Which should be the routine cross-sectional reconstruction mode in spectral CT imaging: monochromatic or polychromatic?

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Objective: To provide evidence for the selection of an optimal cross-sectional reconstruction mode in spectral CT imaging of the abdomen, we compared the monochromatic images with polychromatic images.

Methods: Three phase-enhanced CT scans of the abdomen were recorded using the spectral imaging technique on 100 patients. Images were reconstructed using two modes: polychromatic and 70 keV monochromatic. The following variables were then compared: contrast-to-noise ratio (CNR) of the liver, spleen, gallbladder, kidney and pancreas, and the noise. Paired *t*-tests were used to compare differences between the two sets of images. Three experienced doctors graded the quality of the images with a five-point scale. The image quality scores were compared with a non-parametric rank sum test.

Results: Compared with polychromatic images, the 70 keV monochromatic mode images yielded significantly greater tissue-to-fat CNR and lower noise ($p < 0.001$ for all comparisons). The image quality of the 70 keV monochromatic mode showed significantly better results than the polychromatic mode ($p < 0.001$).

Conclusions: In abdominal spectral CT imaging, 70 keV monochromatic mode reconstruction images were better than those reconstructed using the polychromatic mode. The monochromatic mode may become the routine reconstruction mode for cross-sectional images.

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Although the utility of dual-energy spectral CT was demonstrated as early as the 1970s to 1980s [1–3], its clinical application was hampered because of technical limitations. Recently, the advancement of CT technology, such as dual-source technology or fast peak kilovoltage switching technology, has enabled the routine clinical application of dual-energy spectral CT for the abdomen [4]. The results of preliminary investigations suggest that dual-energy techniques may be used to provide information about tissue composition and how tissues behave at different energies in the abdomen [5–9]. New parameters, such as the iodine concentration and the spectral curve, can be acquired using spectral CT. However, because the ability of spectral CT to characterise lesions is still uncertain, no diagnosis is possible, only reference to the pattern of spectral curves or other spectral CT parameters. Therefore the morphological characteristics and enhancement features of lesions in cross-sectional images still remain the basis of diagnosis of abdominal spectral CT images. In addition, the reconstruction of cross-sectional images remains a routine procedure for spectral CT imaging of the abdomen. In the present spectral CT system based on fast peak kilovoltage switch-

ing technology, there are two cross-sectional image reconstruction modes available: monochromatic and polychromatic modes. To our knowledge, there has not been a study designed to demonstrate which routine reconstruction mode should be used after spectral CT imaging. To answer this question, our study seeks to compare the quality of CT images of the abdomen reconstructed in monochromatic mode with those from a polychromatic mode, and therefore provide evidence for the selection of the optimal reconstruction mode.

Methods and materials

Patients

This prospective single-institution study was approved by our institutional review board. From August 2010 to March 2011, 100 consecutive adults (18 years and older; no childbearing or lactating females) were referred for enhanced CT of the abdomen and enrolled in the study. The study population consisted of 69 males and 31 females, whose ages ranged from 23 to 80 years (mean 55.5 years). Informed consent was obtained from all patients.

Imaging technique

All patients underwent three-phase (plain, arterial and portal vein phase) spectral CT imaging scans with a

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single tube, fast kilovoltage switching technique (80 and 140 kVp) on a high-definition CT scanner (Discovery® CT750 HD; GE Healthcare, Waukesha, WI). The scanning parameters were as follows: spectral imaging scan mode with fast tube voltage switching between 80 and 140 kVp on adjacent views during a single rotation; detector collimation 0.625 mm × 64; gantry rotation speed 0.8 s per rotation. The tube currents were fixed at 600 mA, but the data acquisition duration for any given detection view (mA multiplied by integration time) between the two tube voltages was optimised by the manufacturer to provide similar signal strength for both voltages. The scan coverage was from 1 cm above both diaphragmatic domes to the lower sides of both kidneys. After the plain scan, the non-ionic contrast medium iohexol (Omnipaque™ 300; GE Healthcare) at a dose of 1.5 ml kg⁻¹ was injected with a power injector at a rate of 3 ml s⁻¹ through the median cubital vein. The arterial phase and portal venous phase scans were carried out 30 and 60 s, respectively, after injection of the contrast medium. The reconstruction thickness was 5 mm, at intervals of 5 mm. The data acquired in the spectral CT imaging mode were used to produce one set of conventional polychromatic images and one set of monochromatic images (70 keV) [10]. The polychromatic images were reconstructed using a standard CT reconstruction algorithm. The monochromatic images were generated using a special reconstruction algorithm from the projections of the paired-energy spectra (80 and 140 kVp) through material decomposition.

Data analysis

The reconstructed image sets were transferred to a workstation (Advantage Workstation 4.4; GE Healthcare), and the image noise and contrast-to-noise ratio (CNR) of the abdominal organs (liver, spleen, kidney, gallbladder and pancreas) were measured for both the polychromatic and monochromatic (70 keV) portal venous phase axial images through the hepatic hilum, hilum of the spleen, the renal hilum and the largest section of the gallbladder and pancreas head separately. The regions of interest (ROIs) with pixels ranging from 100 to 400 were marked on organ parenchymas (liver, spleen, kidney and pancreas) or inner lumens (gallbladder) by 1 radiologist with 15 years of experience in CT. Three ROIs within the fat tissues in the abdominal cavity and three other ROIs within air before the anterior abdominal wall in the same slice were measured at the same time. The same ROIs were chosen for the corresponding images of different sets. The mean CT numbers and mean standard deviation in the ROIs were calculated automatically with the workstation measurement tool.

The CNR was estimated using the following formula: $CNR = |ROI_o - ROI_b| / SD$, where ROI_o is the CT number of the abdominal organ, ROI_b is the CT number of the background contrast tissue (mean CT number of three ROIs of abdominal cavity fat tissue) of the same slice, and SD is the mean image noise. The mean standard deviation of the three ROIs within air before the anterior abdominal wall in the same slice was used as the mean image noise.

Image quality in both sets of images was graded on a five-point scale by three radiologists (two of them with 15 years of experience and one with 6 years of experience with CT) on the Advantage Workstation. All CT images—both the polychromatic and monochromatic (70 keV) axial images—were anonymised and presented randomly, with a window level of 50 HU and a window width of 350 HU. The evaluation items included sharpness of normal vessels, duct structures (arteries, veins and bile ducts) and the borders of organs in the sections of the hepatic hilum, the hilum of the spleen, the renal hilum, and the largest sections of the gallbladder and pancreas head. These structures were scored as follows: 5, very sharp; 4, sharp; 3, fairly sharp; 2, less sharp; 1, blurred. For each patient, if the scores of the three radiologists were the same, this was used as the final score for this patient. If they were different, the three radiologists reviewed the patient's images together and reached a consensus score for the patient. Then the scores were used as subjective criteria for evaluation of the quality of the two types of images.

Statistical analysis

A paired *t*-test was performed on the image noise and the CNR for the abdominal organs obtained from the polychromatic and monochromatic image sets. The subjective scores of each set of images were compared with the Wilcoxon non-parametric tests. All statistical analyses were done with software SPSS v. 13.0 for Windows (SPSS Inc., Chicago, IL). All values are presented as the mean ± standard deviation. For all comparisons, a *p*-value <0.05 was considered significant.

Results

All 100 patients were scanned successfully in dual-energy spectral imaging mode.

The image noise values for the two modes of imaging were different. The mean image noise on the polychromatic images was 4.97 ± 1.07 HU (range 3.2–8.0 HU), which is 10% higher than the mean image noise on 70 keV monochromatic images (4.53 ± 1.07 HU; range 2.8–8.4 HU; $t=9.91$, $p<0.001$).

The mean CNRs for each organ from the two reconstruction mode images are shown in Table 1. The CNRs of the abdominal organs to their corresponding contrast tissues differed for different organs and for different image reconstruction modes. Generally, the CNRs on the 70 keV monochromatic images were significantly higher than those on the polychromatic images. Compared with the polychromatic images, the 70 keV monochromatic images had 13.8–24.7% higher mean CNRs.

The 70 keV monochromatic reconstruction mode was found to provide better quality images for the abdominal organs (Figures 1 and 2). The mean subjective score for the 70 keV monochromatic images was 4.80 ± 0.40 . This was significantly higher than that of the polychromatic images (3.93 ± 0.36 ; $z=9.23$, $p<0.001$).

Table 1. The mean contrast-to-noise ratios (CNRs) of the abdominal organs to their corresponding contrast tissues for two sets of reconstruction mode images

Index	Liver	Spleen	Gallbladder	Pancreas	Kidney
CNR of monochromatic images	43.72 ± 12.01	45.94 ± 11.56	23.99 ± 7.58	38.95 ± 10.79	55.32 ± 16.07
CNR of polychromatic images	37.33 ± 10.09	38.27 ± 9.70	21.08 ± 6.33	33.60 ± 8.44	44.38 ± 12.51
t-value	13.03	14.75	9.49	9.91	15.44
p-value	<0.001	<0.001	<0.001	<0.001	<0.001

Data are mean ± standard deviation.

Discussion

Cross-sectional images have been the basis of CT diagnosis since it was invented. Although advances in CT technology, software and data storage have made three-dimensional imaging and virtual rendering imaging faster and simpler, these are still based on the acquisition of cross-sectional images of thin slices. Currently, dual-source or fast peak kilovoltage switching technology enables a dual-energy scan of the entire body to be performed in a few seconds, and eliminates misregistration artefacts. Using dual-energy spectral CT, spectral curve, water (virtual non-contrast), greyscale and coloured iodine, monochromatic images can be obtained. Studies have showed that dual-energy CT scanning has significant potential for disease identification and classification [4]. However, the diagnostic capacity of the new types of images needs to be tested further. Therefore, in spectral CT imaging, cross-sectional images remain the main source of diagnostic

information for radiologists, and the acquisition of cross-sectional images is always an important step.

In the fast peak kilovoltage switching technology-based spectral CT system, although different types of spectral images (water, iodine and monochromatic images etc.) can be obtained by using a post-processing software package (GSI Viewer; GE Healthcare), there are only two default reconstruction modes that can be selected in the spectral scan protocol. These are the MONO (monochromatic) mode and the QC (polychromatic) mode. To our knowledge, no previous study has discussed which mode should be used for routine cross-sectional image reconstruction. Accordingly, we have compared the quality of the two reconstruction mode images, aiming to provide some evidence upon which to base a choice.

Our study demonstrates that monochromatic images acquired at 70 keV provide a higher CNR than polychromatic images in the observed abdominal organs (liver, spleen, kidney, pancreas and gallbladder). This can be explained by the energy-dependent characteristic of the attenuation of X-rays. The attenuation of a substance increases as the X-ray photon energy decreases. This relationship between the attenuation number and the monochromatic X-ray energy (kilo-electron volts) is

Figure 1. Monochromatic mode (70 keV) image of the abdomen in a 65-year-old female. This monochromatic image shows better visualisation of the vessels and margin of organs than the polychromatic image in Figure 2; note that the vein (arrow) in the right lobe of the liver was more distinct in the monochromatic image.

Figure 2. Polychromatic mode image of same subject as in Figure 1.

identical to the relationship between the attenuation number and the polychromatic X-ray energy (kilovoltage peak) in conventional CT [11, 12]. Therefore, the attenuation differences between substances are more obvious using lower photon energy than when using higher photon energy [4]. This would allow for increased contrast resolution. Thus, in our study, we obtained better contrast by using monochromatic images at 70 keV.

Furthermore, we observed that the noise of the polychromatic images was 10% higher than that of the 70 keV monochromatic images. Because CNR is calculated as contrast divided by image noise, the low image noise of the monochromatic images may be another factor that contributes to the higher CNR. Previous studies have also shown that the image noise on monochromatic images was lowest at approximately 70 keV within the range 40–140 keV [13] and lower than that of conventional 120 kVp CT [10]. This indicates that the monochromatic mode can yield higher quality images than the polychromatic mode, not only from increasing contrast but also from decreasing noise.

We also observed that the subjective scores for the monochromatic images acquired at 70 keV were higher than those for polychromatic images. This indicates that the monochromatic images provide better performance for normal display of structures, in particular the definition of contours in vessels, ducts and organs. Greater image contrast in monochromatic images may be the main reason for the achievement of better visualisation of normal vessels and the structures of ducts [14, 15]. Furthermore, the elimination of beam-hardening artefacts may contribute to the higher quality of monochromatic images [16]. Because polychromatic imaging cannot detect the energy-dependent variations of the attenuation between substances, it causes beam-hardening artefacts in the image and loss of information. In monochromatic mode imaging, this energy dependence is modelled more accurately, and beam-hardening artefacts can be avoided. All these reasons may contribute to the difference in scores of the two reconstruction mode images.

Our study had some limitations. One was that there were no lesions analysed in the abdominal organs. Although our study showed that, in general, the monochromatic images provide better performance than the polychromatic images for abdominal organs, different types of lesions in different organs may have an optimal operating voltage other than 70 keV. As a myriad of disease categories exist that are relevant to abdominal CT, a comprehensive study of all disease categories did not seem feasible at this time. Focused studies on various disease categories, such as the liver or pancreas, with a different study protocol, will be needed to demonstrate the diagnostic potential of optimal monochromatic CT images with spectral imaging. In addition, there are several types of spectral images (water, iodine and monochromatic images etc.) that can be obtained using a post-processing software package (GSI Viewer), which may also have the potential to be a routine part of the clinical workflow. These have not been discussed. Further study is necessary to explore their diagnostic value and to determine which should be integrated with routine abdominal CT imaging.

Conclusion

In spectral CT imaging of the abdomen, the monochromatic mode reconstruction images measured at 70 keV were better than those reconstructed using the polychromatic mode, and may become the routine reconstruction mode for cross-sectional images.

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