



Review

Clinical application of radiation dose reduction at abdominal CT

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ABSTRACT

Report VII of the Board on Radiation Effects Research (BRER), in which the linear no-threshold hypothesis was applied, estimates the lifetime carcinogenesis risk from computed tomography (CT) as 0.34 to 1.30%. Other studies provided evidence for breaks in double-stranded lymphocyte DNA in human blood during CT examinations. Although it cannot be claimed that such DNA damage is a direct cause of carcinogenesis, it is important to reduce the radiation exposure of patients subjected to CT studies. Here we focus on techniques and clinical applications of abdominal reduced-dose CT. With automatic exposure control (AEC), the X-ray tube current can be optimized and the noise level maintained uniformly, regardless of the target size. Iterative reconstruction can reduce the image noise on scans acquired at reduced radiation doses. Use of these techniques helped to reduce radiation exposure at routine examinations by about 20–40%. We also discuss advanced imaging methods such as dynamic perfusion CT.

1. Introduction

The effective dose in most abdominal computed tomography (CT) studies is below 30 mSv. Epidemiological studies on atomic bomb survivors from Hiroshima and Nagasaki did not confirm an increase in carcinogenesis after radiation exposure to less than 100 mSv [1,2]. However, according to report VII of the Board on Radiation Effects Research (BRER) [3] that applied the linear no-threshold (LNT) hypothesis, based on the patient age and gender, and the effective dose, the lifetime carcinogenesis risk from CT examinations was estimated to be 0.34–1.30% [4–6]. Double-stranded DNA damage in lymphocytes due to a single CT examination has been reported [7]. Although no direct link between DNA damage and carcinogenesis has been established, their possible connection demands that the radiation exposure of patients subjected to CT studies be curtailed. The diagnostic value of CT studies must be retained although the image quality is degraded on scans acquired at low radiation doses.

Here we focus on the features and clinical applications of abdominal reduced-dose CT. Low X-ray tube current- and low X-ray tube voltage scanning are techniques that reduce radiation exposure at abdominal CT. Iterative reconstruction (IR) helps to reduce the image noise on reduced-dose CT images. The clinical applicability of radiation dose reduction techniques used for routine examinations and advanced imaging methods are discussed.

2. Techniques for radiation dose reduction

2.1. X-ray tube current reduction

As radiation exposure increases or decreases in proportion to the X-ray tube current, it can be controlled by the tube current. The image noise is inversely proportional to the square root of the tube current, consequently, it is increased when the tube current is low (Fig. 1). There is a trade-off between the image quality and radiation exposure and the diagnostic performance is degraded as the image noise increases. This phenomenon is particularly striking when abdominal CT is used for the detection of low-contrast lesions. To select the tube current, automatic exposure control (AEC), which optimizes for each structure by referring to the radio-translucency image, is frequently applied. A change in the gantry rotation speed or the helical pitch affects the product of the tube current and the exposure time (milli-ampere second: mAs), even when the tube current is constant. This effect is similar to that elicited by changing the tube current.

Although radiation exposure can be reduced easily by decreasing the X-ray tube current, its level must be determined carefully to avoid degrading diagnostic ability. Noise reduction techniques such as iterative reconstruction (IR) facilitate the acquisition of low-tube current images with a noise level equivalent to that on images acquired with conventional doses [8,9]. However, to confirm that the diagnostic

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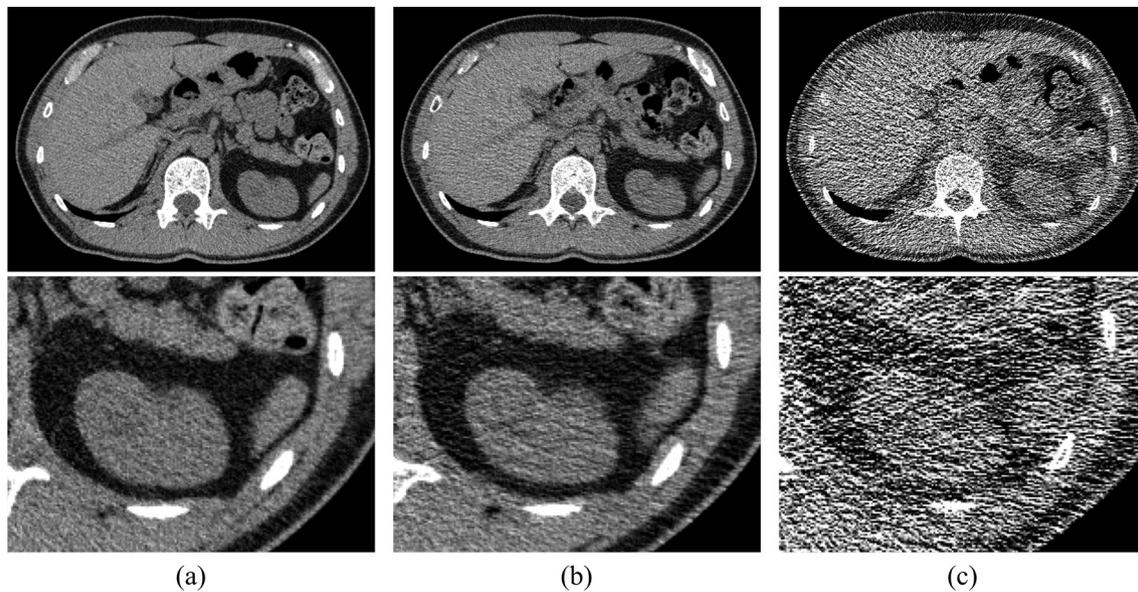


Fig. 1. Changes in image noise at different X-ray tube currents. Bottom row: close-up images.

- (a) 440 mA.
 (b) 90 mA.
 (c) 10 mA.

ability of images acquired with/without radiation exposure reduction is equivalent, not only the image noise, but also the results of task-based reading experiments must be considered [8,10,11].

2.2. X-ray tube voltage reduction

Although 120 kV is the X-ray tube voltage used in routine CT studies, radiation exposure can be reduced by applying lower tube voltages, e.g. 100- or 80 kV [12]. However, at a constant X-ray tube current, the image noise increases as the tube voltage decreases. Like reduced tube current scanning, IR is an effective method for reducing the image noise.

The contrast of the iodine contrast material increases as the X-ray tube voltage decreases. Consequently, the contrast-to-noise ratio (CNR) remains high even at increased image noise. Figs. 2a and c presents contrast-enhanced images acquired at 80-, 100-, and 120 kV using an abdominal phantom and Fig. 2d shows the aortic CNR. To obtain a CNR of 6.0, radiation exposure is approximately 2.0 mGy at 120-, 1.3 mGy at 100-, and 0.9 mGy at 80 kV. Therefore, when iodine contrast material is injected for the evaluation of target structures, low-tube voltage scans effectively reduce radiation exposure [8,12,13]. When it is fixed at 2.0 mGy, the CNR is approximately 6 at 120-, 8 at 100-, and 10 at 80 kV. Consequently, the contrast material dose can be reduced for low-tube voltage contrast-enhanced CT scans [13–16].

The energy of X-rays decreases as the X-ray tube voltage decreases. Low-energy X-rays are easily absorbed; as they pass through the human body, much is absorbed by the epidermis and the radiation exposure of superficial body regions is increased [12]. Also, because most of the X-rays are absorbed, especially in patients of large size, low-tube voltage imaging is not recommended due to the manifestation of photon starvation artifacts [13].

2.3. Automatic exposure control (AEC)

AEC automatically modulates the intensity of X-rays based on the subject's X-ray absorption [17–20]. Z-axis modulation controls the X-ray tube current along the body axis, angle modulation controls the tube current in each direction based on the anterior-posterior (AP)- and the left-right (LR) body thickness. Although the tube current is usually

modulated, automatic tube voltage selection (ATVS) automatically selects the optimal X-ray tube voltage [21,22]. By inputting the target noise level (standard deviation: SD) as a parameter, AEC maintains a uniform noise level regardless of the target size. Since AEC yields the required image quality at minimal exposure, it helps to optimize the X-ray tube current and reduces radiation exposure.

2.4. Iterative reconstruction (IR)

To improve the image quality, CT vendors developed IR techniques that apply an image reconstruction algorithm for reducing the image noise. Based on their technical features, IR techniques are classified as hybrid- and model-based.

Hybrid IR (h-IR), a reconstruction method based on filtered back projection (FBP), has been used conventionally for CT image reconstruction; the iterative image noise reduction algorithm is combined with the reconstruction process. Since the reconstruction time of h-IR is close to FBP, it has widely replaced FBP [23].

Model-based IR (MBIR) is completely different from h-IR. Unlike the FBP process, the correct reconstructed image is acquired by iterating forward and back projections. By incorporating an optical- and a statistical noise model into the iterative processes, spatial resolution is improved, and the image noise is effectively eliminated from the reconstructed image [8]. However, as MBIR involves longer computational time than FBP and h-IR, throughput is reduced. Fig. 3 shows pelvic CT images reconstructed with FBP, h-IR, and MBIR. The image noise is lower on the h-IR- than the FBP image and the image quality, including image noise and sharpness, is highest on the MBIR images.

2.5. Virtual non-contrast enhanced images

The radiation dose can also be reduced by using virtual non-contrast enhanced (VNE) imaging for dual-energy CT (DECT) scanning. As the VNE technique removes the iodine component from a contrast-enhanced image by applying material decomposition, its application yields a virtual non-contrast-enhanced CT image. By generating a VNE image, one of the post-processed DECT image obtained from contrast-enhanced images omits the non-contrast enhanced phase during dynamic contrast-enhanced CT examination [24,25].

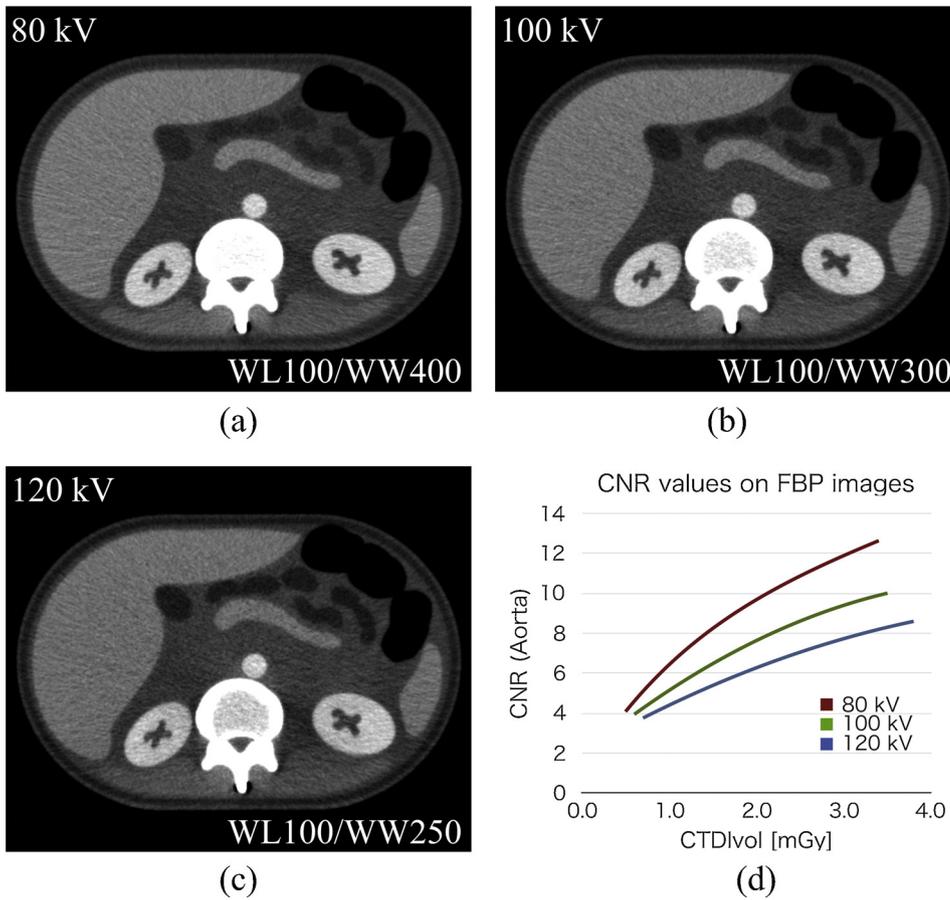


Fig. 2. Contrast-enhanced abdominal phantom images and aortic CNR at different X-ray tube voltages.

(a) 80 kV, 0.9 mGy.
 (b) 100 kV, 1.3 mGy.
 (c) 120 kV, 2.0 mGy.
 (d) Comparison of the CNR at different radiation exposures. Despite a change in the tube voltage, the CNRs are similar although radiation exposure is different. The appearance is the same after adjusting the window level and the window width (WL/WW).

3. Clinical application of reduced-dose CT

3.1. Routine examination

To benefit patients undergoing CT studies, one of the different dose reduction techniques described above must be applied. As AEC automatically modulates the intensity of X-rays based on the X-ray absorption of the target, it is the most widely used technique in clinical

practice. Initial reports on its usefulness first appeared after the year 2000. AEC optimizes only excess X-rays, therefore, radiation exposure can be reduced without degrading the image quality. Greess et al. [26] who applied four scan ranges at pediatric CT studies found that AEC reduced radiation exposure in the thoracoabdomus and abdomen by 22% and 23%, respectively. Kalra et al. [27] implemented AEC at abdominal and pelvic CT studies of adults; they found that the image noise was not significantly increased and that the degradation of the

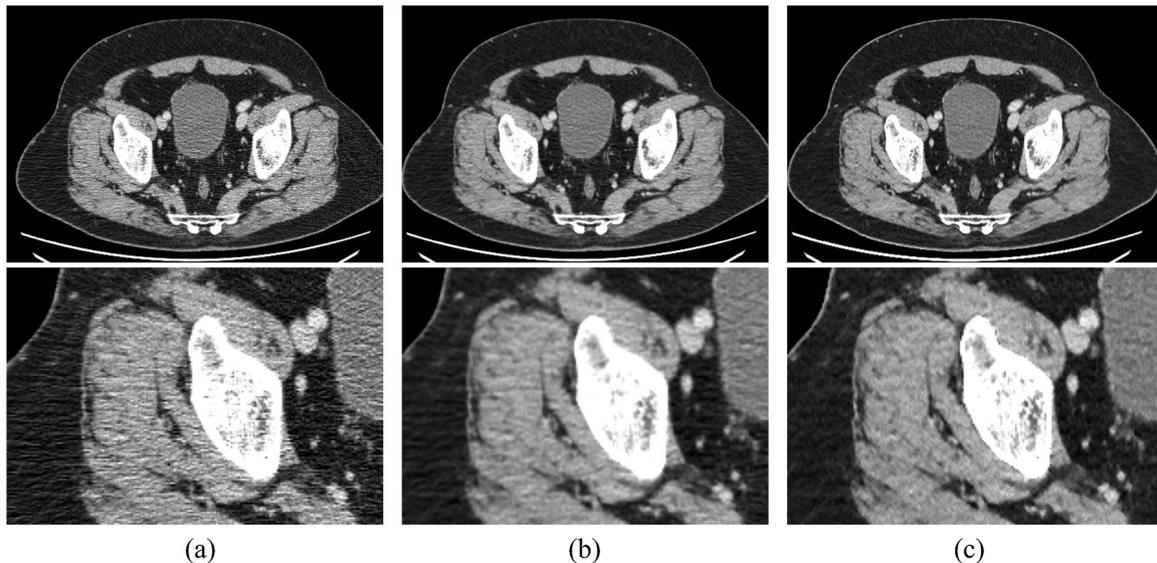


Fig. 3. Pelvic CT images reconstructed with FBP (a), h-IR (b), and MBIR (c).

Bottom row: close-up images. The image noise (SD) for the bladder (in Hounsfield units) is 37.8 (a), 17.1 (b), and 15.3 (c).

Table 1
Summary of reports on radiation dose reductions for routine examination.

Author	Year	Protocol	Dose reduction technique	Target	Dose reduction rate	Clinical results
Greess et al. [26]	2002	CECT	AEC	Thorax-abdomen Abdomen	22% 23%	At the pediatric CT examination, the radiation dose may be reduced without degrading image quality by using AEC.
Kalra et al. [27]	2004	CECT	AEC	Abdomen-pelvis	32%	At the abdo-pelvic CT, tube current time product was reduced without changing diagnostic acceptability by using AEC.
Mulkens et al. [28]	2005	CECT	AEC	Liver Pelvis	38% 32%	At the abdo-pelvic CT, AEC delivered good image quality with a significantly reduced radiation dose.
Sagara et al. [29]	2010	CECT	IR	Abdomen	33%	Diagnostic acceptability of reduced-dose CT with h-IR was comparable to that of routine-dose CT with FBP.
Jensen et al. [30]	2016	Plain CT	IR	Liver phantom	33%	At liver phantom study, MBIR showed similar or improved lesion conspicuity at reduced-dose compared with FBP at routine-dose.
Bahn et al. [31]	2016	CT urography	IR	Urinary tract	25%	There was no difference in detectability of urothelial cancer between reduced-dose h-IR image and standard-dose FBP image.
Grosser et al. [32]	2017	CT fluoroscopy	IR	Abdomen Pelvis	38% 20%	At CT fluoroscopy, h-IR reduced of image noise and increased readers' confidence compared to FBP.
Marin et al. [33]	2010	CECT	Low kV, IR	Abdomen	71%	By using h-IR and low-tube voltage scan, image quality during the late hepatic arterial phase was improved compared with FBP.
Gonzalez-Guindalini et al. [34]	2013	CECT	Low kV, ATVS, IR	Neck-pelvis	37%	By using ATVS and h-IR, radiation dose was reduced while maintaining objective image quality compared to conventional protocols.
Zamboni et al. [35]	2014	CECT	Low kV	Pancreas	41%	Low-tube voltage scan for pancreatic phase scanning resulted in higher conspicuity of pancreatic adenocarcinoma.
Nakaura et al. [14]	2015	CECT	Low kV	Liver	CM dose 20%	By using low-tube voltage scan, the volume of CM in HCC patients with renal dysfunction could be reduced without increasing radiation exposure.
Mangold et al. [22]	2016	CT angiography	Low kV, ATVS, IR	Aorta	44%	Aortic CTA performed with ATVS and h-IR allowed a substantial reduction of radiation exposure while improving image quality in comparison to conventional imaging.
Sahni et al. [36]	2013	CU urography	VNE	Urinary tract	35%	By using VNE, the radiation dose was able to theoretically be reduced, but the accuracy of attenuation values and detection of small stones was limited.

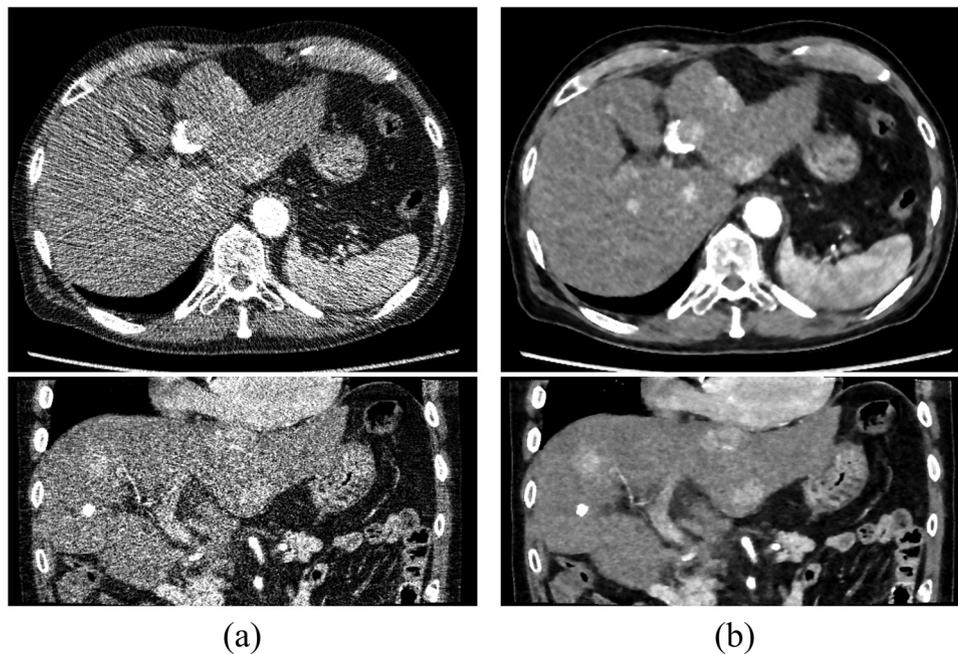


Fig. 4. Perfusion CT images acquired at low X-ray tube voltage- and low X-ray tube current settings (80 kV, 75 mAs, CTDI: 2.5 mGy). Bottom row: coronal images. (a) reconstructed with FBP. (b) reconstructed with MBIR.

diagnostic acceptability scores was not statistically significant although radiation exposure was significantly reduced by an average of 32%. Mulkens et al. [28] compared combined AEC (angular and z-axis modulation) with single AEC (angular modulation). With single AEC the radiation reduction rate was 18% in the abdomen and 26% in the pelvis, with combined AEC, these rates were 38% and 32%, respectively, and the quality of images obtained was not significantly different.

Although lowering the X-ray tube current is the easiest way for reducing radiation exposure, a noise reduction method such as IR should be used simultaneously to compensate for the increase in the image noise. Sagara et al. [29] compared abdominal CT scans obtained at reduced doses and reconstructed with h-IR with scans acquired at routine doses and reconstructed with FBP. Although sharpness was significantly lower on reduced-dose CT images, the image noise was not increased and diagnostic acceptability was not degraded. The overall dose reduction rate in their study was 33%. Jensen et al. [30] used a liver phantom that included simulated cystic lesions to examine their conspicuity on scans subjected to FBP, h-IR, and MBIR. They reported a 33% dose reduction with h-IR and MBIR and no degradation in lesion conspicuity. Bahn et al. [31] who evaluated the detectability of urothelial carcinomas on reduced-dose CT scans found that the application of IR did not impair their detectability even on scans obtained with a 25% dose reduction. Grosser et al. [32] applied h-IR for reduced-dose CT fluoroscopy, they found that the image noise was significantly lower on reduced-dose images reconstructed with h-IR than on routine-dose images reconstructed with FBP. Also, their diagnostic confidence scores were higher for h-IR- than FBP images and their application of various procedures achieved a radiation dose reduction of 38% in the abdomen and 20% in the pelvis.

At low X-ray tube voltage settings, the contrast of the iodine contrast material increases; a high CNR can be obtained if the image noise is suppressed with noise reduction techniques such as IR. When iodinated- are the target structures, the radiation dose can be reduced more effectively with IR than with other dose reduction techniques and the amount of contrast medium can be reduced. Marin et al. [33] compared abdominal contrast-enhanced 80 kV scans reconstructed with h-IR and routine 120 kV scans subjected to FBP. The radiation dose reduction

rate for their low-tube voltage images was 71% and although the image noise was higher, the CNR was significantly higher than on the 120 kV images. In their study of the effects of ATVS applied at follow-up neck-to-pelvic CT of individual patients who had undergone conventional 120 kV examinations, Gonzalez-Guindalini et al. [34] selected low-tube voltage scanning in 60% of their patients. The average radiation dose reduction rate was 37% and neither the CNR nor the qualitative evaluation score was lower on the follow-up than the original CT studies. Zamboni et al. [35] compared the conspicuity of pancreatic adenocarcinoma on 80- and 120 kV CT images quantitatively and qualitatively. They found that the average radiation dose reduction rate was 37% for the low voltage images. Both the tumor CNR and tumor conspicuity were higher on the 80 kV images. When Nakaura et al. [14] applied equal radiation exposures in their 100- and 120 kV scan protocols, they could reduce the contrast material volume for 100 kV imaging by 20%. They found no significant difference in the image noise on their 100- and 120 kV scans and the tumor-to-liver contrast and the CNR were higher on the 100 kV image despite the delivery of a smaller amount of contrast medium. Mangold et al. [22] assessed the effect of ATVS on aortic CT angiographs. They compared a conventional- (120 kV, FBP) with a reduced-dose protocol (ATVS, IR). Under the reduced dose protocol, the average radiation dose was 44% lower, the image noise was significantly lower, and the CNR was significantly higher than under the standard protocol.

VNE images are virtual non-contrast enhanced images generated from post-contrast enhanced images using DECT technology. Omission of the scan for the true non-contrast enhanced (TNE) CT image allows for a reduction in the radiation dose. Sahni et al. [36] used VNE imaging during CT urography to reduce radiation exposure. By omitting TNE scanning, radiation exposure was reduced by 35%. However, the quality of VNE images was unsatisfactory, the accuracy of the CT attenuation number was uncertain, and the accurate representation of small structures could not be confirmed.

Table 1 is a summary of publications reporting radiation dose reductions on images acquired at routine examinations. The dose reduction rate indicates the decrease in the radiation dose vis-à-vis the standard protocol. The rates were calculated from the values of the CTDI or the mAs product.

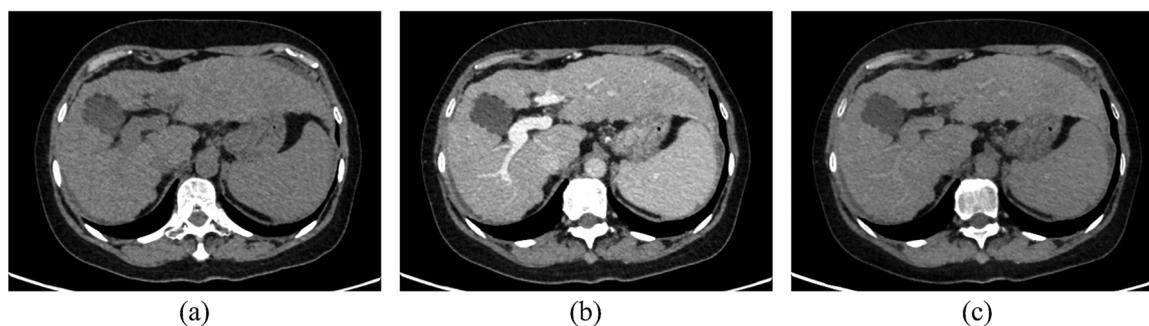


Fig. 5. Hepatic dynamic CT images acquired with dual-energy scanning. The images were reconstructed as virtual monochromatic 70 keV images. (a) Pre-contrast enhanced. (b) Portal venous phase. (c) Virtual non-contrast enhanced image generated from the portal venous phase image.

Table 2

Summary of reports on radiation dose reduction techniques for advanced CT imaging.

Author	Year	Protocol	Dose reduction technique	Target	Radiation exposure
Negi et al. [37]	2012	Perfusion CT	Low mA, Low kV, IR	Liver	Half of conventional examination
Watanabe et al. [38]	2012	Perfusion CT	Low mA	Liver (Intra-artery injection)	One-sixth of conventional examination
Ronot et al. [39]	2010	Perfusion CT	Low mA, Low kV	Liver	Correspond to an adult abdominal CT examination
Motosugi et al. [40]	2012	Perfusion CT	Low mA, Low kV, IR	Abdomen	Not higher than in similar studies
Nakamura et al. [41]	2018	Perfusion CT	Low mA, Low kV, IR	Liver	Not higher than the diagnostic reference level for hepatic dynamic studies
Kanda et al. [42]	2010	Perfusion CT	Low mA, Low kV	Liver	Not higher than routine liver dynamic
Kanda et al. [43]	2012	Perfusion CT	Low mA, Low kV	Liver	Not higher than routine liver dynamic
Song et al. [45]	2011	DECT	IR, VNE	Iodine	19% lower than with the conventional protocol
Hyodo et al. [46]	2017	DECT	IR	Liver fat	Comparable to conventional CT

3.2. Advanced imaging

As the effectiveness and safety of many advanced imaging techniques are still under evaluation, they are not applied in routine clinical studies and their radiation dose must be as low as reasonably achievable (ALARA).

For dynamic perfusion CT, many serial images must be acquired to analyze the blood flow and the radiation dose per scan must apply the ALARA concept. Fig. 4 presents perfusion CT images obtained at low X-ray tube voltage- and low-tube current settings. The noise on the image reconstructed with FBP is high; it is drastically reduced with MBIR. However, on the MBIR image, sharpness of the structure contour is degraded due to strong noise reduction. Perfusion analysis is performed based on the time density curve (TDC) which indicates the change in the CT attenuation number for each pixel. The image noise is an outlier on the TDC, thus it adversely affects blood flow analysis. In the maximum slope method, a common analytical method, the blood flow value is calculated based on the TDC slope; it is often overestimated due to the influence of the image noise. Negi et al. [37] confirmed the accuracy of reduced-dose hepatic perfusion CT using h-IR; they found that the blood flow value was not affected even when radiation exposure was reduced by half. Watanabe et al. [38] investigated the effect of the radiation dose at perfusion CT in patients undergoing transcatheter arterial chemoembolization. They confirmed that there was no difference in the analysis value of scans performed at the conventional dose or at 1/6 of that dose. Ronot et al. [39] examined the relationship between liver fibrosis and blood flow by subjecting patients with chronic hepatitis C virus (HCV) infection to perfusion CT. They reported that perfusion changes in the early stage of fibrosis were detectable on perfusion CT scans obtained with low-tube voltage-, low-tube current settings. The effective dose was as at adult abdominal CT. Motosugi et al. [40] performed dynamic perfusion CT in patients with or without liver cirrhosis. To reduce the radiation dose to below that of similar studies, the tube voltage and tube current were low (100 kV and 50 mAs, respectively); h-IR was used for noise reduction. Nakamura et al.

[41] used the arterial tumor blood flow on dynamic perfusion CT scans as an early imaging biomarker to evaluate the effectiveness of chemotherapy in patients with hepatocellular carcinoma. They found that hepatic perfusion CT yielded early imaging biomarkers for predicting overall survival. Their study applied 80 kV and a reduced tube current setting; h-IR was used for noise reduction. Consequently, the radiation dose was lower than the diagnostic reference level for hepatic dynamic contrast-enhanced CT. The application of a low-tube voltage also contributed to a reduction in the contrast medium volume. Kanda et al. [42,43] who investigated the effect of different perfusion CT analysis methods on blood flow values found that hepatic perfusion values obtained with three different methods were not interchangeable. Radiation exposure in their study was lower than at routine examinations.

Dual-energy CT is another advanced imaging technique that can generate virtual monochromatic X-ray images with characteristics that are almost the same as on conventional CT scans. The quantification of materials such as iodine and fat is more accurate than of conventional images. Because DECT scanning requires the acquisition of low- and high kV images, the radiation dose tends to be higher [44] and the combined application of a radiation dose reduction technique such as IR is desirable. Song et al. [45] who evaluated renal masses on an iodine map generated from DECT data, reported that TNE scanning can be omitted by using VNE and that the radiation dose was reduced by 19% compared with the conventional protocol. They also found that the iodine map was useful for the identification of slight contrast enhancement in renal masses. Fig. 5a and b show dynamic contrast-enhanced CT images of the liver scanned with dual-energy; Fig. 5c is a VNE image generated from 5b. Iodine components are removed on the VNE image, and it is almost the same as the pre-contrast CT image (Fig. 5a) although some iodine components are present at strongly enhanced sites such as the portal vein. If the quality of VNE images is acceptable, the radiation exposure of one phase can be reduced. Hyodo et al. [46] quantified the amount of liver fat with the material decomposition method using DECT. The application of h-IR limited the radiation dose to within the range of conventional liver CT studies.

Table 2 is a summary of publications reporting radiation dose reduction techniques for advanced CT imaging. Selection of the optimal radiation dose must balance diagnostic effectiveness and radiation risks and the optimal dose for advanced CT imaging techniques remains to be determined.

4. Conclusion

Various radiation dose reduction techniques for CT studies are presented. Their implementation depends on the scanner hardware and software available at different institutions. Degradation of the image quality on scans acquired at reduced radiation doses may compromise their diagnostic ability and CT imaging must deliver the ALARA radiation dose that is consistent with the acquisition of the desired diagnostic information.

Automatic exposure control is a technique to optimize the X-ray tube current; it yields a uniform noise level regardless of the target size. Iterative reconstruction can reduce the image noise on scans obtained with reduced radiation doses. With these techniques, the radiation exposure at routine examinations can be reduced by about 20–40%. Therefore, their application at such examinations is highly recommended. As advanced imaging studies such as perfusion CT or dual energy CT tend to increase radiation exposure, so it should be better to utilize these techniques.

Conflict of interest

Kazuo Awai has following COIs, and the other authors declare that they have no conflict of interest.

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Toru Higaki and Kazuo Awai contributed to article concepts, manuscript editing, and manuscript review. Yuko Nakamura, Wataru Fukumoto, Yukiko Honda, and Fuminari Tatsugami contributed to the investigation of related articles and techniques.

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