Review

Vendor free basics of radiation dose reduction techniques for CT

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ABSTRACT

Although radiation dose in computed tomography (CT) decreased and CT became safer examinations than before, CT is the most significant source of the medical radiation exposure. Knowledge about available radiation dose reduction methods in CT is essential.

Substantial improvement occurred regarding tube current selection (automatic exposure control) and image production method (iterative reconstruction). Optimizing the tube potential selection is expected to contribute to further CT radiation dose reduction.

This review article summarizes the principles of radiation dose reduction in CT, principal methods of radiation dose reduction, auxiliary measures of radiation dose saving and recent issues of low dose CT.

1. Background

Computed tomography (CT) is one of the most heavily used diagnostic image procedures. Multidetector CT scanners have remarkably improved the throughput of the CT examinations, making CT examination readily accessible. Radiation exposure during a single CT examination is relatively high, compared with most of the other X-ray examinations. Consequently, CT has become the largest source of the radiation exposure to the patients. The risk of developing malignant diseases related to CT imaging is reported to be significant with the current level of radiation exposure originated from CT examination [1]. Therefore, radiation dose reduction in CT has been rigorously investigated. To use CT examinations safely and judiciously, knowledge about available radiation dose reduction methods is essential. This review article summarizes the principles of radiation dose reduction in CT, principal methods of radiation dose reduction, auxiliary measures of radiation dose saving and recent issues of low dose CT.

2. General principle of CT radiation dose reduction

The radiation dose of CT examinations has been reduced with the comparable or improved quality of images. The dose reduction has been made possible as a result of efforts and improvements in various areas [2].

First, radiation dose reduction was made possible through technological refinement of CT scanner [3,4]. For example, improvement of generators and X-ray optical systems and increased efficiency of data acquisition systems contributed to improved dose efficiency. More recently introduced model has higher dose efficiency that enables radiation dose reduction keeping the same level of image quality.

Second, dose reduction can be attained with a change in the scanning parameters [5]. Table 1 shows scan parameters and other factors that the operator of the scanner can select. Among others, X-ray tube current and tube potential are the most frequently adjusted factors to reduce radiation dose to the patent. Today, a scanner function called automatic exposure control (AEC) facilitates the selection of the adequate tube current. Adjusting tube voltage for dose reduction is another method of parameter modification. The effect of tube potential adjustment is more complicated than tube current, but advanced manipulation methods of tube potential are supposed to contribute to the further radiation dose efficiency.

Third, image production methods can be altered to improve image quality. Application of image filters and selection of more sophisticated image reconstruction algorithms are reported to lead to better image quality without escalating radiation exposure. Conversely, the same method can be used to lower the radiation dose while keeping the level of image quality. Image filters and iterative reconstruction algorithms had a major contribution to radiation dose reduction.

Finally, these radiation dose reduction measures should be accompanied by observation of the adequate scanning practice and effort to stick to the thoughtful and intelligent use of medical imaging. Besides, the usage pattern of CT examination could be modified to contribute to the patient safety. Low-yield examinations lead to increased radiation exposure to the patients and also raise the cost of the health care systems with uncertain benefit to the patients. Therefore, methods to avoid clinically unwarranted examinations should be valuable. Clinical decision support based on information technology is expected to increase the diagnostic yield of CT examinations [6].

Table 1
Parameters and factors that May influence radiation dose in CT examinations.

|		Rationale/Method	Advantage	Disadvantage/Pitfall	References
Scan parameters and related factors	X-ray tube current	Tube current is proportional to numbers of the photon emitted.	Predictable effect, dynamically adjustable using automatic exposure control.	Potentially requiring additional methods to overcome noise increase.	[10,12]
	Image quality index (automatic exposure control)	Programmed adjustment to optimize dose efficiency.	May also improve the image quality.	Proper image quality setting required.	[13,14]
	X-ray tube potential (peak kilovoltage and energy profile)	Decreased photon counts. Lower energy X-ray can boost the contrast enhancement by iodine.	Possible improvement of contrast of the images	May require higher tube current. Effect on image quality is less predictable than tube current.	[17,19]
	Gantry rotation speed	Shorter exposure time.	Shortening of examination time	Image quality may be affected negatively.	[8,9]
	Helical pitch	Shorter exposure time.	Shortening of examination time	Image quality may be affected negatively.	[7,48]
Image production methods	Image filters	Noise removal and streak artifact mitigation improve the image quality of reduced dose CT.	Can be applied to the reconstructed images.	Decrease the sharpness of the images to some degree.	[23,24,25,26]
	Reconstruction algorithms	Use of iterative reconstruction can decrease the image noise.	Dose reduction is possible while retaining the quality of the images.	Longer reconstruction time can limit the routine use.	[27,28]
	Section thickness	Image noise is decreased by increasing the thickness of the image.	Readily feasible for selected purposes.	Risk of compromising the diagnostic quality.	[49]
Observation of proper techniques	Scan length	Eliminates unnecessary radiation exposure	No extra financial cost.	none	[30]
	Patient positioning	CT scanner efficiency is the best when the subject is located right at the center of the gantry.	No extra financial cost.	none	[29]
Administrative	Dose monitoring	Detection of variation of radiation dose for a particular scan protocol.	May lead to a substantial decrease in the total radiation dose.	Cost of interfacility connectivity	[40,41]
	Adequacy of diagnostic procedures	Discourage the prescription of the unwarranted imaging procedure.	Possibly lower the healthcare cost.	Define "inadequate" procedures are not always easy.	[6,31,32,33,34,35]
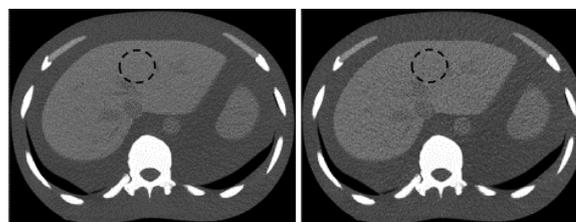
Fig. 1. Tube current and image quality. CT Images of an anthropomorphic phantom obtained with (a) 125 mAs and (b) 55 mAs at the level of lung bases. Standard deviations of Hounsfield unit in the region of interest are 14.5 and 19.3 in the image (a) and (b), respectively. Streak artifacts originating from the thoracic vertebra are seen as black linear structures and more readily perceptible in the image (b). The image acquired with lower radiation dose (b, 55 mAs) has more noise and streak artifacts the one with higher radiation dose (a, 125 mAs).

3. Tube current reduction

Reducing tube current is the most straightforward approach to CT dose reduction. Radiation dose is proportional to the effective current-time product, i.e., the product of the tube current and the exposure time per rotation divided by the pitch (the table feed per gantry rotation divided by the beam width/collimation).

Radiation dose can be reduced by either reduction of tube current or increase in the gantry rotation speed or the table feed [5]. Increase in rotation speed and table feed is advantageous when shortening the examination time is crucial as in the examination of pediatric patients [7]. However, the increase in rotation speed and table feed can cause image quality deterioration [8,9]. Therefore, lowering the tube current is generally the most convenient and reliable method.

When the current time product is reduced, a smaller number of photons is emitted from the X-ray tube, leading to a decrease in radiation dose. At the same time, image noise increases because of the smaller number of incident photons. Streak artifacts become more pronounced when the number of photons at the detector is low (Fig. 1). Selection of the optimal tube current should be made based on the desired image quality and body size of the patients, among others. Currently, selection of tube current can be assisted by scanner function called automatic exposure control (AEC) systems. Studies of tube current reduction started with reduced dose lung HRCT studies in the late 80 s [10]. Structures in the lungs have conspicuously high contrast surrounded by gas in the alveoli and airways. Therefore, it is logical that the targets of early dose reduction studies were reduced dose lung CT.

Studies using tube current reduction showed the possibility of substantial radiation dose reduction without significant image quality degradation or diagnostic value [11,12]. However, the practice of selecting the appropriate tube current takes careful attention by the experienced technologists and radiologists. Various factors should be taken into consideration to achieve the optimal radiation exposure level, including parts of the body to be examined, the purpose of the examination, body habitus of the patients. It is not easily practicable to cut the radiation dose without compromising the diagnostic quality.

Today, selection of tube current is mostly assisted by the automatic exposure control systems that are implemented in the scanner and the choice of the optimal tube current has become more readily achievable [13,14]. The operators of the CT scanner with an automatic exposure control system select the image quality needed for the study instead of an actual value of tube current.

It is important to note that the use of automatic exposure control does not guarantee the reduced radiation dose. The dose-sparing effect is dependent on the choice of the users. Parameter setting for lower image quality will lead to lower radiation dose. Meanwhile, parameter setting for higher image quality can result in higher radiation dose.

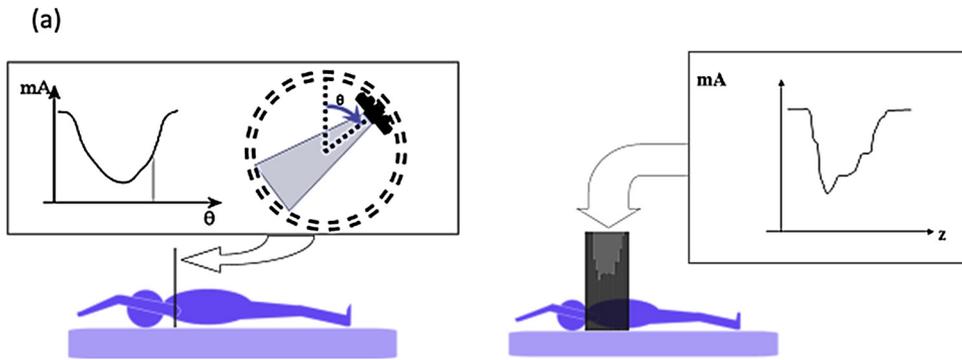Once the image quality is specified, scan parameters are adjusted to

the body habitus of the patient. CT scanners set the baseline tube current according to designated image quality and body size of the patient, based on the CT localizer radiograph that was taken for scan planning. Large patients have higher mAs setting, and small patients have lower mAs setting to obtain images with preset image quality.

Automatic exposure control systems also adjust tube current dynamically during a scan. X-ray attenuation of the human body is not uniform. Therefore, if the tube current is fixed throughout the whole scan, the quality of the image becomes uneven. Consequently, to attain the optimal dose efficiency, tube current needs to be modulated while the scan is in progress. Three-dimensional exposure control is commonly used (Fig. 2). Two modes of tube current modulation work concertedly to achieve the three-dimensional current modulation: current adjustment during gantry rotation (angular or rotational modulation) and current adjustment according to the table location (z-axis exposure control). The current adaptation is based on the information from localizer radiographs.

Angular tube current modulation changes the tube current as the X-ray tube turns around the patient to offset the attenuation variation with view angle. Angular tube current modulation is used to adjust the tube current to attempt to equalize the image quality for all view angles. Longitudinal tube current modulation alters the tube current in along the longitudinal (z-axis) direction to equalize the image noise.

Automatic exposure control system can improve the image quality by reducing the regional variability of the image noise (Fig. 3). Consequently, automatic exposure control systems improved the dose efficiency significantly contributing to radiation dose reduction [15].

4. Tube potential modification

Reduction of tube potential (peak kilovoltage, kVp) is an alternative method for reducing X-ray output. Compared with tube current reduction, application of tube potential reduction has been limited. One of the reasons for the underutilization is that the effect of the tube energy alteration is more complicated than the tube current. Another reason is that tube potential is not as easily adjustable as tube current. However, X-ray energy modification has unique potential advantages and the techniques to optimize tube potential and X-ray energy profile are expected to develop (Fig. 4). Lowering tube potential will lead to significant reduction of photon fluence [16]. Radiation dose is not linearly proportional to the peak kilovoltage but is exponentially related to peak kilovoltage with a base of more than 2. Therefore, tube potential reduction is usually used in conjunction with the increase in the tube current. Therefore, low voltage setting needs high power X-ray tube. At 80 kV or lower peak energy may be impractical because of the limit of the X-ray output.
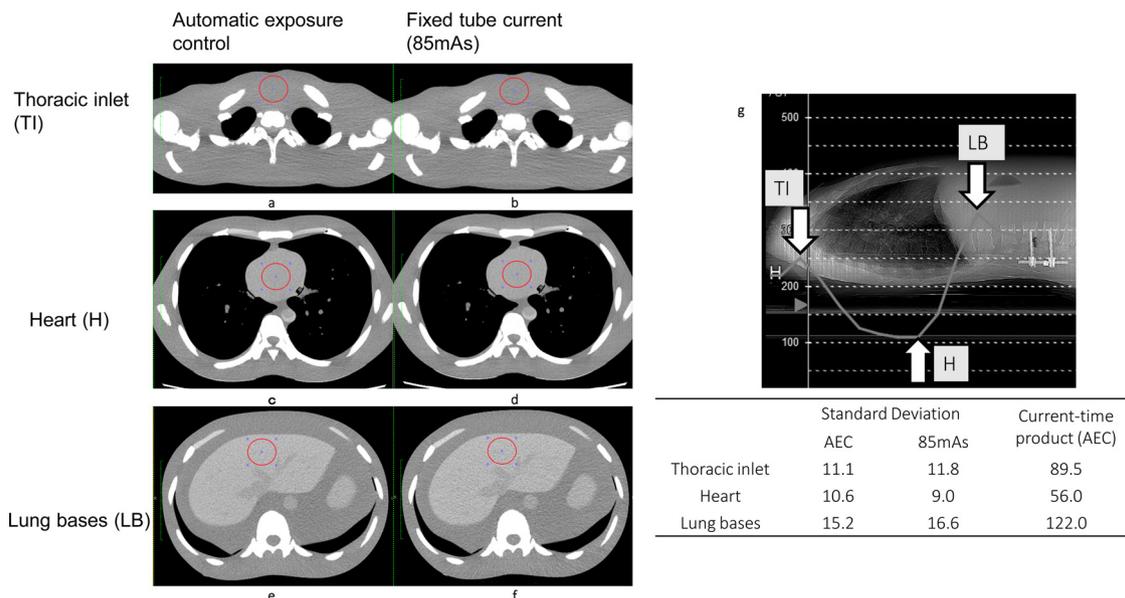

| | Standard Deviation | | Current-time |
	AEC	85mAs	product (AEC)
Thoracic inlet	11.1	11.8	89.5
Heart	10.6	9.0	56.0
Lung bases	15.2	16.6	122.0

Fig. 3. Tube current adjustment by automatic exposure control system.
CT Images of an anthropomorphic phantom obtained with automatic exposure control (a, c, e) and fixed tube current (85 mAs; b, d, f). Both scans were performed with almost the same level of radiation exposure. In body parts with lower attenuation, as in the middle thorax (c, d), AEC depresses the tube current and consequently, the AEC image has more noise. In parts of the body with higher attenuation such as lung bases (e, f), AEC raises the tube current, and the images of the AEC images were, therefore, less noisy. In some areas, the tube current may be at nearly the same level both in AEC images and fixed tube current images. These pairs of images demonstrate how automatics exposure control contributes to the radiation dose reduction by improving the radiation dose efficiency.
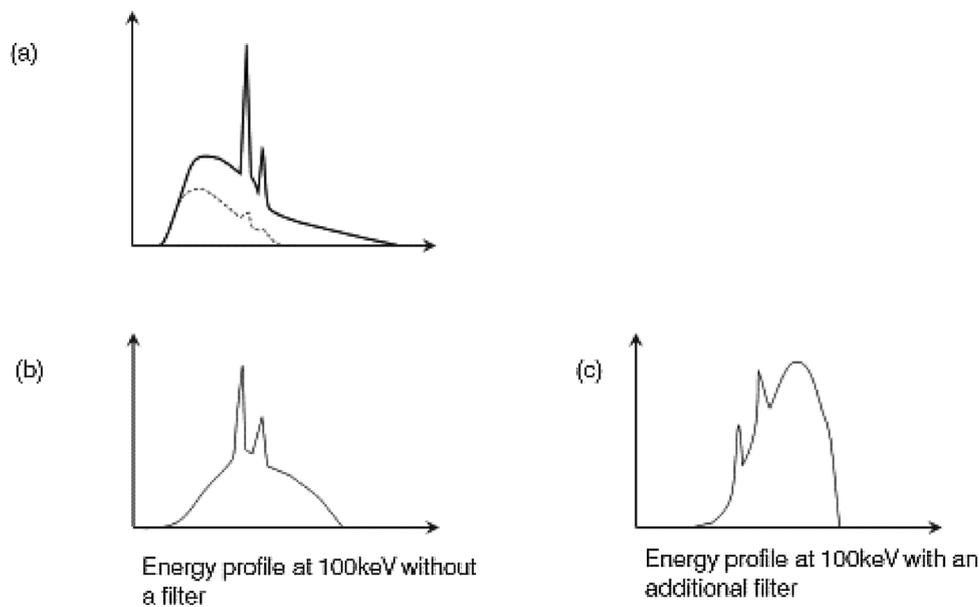
Fig. 4. Modification of X-ray energy profile (a) X-ray energy profile at 140kVp (solid line) and 80 kVp (dashed line). (b, c) Modification of energy profile with an extra X-ray filter. Energy profile at 100 keV without a filter (b) and at 100kVp with an additional filter (c). Low energy X-ray is mostly removed with the additional filter.

The primary application of lower tube potential for CT is the enhancement of contrast bestowed by iodine contrast medium [17]. Lowering tube potential can be beneficial for contrast enhancement CT because it boosts the contrast enhancement effect conferred by the iodine-containing contrast medium. Iodine 41 has a K-absorption edge at 33 keV. Therefore, shifting tube potential peak to the lower energy (e.g., 120kVp to100kVp) raise the low-energy portion of the X-ray that can be absorbed by the iodine, thereby augmenting the contrast enhancement effect of the iodine. Many reports demonstrated the effectiveness of reduced tube potential CT to improve the contrast noise ratio of the CT angiograms and to reduce the radiation dose [18].

Lowering tube potential is not thought to be particularly useful for non-contrast CT as it does not improve contrast as it does for contrast-enhanced CT. However, Selective use for pediatric patients and adults with lower body weight was attempted and reported to be beneficial. Automated selection systems of tube potential are available in some scanners. Those systems may facilitate the use of lower tube potential for the advantage of dose reduction [19].

The energy of X-ray emanating from X-ray tube is not uniform (monochromatic) but ranges broadly forming a spectrum of energy with a particular kilovolt peak (polychromatic). X-rays emitted by an X-ray tube consist of two classes of X-rays, i.e., characteristic X-rays and bremsstrahlung. In X-ray, bremsstrahlung occurs with deceleration of an electron by an atomic nucleus. Kinetic energy lost during the interaction turned into photons, which has a continuous spectrum. Therefore, in addition to adjusting peak X-ray energy, X-ray energy profile can be modified to reduce radiation dose. X-ray spectrum modulation technology alters X-ray energy profile to improve dose efficiency.

Low energy photons are less dose-efficient than the photons at the peak energy level. Additional X-ray filter removes low energy photons. Increasing the mean photon energy of the X-ray by excluding low energy photon improves dose efficiency and consequently leads to radiation dose reduction [20] (Fig. 4). Moreover, the X-ray spectrum shape can be modified based on the purpose of the examination. Alteration of X-ray energy spectrum can contribute to radiation dose reduction for unenhanced CT as well as contrast-enhanced CT [20].

It is possible by measuring attenuation values with two different X-ray energy because the attenuation values of the material vary with the energy of the X-ray. Dual-energy imaging is a method of acquiring X-ray image data using two distinctly different energy to obtain more information about tissue composition. Dual-energy techniques have been applied to bone densitometry or dual-energy x-ray absorptiometry (DEXA). Removal or enhancement of bones to assist lesion detection on chest X-ray may be achieved with dual-energy imaging techniques [21]. The popularization of dual-energy imaging to clinical CT scan is brought by the introduction of dual-source CT with two X-ray tubes that works simultaneously with different tube potential [22]. Currently, dual-energy CT examination can also be performed using a scanner with a single X-ray tube. It can be made possible with fast or slow kV switching and dual-layer detector. The radiation dose for dual-energy CT may be slightly higher than single-energy CT [22]. However, dual-energy CT is expected to obviate the need for the pre-contrast CT, at least, for some purposes. It may directly lead to substantial radiation dose reduction.

5. Improvement of image production methods

Image production methods can be improved to lower the radiation dose. Improved image production method can generate images with lower image noise that can be conspicuous in reduced-dose CT images [23]. If the image noise of the original images is in the tolerable level, the radiation dose can be reduced to obtain the images comparable to the original ones. These noise reduction functions are integrated with the CT scanning and image production systems. Consequently, users may be unaware of the image improvement techniques applied while generating the final output images.

Application of novel image production methods can occur in two ways although they are not always separable. One is to develop or improve the image filter to obtain images with lower image noise and artifacts. The other one is to use the different method of image reconstruction, namely implementation of iterative reconstruction method instead of a conventional filtered back projection method. It is essential to be familiar with the image processing methods used in the scanner and select the most effective processing option available to acquire the image that is the best for the clinical purposes.

Image filters have been used to decrease the image noise. Filters can be applied in the image domain or the sinogram domain. Simple denoising filter that works on the image domain, such as mean filter, may be utilized for noise reduction. Loss of sharpness is an unwanted

adverse effect which blurs the surface of the structures and compromises the visibility of the fine structures. Adaptive filters work selectively in the image domain that resulted in a decrease in the sharpness of images and a decrease in the image noise level [24]. That led to a more favorable tradeoff between image noise and sharpness of the structures. Filters working on sinogram domain are effective in suppressing streak artifacts, especially in reduced dose CT images [25]. More sophisticated image denoising functionality is implemented in some scanner, such as denoising technique originating from iterative reconstruction algorithms or an image noise removal technique utilizing deep-learning [26]. Most of these image noise filters are embedded in the scanner system. The filter may be inherently incorporated in the image production pipeline in the CT scanner. Some filters can be turned on or off explicitly by the user. Independent image denoising system is also available. These additional filters are applied to the image output from the scanner and consequently work on image domain. Users of CT scanner without iterative reconstruction capability may benefit from these add-on systems.

CT image reconstruction was almost universally carried out by filtered back projection (FBP) method. A method called iterative reconstruction (IR) was introduced clinical CT scanners around 2010 [27]. IR involves repetitive processes of data correction and comparison to obtain the output images. The IR images have significantly lower noise and artifacts than FBP images which is reported to enable radiation dose reduction over 50% [28]. Iterative reconstruction can be roughly classified into two types, hybrid-IR and full-IR [2] (Fig. 5). Currently, hybrid IR is the more commonly used type of iterative reconstruction. Hybrid IR methods circumvent the forward projection process that requires sizeable computational resource but perform repetitive image correction in projection data domain, spatial domain, or both. The reconstruction time of hybrid IR is slightly longer than that of conventional filtered back projection algorithms, enabling users to adopt hybrid IR in many routine CT scan and reconstruction protocols. The high computational demand of the full-IR precludes its routine application. Full IR involves multiple steps of forward and backward projections and consequently requires reconstruction time by far longer than scan time. Therefore, image reconstruction lags the progress of scan of the patients, and routine application of this technique is not practical. Presently, use of full-IR for selected purposes would be needed.

6. Protection of radiation-sensitive organs

Radiosensitivity of individual organs needs to be considered to reduce the risk of developing malignant diseases and other adverse effects. Some organs are more susceptible to the adverse effect of ionizing radiation. Mammary glands, gonads, thyroid glands and lens in the eyes are well-known radiation-sensitive parts of the body. It is desirable that radiation dose to these sensitive organs are kept lower than other organs as long as it does not significantly degrade the diagnostic value of the examination.

Protective measures of mammary glands are the most commonly applied [23]. Two methods of mammary gland protection are investigated. Reduction of radiation dose to breast tissue can be achieved with breast shielding or tube current adjustment (organ-based tube-current modulation).

The untoward effects caused by breast shielding include the increase in image noise and artifacts. It is difficult to predict the magnitude of these effects in individual patients. The combined use of breast shielding and automatic current modulation may lead to unexpected results as AEC may adjust the tube current dynamically during the scan to counterbalance the effect of the radiation shield.

Organ-based tube-current modulation adjusts tube current to make a reduced exposure to the area of breast tissue. The fundamental principle of organ-based tube-current modulation is similar to that of angular modulation in the automatic exposure control system. It is reported that organ-based tube-current modulation may not work as expected and the effectiveness of organ-based tube-current modulation are overestimated [24].

There are limited pieces of evidence regarding the effectiveness of protective measures of other radiosensitive organs [25]. Although shield of the pelvis can block scattered X-ray from the outside the shield, the effect is limited. Routine use of the pelvic shield is not warranted [26]. Organ-based dose modulation or thyroid shield may be applied for thyroid gland dose reduction [27] of the patients at higher risk.

7. Observation of proper techniques

Although various built-in function in CT scanners, such as automatic exposure control, helped optimize the scanning parameters, careful observation of proper techniques is still crucial. For example, improper patient positioning and scan range will raise the radiation dose.

Location of the patient in the gantry aperture can influence image quality and radiation dose [29]. Automatic exposure control systems assume that the subject is placed at the center of the gantry. If a patient is positioned inadequately away from the center of the gantry, rotational automatic exposure control does not work as it is supposed to do.

Likewise, appropriate selection of scan range is essential. Scan range should be set to the minimum. Scanning beyond the area of active clinical interest needs to be avoided [30]. For example, scan range for lung CT should not include upper abdominal region and caudal part of the neck into the scan range, unless the inclusion of these areas is clinically indicated. Education of both physicians and technologists is necessary to achieve the goal.
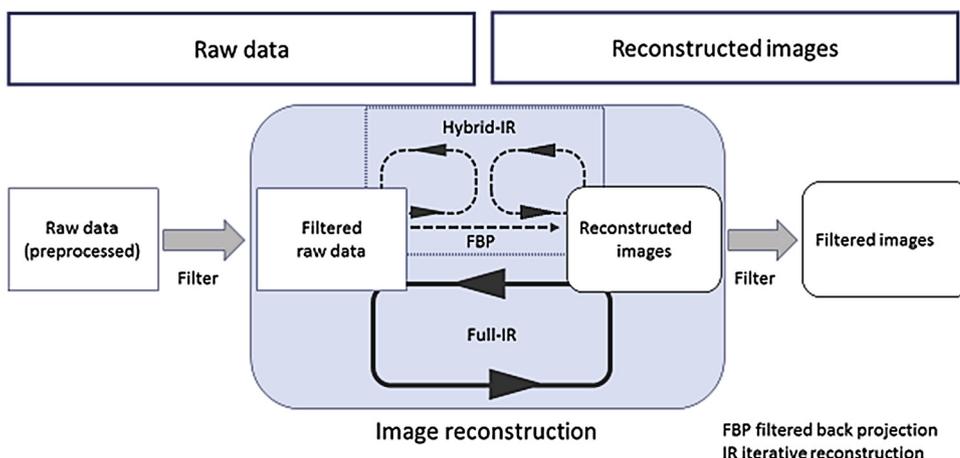
Fig. 5. Schematic presentation of various image production processes that can contribute to the radiation dose reduction. Filters can be applied to raw data, reconstructed images, or both. Iterative reconstruction methods (hybrid-IR or full-IR) may replace the conventional filtered back projection, which results in images with less noise.

8. Adequacy of diagnostic procedures

These radiation dose reduction measures should be accompanied by an effort to stick to the thoughtful and intelligent use of medical imaging. Improved radiation dose reduction techniques alone will not keep the risk of the patient to minimal. If a CT examination is inappropriately prescribed, even the state-of-art dose reduction technology will not function. Securing patient safety is possible only with judicious users, especially radiologists and referring physicians.

To achieve the wise use of CT imaging, behavior modification of physicians is necessary. In that sense, it is far more demanding than just adopting novel technologies of radiation dose reduction. Efforts to induce physicians to make efficient use of medical imaging are already made: guidelines for medical imaging application are published by many professional associations, such as ACR Appropriateness Criteria® by American College of Radiology [31], iRefer by The Royal College of Radiologists [32] and Referral Guidelines for Medical Imaging by European Commission [33].

Reports are suggesting that these guidelines tend to be underused and that suggests publishing guidelines alone are not enough. An all-around approach including educational, administrative and financial measures will be required. Clinical decision support (CDS) systems that integrate the content of these guidelines are expected to decrease the numbers of inadequately ordered medical imaging examinations. [6]. For example, CT pulmonary angiography (CTPA) is commonly performed for the diagnosis of pulmonary embolism. CTPA is reported to be overused for the diagnosis of pulmonary embolism despite the well-known guidelines. [34,35] An evidence-based CDS in the emergency department is reported to be associated with a significant increase in the diagnostic yield of CTPA with fewer CTPA examinations performed.

9. Assessment of the reduced dose CT images

For the safe application of radiation dose reduction methods, the result of radiation dose reduction should be assessed adequately. The result of reduced dose examination is compared with that of standard dose examination to determine the validity of the dose reduction method. Usually, novel radiation dose reduction technique is used in the dose reduction protocol to compensate the image quality degradation caused by reduced dose. In principle, there are two methods of assessment of image quality: evaluation of image quality itself or comparison of diagnostic results. Evaluation of image quality can be made subjectively or objectively.

For comparison, two or more sets of images obtained with different radiation dose levels are required. Although performing two scans at the same time with varying radiation dose is a straightforward method, it can be difficult because additional radiation exposure to the subject is necessary and the patients do not benefit from an extra scan. Therefore, special techniques have been used instead of performing multiple scans. Dual source CT has two X-ray tubes and two sets of data acquisition systems. Data from two acquisition systems can be separated. Images can be reconstructed using data originating from one set of data acquisition system that can be virtually equivalent to reduced dose CT images [36]. If the same tube potential and tube current setting is used for both X-ray tubes, virtual half-dose CT images can be obtained without making additional scans, while standard dose CT images are generated from data of two sets of data acquisition systems. Images of low radiation dose can be simulated with computers. Simulation of low dose images needs dedicated computer application software. Addition of artificial noises can be made on reconstructed images (image-based simulation) [37]. Noise patterns were collected by the repeated scans of a phantom, which were introduced into the target images to produce the simulated low dose images. Alternatively, noise pattern may be added to the projection data. Simulated projection data are reconstructed to obtain the simulated low dose images. The simulation methods are more flexible in the selection of simulated dose levels than

splitting signals using dual-source CT.

Image quality assessment can be performed objectively or subjectively. Objective image quality assessment is performed with indexes calculated from CT numbers within the region of interest such as standard deviation of CT numbers and signal-noise ratio. Images acquired with lower radiation dose have invariably higher image noise and lower signal-noise ratio. Therefore low dose images improved with a novel method are usually compared with standard dose images produced with the conventional method, demonstrating the value of the newly introduced method. There are limitations of assessment with these indexes. For example, images with the same standard deviation can have different noise power spectrum and consequently different image texture. Images produced with a newer technique often have significantly different image texture. Change in the image texture might affect the confidence in the diagnosis. Subjective image quality assessment is performed typically with Likert scale. Readers review the images and record scores about image noises, sharpness, overall quality, etc. The result of subjective assessment can be more informative than the objective value. However, the score reproducibility needs to be confirmed by calculating the inter- and intraobserver variability.

When we consider making a transition to a lower radiation dose protocol, securing the same diagnostic result as the conventional dose CT protocol is the most important. Therefore, the comparison of diagnostic results with images with different radiation exposure levels is the most reliable method to determine the feasibility of radiation dose reduction. If the diagnostic results by low dose images are comparable to the results by standard dose images, it suggests that the standard dose CT protocol may be harmlessly replaced with low dose CT protocol. Some studies compared the diagnostic results for the selected specific abnormal findings [2]. Pulmonary nodule detection tasks in the lung CT is one of the examples. The positive results of these studies facilitated the shift to the lower dose protocols for specific purposes. Examination of low dose CT techniques for general purposes is desirable to expand the application of reduced dose techniques. Other studies attempted to assess the diagnostic accuracy of multiple common and fundamental findings. For example, the diagnostic value of low dose CT was studied by comparing the essential pulmonary abnormalities including emphysema, ground-glass opacity, reticular opacity, micronodules, bronchiectasis, honeycomb, nodules (> 5 mm) [38].

10. Recognition of overdose in CT

An essential feature of CT radiation dose is that the visual recognition of excessive radiation dose is not easy but requires careful observation [5]. If overdose ever happens in an X-ray examination, it changes the appearance of the obtained images. Overpenetration or under-penetration is readily perceptible. Undershooting in CT degrades the image quality. The images are likely to be considered to be unsatisfactory. Then, the inadequately low dose is readily realized. Meanwhile overshooting in CT examination results in a lower amount of noise appearing on the CT images and the quality of images will be higher. Excessive radiation dose does not harm image quality and consequently may be left unrecognized. Some readers might notice that the noise level is lower than usual if the dose was significantly higher than usual. However, if an inadequately high dose of radiation is consistently applied, the users probably do not have a chance to realize that the images were obtained with a too high level of radiation. In the past, a series of examination with excessive radiation dose underwent unnoticed until obvious health problem for the examinee [39]. Therefore, special measures need to be taken to recognize the radiation dose and evaluate the adequacy of the examination protocols.

11. Dose monitoring

To facilitate the effort of radiation dose reduction, correct

awareness of the level of radiation dose is crucial. It is hard to realize the possible adverse effect of ionizing radiation because there is no immediate and visible effect. Efforts to make radiation dose readily apparent can direct more attention to radiation dose saving. That is why the establishment of dose monitoring system is desired.

Dose monitoring has two purposes. One is to lower the collective radiation dose to the patients as a whole. Radiation dose registry (e.g., dose index registry by American College of Radiology) can contribute to the dose reduction by defining current standards and identifying the sites with an unusually high level of radiation exposure [40]. Those sites may significantly reduce the radiation exposure to the patients once they realized that the radiation exposure might be reduced according to the current standards. A diagnostic reference level is set to give a standard dose level for a specific examination type. The third quartile value of the dose distribution is commonly set as the diagnostic reference level so that 75 percent of the institutions are using the dose below the diagnostic reference level. The diagnostic reference level is not an optimal dose level but is expected to inform facilities with a high dose level of the possibility of overdose that could be avoided by revising their protocols.

The other purpose is to lower the risk of individual patients. To accomplish the purpose, tracking the radiation exposure history is required. For example, SmartCard / SmartRadTrack project is a radiation exposure history collection and retrieval system proposed by the International Atomic Energy Agency (IAEA) [41].

12. Computer analysis of reduced dose images and quantitative imaging

Production of images with lower noise will lead to radiation dose reduction as described above. Low noise images can be produced with image filters and iterative reconstruction methods. Images processed with noise reduction filters or reconstructed with iterative reconstruction algorithm tend to have margin characteristics different from those reconstructed with filtered back projection [42,43]. Filtered back projection images are generated with a filter processing before the back projection. Generally, lung images are created with relatively strong edge-enhancement filter resulting in the augmented contour of the nodules. In comparison, images processed with noise reduction filters or reconstructed with full-IR might appear "blurred."

The change in the image quality may influence the result of computer analysis of the CT images. The variation in the margin characteristics may need special attention in the lesion size measurement. Chen et al. demonstrated that there is a systematic bias in the calculated nodule volume using workstation software [44]. One should be careful when performing a longitudinal volume comparison of small lesions using the computer-assisted volumetry because the difference in the image production method may influence the result. Modification of volumetry algorithm or introduction of a calibration method is needed to make the result of computer-assisted volumetry reliable.

As a computer-assisted diagnostic tool, quantitative analyses of medical images are actively studied recently [45]. Radiological Society of North America (RSNA) organizes Quantitative Imaging Biomarkers Alliance® (QIBA), an initiative to advance quantitative imaging and the use of biomarkers. Three biomarker committees concerning quantitative analysis of CT images (CT volumetry, lung density, small lung nodule) were organized.

Therefore, whether reduced dose images can be used as a quantitative indicator need to be evaluated. Use of image-generated biomarker requires low variability of measurement. As the technology of CT image production is evolving, image quality variability depending on vendor, model of the scanner exists. Radiation dose reduction methods utilizing image processing techniques modify the texture of the image, which can affect the calculated indexes. The examination of the effect of novel radiation dose reduction method on those quantitative indexes will become more important as those indexes are more

universally utilized.

13. Transition to a newer method of dose reporting

Accurate measurement and reporting are crucial in the evaluation of radiation dose reduction. DLP and CTDIvol are commonly used as indices of radiation exposure in the CT examination [16]. The weakness of the CTDIvol is that CTDIvol is an index obtained using the fixed, standardized phantom. CTDIvol is calculated based on the measurement using a standard acrylic phantom of 16 cm or 32 cm in diameter. Therefore, CTDIvol is calculated by supposing that the sizes of the parts of the body in different patients are the same. However, CTDIvol of small patients is lower than that of larger patients if both are imaged with the similar scan parameters.

Recently, as a newly-developed dose index representing this body difference, size-specific dose estimation (SSDE) is also widely used. SSDE is a dose index developed and proposed to overcome shortcomings of CTDIvol by American Associations of Physicist in Medicine (AAPM). SSDE is an estimated value of CT radiation exposure which integrates the body shape of the patient. It is calculated using a cross-sectional width of an individual patient.

Methods of SSDE calculation are explained in AAPM Reports Nos. 204 and 220 [46,47]. In one approach, the effective diameter is obtained based on the sum of the lateral and anteroposterior dimensions of the body. In the other way of calculation, the water equivalent diameter is calculated from the cross-sectional area and HU value of the body. The merit of the latter method is that it can be more accurate when the attenuation value of the body in the scanned plane is heterogeneous, e.g., thorax.

14. Conclusion

Although radiation dose in computed tomography decreased significantly and CT became safer examinations than before, the number of CT examination dramatically increased with CT being the most important source of medical radiation exposure. Attention to CT radiation dose is still essential. Notable improvement occurred regarding tube current selection (automatic exposure control) and image production method (iterative reconstruction). Optimizing the tube potential selection is expected to contribute to further CT radiation dose reduction. Efforts need to be made to decrease the low-yield CT examination. Clinical decision support is expected to play a significant role in leading to the more meaningful application of CT examinations.

Acknowledgment

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