (CARE kV), allows the automation of this process and automatically calculates the optimal tube current and tube potential for each patient depending on the type of study being performed, the body region being imaged, and the patient's body habitus. On the basis of the topographic image, the software calculates the total tissue attenuation along the z axis of the patient and calculates the mAs that would be required for each of the tube potential settings on the basis of the user-defined examination type and image quality and noise preferences. The system then determines the optimal combination of kVp and mAs to produce the desired image quality at the lowest patient dose (in terms of volume CT dose index), and these settings are used to scan the patient.

In a study by Winklehner et al [15], this software was used to scan 40 patients undergoing abdominal CTA; all the CARE kV images were found to be of diagnostic quality, and the authors found an overall 25% reduction in radiation dose compared with standard 120-kVp protocols. Similarly, Gnannt et al [6] used the software to scan 40 patients undergoing thoracoabdominal CT and found that every study was diagnostic, with a corresponding 12% reduction in radiation dose compared with a conventional 120-kVp protocol. Clearly, the radiation dose savings depend on the type of study being performed and the patient size: The maximum dose savings are seen with CT angiographic studies, for which the reduction of kVp brings the tube potential closer to the k-edge of iodine, resulting in a marked increase in the attenuation of contrast. This allows the contrast-to-noise ratio to be preserved despite the increase in image noise, producing significant reductions in patient dose. Lesser degrees of dose reduction would be expected in conventional venous phase studies or noncontrast studies, as the improvements in tissue contrast from lowering kVp are much less evident, and larger compensatory increases in mAs are required to reduce image noise [16].

ITERATIVE RECONSTRUCTION

Until recently, CT reconstruction methods were all based on filtered back projection (FBP). Although the technical details of FBP are beyond the scope of this discussion, the algorithms underlying FBP offer only an approximate mathematical relationship between the "projection data" (ie, the x-ray attenuation data measured during CT acquisition) and the data displayed in the final CT image. If the acquired data were perfectly devoid of noise with unlimited resolution, then the displayed image would also be perfect (artifact free). Although this assumption generally holds true at high radiation doses (a situation in which noise is relatively diminished), this assumption breaks down when the radiation dose falls and there is increased noise in the data acquired at the scanner. By assuming a nonperfect mathematical model between the projection data and the final image, FBP removes only a limited amount of noise from the image [17]. As a result, FBP significantly limits the use of data with lower contrast-to-noise ratios: Even if one were to scan the patient with much lower mAs and kVp to lower dose, the use of FBP would prevent the images from being diagnostic in quality.

The limitations of FBP in dealing with noise in images, and the resulting need to impart greater radiation doses to the patient to acquire readable images, have placed a renewed emphasis on the use of iterative reconstruction techniques as a replacement for FBP. Additionally, recent advances in hardware have allowed the computational demands of iterative reconstruction to become less prohibitive. Several different iterative reconstruction methods have been introduced by all the major CT manufacturers (Table 2), each of which operates using a slightly different algorithm, but all of which are based on the same basic premise: Iterative reconstruction works using a "trial-and-error" algorithm, using a "correction loop" during the reconstruction of an image from projection data. Each time the image is reconstructed from the projection data, the reconstruction is compared with the software's initial "guess" of the ideal image, and the image continues to be reconstructed repeatedly until the deviation between the image reconstruction and the "guess" is deemed acceptable [17-19]. Each of these iterative "correction loops" can be extremely time consuming, and as the development of different algorithms has progressed, developers have found that these loops could be performed both in "raw-data" space (ie, the projection data directly from the CT scanner) and in "image" space

Table 2. Various available iterative reconstruction algorithms available in the United States from major manufacturers

Vendor	Acronym	Name	Primarily Uses Image Space	Primarily Uses Raw-Data Space
Siemens	IRIS	Image Reconstruction Iterative Reconstruction	Yes	No
Siemens	SAFIRE	Sinogram Affirmed Iterative Reconstruction	Yes	Yes
GE	ASiR	Adaptive Statistical Iterative Reconstruction	Yes	No
Philips	iDose	iDose	Yes	No
Toshiba	ADIR	Adaptive Iterative Dose Reduction	Yes	No
Toshiba	ADIR 3D		No	Yes

(ie, after an initial reconstruction). Although the details of the different algorithms in use are beyond the scope of this review, it has gradually become clear that performing reconstructions fully in raw data space is too time consuming and thus a barrier for clinical use [20]. Furthermore, it has been shown that all noise reduction can occur in image space. Thus, by performing reconstruction loops in both image space and raw-data space, it is possible to markedly reduce image reconstruction times while still significantly reducing noise, improving image resolution, and reducing artifacts [21]. The use of raw-data space and image space is perhaps the main differentiating factor among the various vendors' algorithms in use today, and each vendor uses these two spaces in a unique fashion.

A couple of the manufacturers' algorithms "blend" iterative reconstruction with traditional FBP, producing hybrid reconstruction techniques that serve two primary purposes: (1) Given the computational and time demands of iterative reconstruction as a result of the need to repeat the reconstruction process over several cycles, hybrid algorithms can reduce reconstruction times and make the use of iterative reconstruction more practical in day-to-day practice. (2) Images acquired with iterative reconstruction can have a smoothed, artificial appearance compared with FBP images, particularly in the axial plane, which can be disconcerting to radiologists used to FBP images. The use of hybrid techniques can make images look more akin to traditional FBP images. For example, GE's Adaptive Statistical Iterative Reconstruction (ASiR) allows for a "mix" of FBP and iterative reconstruction to be determined by the user, with resultant changes in the appearance of the images and the amount of possible radiation dose savings. Siemens's Sinogram Affirmed Iterative Reconstruction (SAFIRE) gives 5 different "strength" options that tune the different parameters of iterative reconstruction, leading to images with different noise levels and appearances.

As a result, iterative reconstruction techniques produce significant increases in image quality and decreases in image noise, even in situations in which the contrast-to-noise ratio is quite low. As a result, CT studies can be performed at a significantly lower dose but still remain of diagnostic quality. Multiple studies (performed using multiple different vendors' equipment) over the past 24 months have looked at the effects of various iterative reconstruction methods on patient dose and image noise, and all have shown significant decreases in radiation dose (up to 40%-50% in some cases) [19,22-32]. Moreover, even at much lower radiation doses, these studies have shown images with unchanged or decreased noise levels compared with FBP images acquired at significantly higher radiation doses.

The latest version of raw data-based iterative reconstruction by Siemens, SAFIRE, recently approved by the FDA, allows the reconstruction of up to 20 images per second and provides the user with the option of 5 different "strengths" for the reconstruction, each with a varying degree of noise reduction and image "smoothing." A study looking specifically at the use of the SAFIRE algorithm in body CTA showed >50% dose reduction with preservation of image quality [32]. At a constant radiation dose, SAFIRE can reduce image noise by 35% and improve contrast to noise by 50% [20].

CONCLUSIONS

Although all the major CT manufacturers offer significant tools to reduce radiation dose, many centers do not take advantage of the dose reduction capabilities of their scanners because of a lack of familiarity and understanding as to how these tools work. However, these tools are now built into scanner software with relatively simple, intuitive interfaces, and little or no day-to-day manipulation of the scanner's settings by technologists or radiologists is required. Moreover, each of the tools we have detailed can not only be used in isolation but have a synergistic effect on radiation dose reduction when used in conjunction. Although many of the readers of this review undoubtedly use different scanners from different manufacturers, this review should serve as an impetus for a careful appraisal of the dose reduction options available on each group's individual scanner.

TAKE-HOME POINTS

- Automatic tube current modulation is a tool designed to modulate the imparted radiation dose, via changes in mAs, on the basis of the patient's size and attenuation.

- Automated tube potential selection automatically calculates the optimal tube potential and corresponding tube current for each patient depending on the type of study being performed, the body region being imaged, and the patient's body habitus.
- Iterative reconstruction algorithms have emerged as an alternative to traditional FBP and allow the acquisition and reconstruction of diagnostic-quality images at far lower radiation doses.

REFERENCES

1. Larson DB, Johnson LW, Salisbury SR, Forman HP. National trends in CT use in the emergency department: 1995-2007. Radiology 2011;258: 164-73.
2. Bruesewitz MR, Yu L, Vrieze TJ, et al. Smart mA—automatic exposure control (AEC): physics principles and practical hints. Presented at: Annual meeting of the Radiological Society of North America; 2008.
3. Lee CH, Goo JM, Lee HJ, et al. Radiation dose modulation techniques in the multidetector CT era: from basics to practice. Radiographics 2008; 28:1451-9.
4. Soderberg M, Gunnarsson M. Automatic exposure control in computed tomography—an evaluation of systems from different manufacturers. Acta Radiologica 2010;51:625-34.
5. Singh A, Kalra MK, Thrall JH, et al. Automatic exposure control in CT: applications and limitations. J am Coll Radiol 2011;8:446-9.
6. Gnannt R, Winklehner A, Eberli D, et al. Automated tube potential selection for standard chest and abdominal CT in follow-up patients with testicular cancer: Comparison with fixed tube potential. Eur Radiol 2012; 22:1937-45.
7. Paul JF. Individually adapted coronary 64-slice CT angiography based on precontrast attenuation values, using different kVp and tube current settings: evaluation of image quality. Int J Cardiovasc Imaging 2011; 27(suppl):53-9.
8. Sodickson A, Weiss M. Effects of patient size on radiation dose reduction and image quality in low-kVp CT pulmonary angiography performed with reduced IV contrast dose. Emerg Radiol. In press.
9. Feuchtner GM, Jodocy D, Klauser A, et al. Radiation dose reduction by using 100-kV tube voltage in cardiac 64-slice computed tomography: a comparative study. Eur J Radiol 2010;75:e51-6.
10. Kayan M, Köroğlu M, Yeşildağ A, et al. Carotid CT-angiography: low versus standard volume contrast media and low kV protocol for 128-slice MDCT. Eur J Radiol 2012;81:2144-7.
11. Szucs-Farkas Z, Schibler F, Cullmann J, et al. Diagnostic accuracy of pulmonary CT angiography at low tube voltage: intraindividual comparison of a normal-dose protocol at 120 kVp and a low-dose protocol at 80 kVp using reduced amount of contrast medium in a simulation study. AJR Am J Roentgenol 2011;197:W852-9.
12. Wang D, Hu XH, Zhang SZ, et al. Image quality and dose performance of 80 kV low dose scan protocol in high-pitch spiral coronary CT angiography: feasibility study. Int J Cardiovasc Imaging 2012;28:415-23.
13. Yeh BM, Shepherd JA, Wang ZJ, Teh HS, Hartman RP, Prevrhal S. Dual-energy and low-kVp CT in the abdomen. AJR Am J Roentgenol 2009;193:47-54.
14. LaBounty TM, Leipsic J, Poulter R, et al. Coronary CT angiography of patients with a normal body mass index using 80 kVp versus 100 kVp: a prospective, multicenter, multivendor randomized trial. AJR Am J Roentgenol 2011;197:W860-7.
15. Winklehner A, Goetti R, Baumueller S, et al. Automated attenuation-based tube potential selection for thoracoabdominal computed tomography angiography: improved dose effectiveness. Invest Radiol 2011;46: 767-73.
16. Grant K, Schmidt B. CARE kV: automated dose-optimized selection of x-ray tube voltage. Available at: http://www.medical.siemens.com/siemens/en_US/gg_ct_FBAs/files/Case_Studies/CarekV_White_Paper.pdf. Accessed August 13, 2012.
17. Fleischmann D, Boas FE. Computed tomography—old ideas and new technology. Eur Radiol 2011;21:510-7.
18. Korn A, Fenchel M, Bender B, et al. Iterative reconstruction in head CT: image quality of routine and low-dose protocols in comparison with standard filtered back-projection. AJNR Am J Neuroradiol 2012;33: 218-24.
19. Xu J, Mahesh M, Tsui BM. Is iterative reconstruction ready for MDCT? J Am Coll Radiol 2009;6:274-6.
20. Grant K, Raupach R. SAFIRE: Sinogram Affirmed Iterative Reconstruction. Available at: http://www.medical.siemens.com/siemens/en_US/gg_ct_FBAs/files/Definition_AS/Safire.pdf. Accessed August 13, 2012.
21. Bruder H, Raupach R, Sunnegårdh et al. Adaptive iterative reconstruction. Proc SPIE 2011;7961.
22. Desai GS, Uppot RN, Yu EW, Kambadakone AR, Sahani DV. Impact of iterative reconstruction on image quality and radiation dose in multidetector CT of large body size adults. Eur Radiol 2012;22:1631-40.
23. Katsura M, Matsuda I, Akahane M, et al. Model-based iterative reconstruction technique for radiation dose reduction in chest CT: comparison with the adaptive statistical iterative reconstruction technique. Eur Radiol 2012;22:1613-23.
24. Kaza RK, Platt JF, Al-Hawary MM, Wasnik A, Liu PS, Pandya A. CT enterography at 80 kVp with Adaptive Statistical Iterative Reconstruction versus at 120 kV with standard reconstruction: image quality, diagnostic adequacy, and dose reduction. AJR Am J Roentgenol 2012;198:1084-92.
25. Martinsen AC, Sæther HK, Hol PK, Olsen DR, Skaane P. Iterative reconstruction reduces abdominal CT dose. Eur J Radiol 2011;81: 1483-7.
26. Mitsumori LM, Shuman WP, Busey JM, Kolokythas O, Koprowicz KM. Adaptive statistical iterative reconstruction versus filtered back projection in the same patient: 64 channel liver CT image quality and patient radiation dose. Eur Radiol 2012;22:138-43.
27. Moscariello A, Takx RA, Schoepf UJ, et al. Coronary CT angiography: image quality, diagnostic accuracy, and potential for radiation dose reduction using a novel iterative image reconstruction technique-comparison with traditional filtered back projection. Eur Radiol 2011;21:2130-8.
28. Oda S, Utsunomiya D, Funama Y, et al. A hybrid iterative reconstruction algorithm that improves the image quality of low-tube-voltage coronary CT angiography. AJR Am J Roentgenol 2012;198:1126-31.
29. Park EA, Lee W, Kim KW, et al. Iterative reconstruction of dual-source coronary CT angiography: assessment of image quality and radiation dose. Int J Cardiovasc Imaging. In press.
30. Ren Q, Dewan SK, Li M, et al. Comparison of adaptive statistical iterative and filtered back projection reconstruction techniques in brain CT. Eur J Radiol. In press.
31. Singh S, Kalra MK, Gilman MD, et al. Adaptive statistical iterative reconstruction technique for radiation dose reduction in chest CT: a pilot study. Radiology 2011;259:565-73.
32. Winklehner A, Karlo C, Puippe G, et al. Raw data-based iterative reconstruction in body CTA: evaluation of radiation dose saving potential. Eur Radiol 2011;21:2521-6.