OPEN

Computed Tomography Number Measurement Consistency Under Different Beam Hardening Conditions: Comparison Between Dual-Energy Spectral Computed Tomography and Conventional Computed Tomography Imaging in Phantom Experiment

Tian He, BA, Xiaojun Qian, MD, Renyou Zhai, MD, and Zongtao Yang, BA

Purpose: To compare computed tomography (CT) number measurement consistency under different beam hardening conditions in phantom experiment between dual-energy spectral CT and conventional CT imaging.

Materials and Methods: A phantom with 8 cells in periphery region and 1 cell in central region were used. The 8 conditioning tubes in the periphery region were filled with 1 of the 3 iodine solutions to simulate different beam hardening conditions: 0 for no beam hardening (NBH), 20 mg/mL for weak beam hardening (WBH) and 50 mg/mL for severe beam hardening (SBH) condition. Test tube filled with 0, 0.1, 0.5, 1, 2, 5, 10, 20, and 50 mg/mL iodine solution was placed in the central cell alternately. The phantom was scanned with conventional CT mode with 80, 100, 120, and 140 kVp and dual energy spectral CT mode. For spectral CT, 11 monochromatic image sets from 40 to 140 keV with interval of 10 keV were reconstructed. The CT number shift caused by beam hardening was evaluated by measuring the CT number difference (ΔCT) with and without beam hardening, with the following formulas: $\Delta CT_{WBH} = |CT_{WBH} - CT_{NBH}|$ and $\Delta CT_{SBH} = |CT_{SBH} - CT_{NBH}|$. Data were compared with 1-way analysis of variance.

Results: Under both WBH and SBH conditions, the CT number shifts in all monochromatic image sets were less than those for polychromatic images (all $P < 0.001$). Under WBH condition, the maximum CT number shift was less than 6 Hounsfield units for monochromatic spectral CT images of all energy levels; under SBH condition, only monochromatic images at 70 keV and 80 keV had CT number shift less than 6 HU.

Conclusion: Dual energy spectral CT imaging provided more accurate CT number measurement than conventional CT under various beam hardening conditions. The optimal keV level for monochromatic spectral CT images with the most accurate CT number measurement depends on the severities of beam hardening condition.

Key Words: CT-quantitative, beam hardening artifacts, dual-energy spectral CT

(*J Comput Assist Tomogr* 2015;39: 981–985)

Computed tomography (CT) number is a calculated value reflecting the X-ray attenuation coefficient in an image voxel, generally expressed in Hounsfield units (HU), where the CT number of water is 0 HU. Because of the fact that X-ray photon absorption by material is energy-dependent and that the standard X-ray source is polychromatic, CT number of any material is generally not constant but variable depending on factors, such as the model of CT scanner, reconstruction algorithm, tube voltage, distribution of the examined object, and patient size.[1–5] Clinically, the CT number of small simple renal cysts may be shifted upward on a contrast-enhanced CT to exhibit "pseudo-enhancement" that may affect the differential diagnosis between tumors and benign cysts. Beam hardening effect has been proposed as a cause for the pseudo-enhancement.[4,6–11] In conventional CT, the polychromaticity of the X-rays causes beam hardening artifacts (BHA)[12] and averaging attenuation effect in the image and leads to CT attenuation value shifts especially in obese patients and for tissues in the central region of body.[5,13] Iterative methods have been proposed to reduce beam hardening artifacts[12] and recover the attenuation map,[14] but iterative methods can be computationally slow.

On the other hand, the recently introduced dual energy spectral CT with single-source dual tube voltage fast switching technique provides monochromatic images depicting how the imaged object would appear under single-energy X-ray photons.[15] Monochromatic images are found to have better correlation between CT numbers and iodine concentrations,[15] and better CT number consistency, regardless of the phantom shape.[16] The purpose of this study was to evaluate the ability of monochromatic images in spectral CT imaging to reduce beam hardening artifact and to provide accurate CT number measurement under various beam hardening conditions in a phantom study.

MATERIALS AND METHODS

Materials

A quantitative analysis standard phantom (Fuyo Corporation QSP-1, as shown in Fig. 1) was used. The phantom section is made of polypropylene material. Eight cylinders were arranged at an interval of 45° on the circumference of the phantom and were filled with iodine contrast agent of different concentrations to simulate different levels of hardening effects: 0 mg/mL (water) for no beam hardening (NBH), 20 mg/mL for weak beam hardening (WBH) and 50 mg/mL for severe beam hardening (SBH) condition. The cylinder in the center cell was used for data measurement and analysis and was filled with iodine solution with 1 of the 9 concentrations (mg/mL): 0, 0.1, 0.5, 1, 2, 5, 10, 20, and 50.

Scanning Method

The phantom assembly was scanned on a Discovery CT750 HD scanner (GE Healthcare, Milwaukee, WI) in 2 scan modes: dual-energy spectral CT mode and conventional polychromatic X-ray imaging mode. Dual-energy spectral CT mode used fast kVp (80/140) switching with tube current fixed at 630 mA. Meanwhile, conventional polychromatic X-ray imaging mode used tube voltages of 80, 100, 120, and 140 kVp, with automatic tube

From the Department of Radiology, Beijing Chaoyang Hospital, Affiliated to Capital Medical University, Beijing, China.
Received for publication March 17, 2015; accepted April 9, 2015.
Correspondence to: Xiaojun Qian, MD, Department of Radiology, Beijing Chaoyang Hospital, 8 Gongti Nanlu, Chaoyang District, Beijing, China, 100020 (e-mail: qian_xj_70@hotmail.com).
The authors declare no conflict of interest.

DOI: 10.1097/RCT.0000000000000287

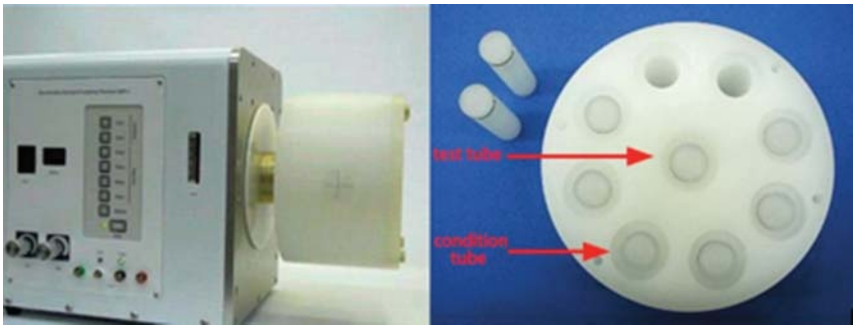

FIGURE 1. Photograph of the standard phantom. Eight cells were arranged at intervals of 45° on the periphery region of the standard phantom and one at the center. In this test, 8 condition tubes on the periphery region were filled with 0, 20, and 50 mg/mL of iodine to simulate NBH, WBH, and SBH conditions, respectively, 1 test tube filled with different concentration iodine solutions was placed in central cell to measure CT number shift under WBH and SBH conditions.

current modulation technique with noise index of 9 for each tube voltage. The other scanning parameters for the 2 scan modes were the same: field of view 25 cm, slice interval 5 mm, tube rotation period 0.8 seconds, and helical pitch 0.984 (Fig. 2).

Image Processing

The gemstone spectral imaging viewer software on the advanced workstation (AW4.5) was used for image processing in the dual-energy spectral CT mode. Eleven monochromatic image sets from 40 to 140 keV with interval of 10 keV were reconstructed. For the 4 polychromatic image sets and 11 monochromatic image sets, CT number of the test tube in the central cell of phantom was measured under the 3 different beam hardening conditions. Each condition was measured 3 times to get an average value. The CT number shift caused by beam hardening was evaluated by measuring the CT number

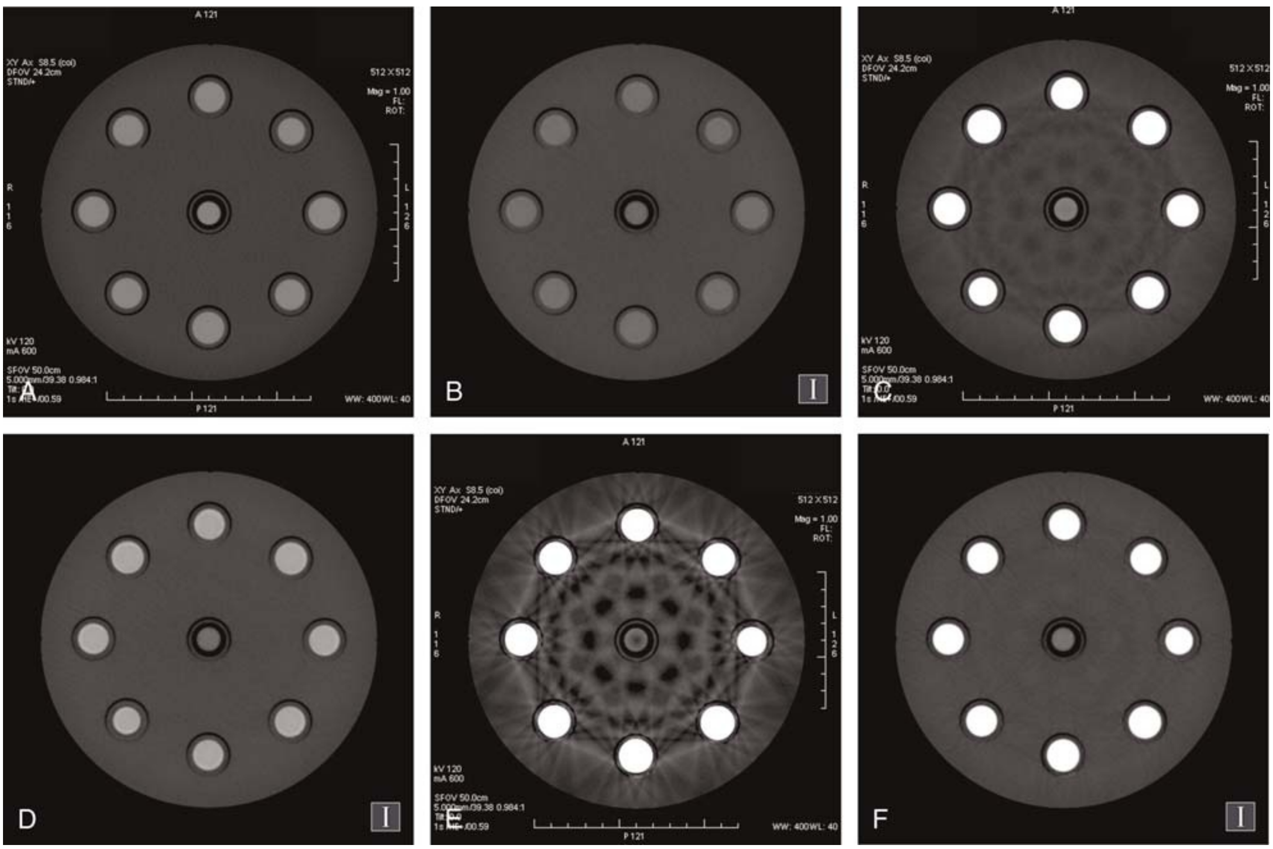

FIGURE 2. Comparisons of 120 kVp polychromatic images and 70 keV monochromatic images of phantom under NBH (A and B), WBH, (C and S), and SBH (E and F) conditions. The central test tube was filled with water. On the 120-kVp polychromatic images, the CT numbers of the central test tube under NBH (A), WBH (C), and SBH (E) condition were 13.02 HU, −5.37 HU, and −78.07 HU, respectively. The ΔCT_{WBH} and ΔCT_{SBH} were 18.39 HU and 91.09 HU. On the 70 keV monochromatic images, the CT numbers of the central test tube under NBH (B), WBH (D) and SBH (F) condition were 1.54 HU, 3.31 HU, and −2.66 HU, respectively. The ΔCT_{WBH} and ΔCT_{SBH} were 1.77 HU and 4.20 HU, respectively.

difference (ΔCT) with and without beam hardening effect, with the formulas: $\Delta CT_{WBH}=|CT_{WBH}-CT_{NBH}|$, $\Delta CT_{SBH}=|CT_{SBH}-CT_{NBH}|$. The BHA index was also calculated for each image, with the formula: BHA index = $SQRT(SDa^2 - SDb^2)$, where SDa denotes to the standard deviation value in the region adjacent to central tube with obvious BHA, SDb denotes the standard deviation value of background in the region far away from the tube without obvious BHA.

Data Analysis

The consistency of CT number measurement under different beam hardening conditions obtained by dual-energy spectral CT mode was compared with conventional CT mode by analyzed the CT number shift using one-way analysis of variance. The ability of beam hardening artifact[12] reduction by monochromatic images with CT spectral image was compared with conventional polychromatic X-ray imaging by analyzed the BHA index using one-way analysis of variance.

RESULTS

(1) CT number shift measurements in traditional polychromatic CT.

The CT number shifts of the central test tube with different iodine concentrations under WBH and SBH conditions in each of the 4 tube voltages in conventional CT are shown in Table 1. Under WBH condition, the mean CT number shifts of different iodine concentrations were 39.1 ± 19.9 (26.7–79.0) HU, 33.1 ± 18.0 (21.2–71.5) HU, 28.8 ± 15.9 (18.3–62.1) HU, and 25.9 ± 14.4 (16.2–57.3) HU corresponding to 80 kVp, 100 kVp, 120 kVp, and 140 kVp tube voltage. The corresponding CT number shift values under SBH condition were 163.8 ± 63.4 (134.2–267.6) HU, 123.0 ± 51.4 (104.9–216.8) HU, 112.4 ± 45.0 (90.5–189.6) HU, and 100.0 ± 40.2 (79.8–170.7) HU, significantly larger than those under WBH conditions analyzed with Student *t* test(each $P < 0.001$) (Table 1).

(2) The mean CT number shift measurements in dual-energy spectral CT

The CT number shifts of different iodine concentrations at each keV level were rather small; therefore, the average values were reported and are shown in Table 2, together with the mean values for conventional CT at 80, 100, 120, and 140 kVp. In both beam hardening conditions, the mean CT number shifts at every energy levels in spectral CT were significantly smaller than those in the traditional CT imaging at all 4 tube voltages (all $P < 0.001$). Under WBH condition, the maximum mean CT number shift at each keV of monochromatic images was less than 6 HU, and 50 keV monochromatic images had the lowest mean CT number shift. Under SBH condition, 70 keV monochromatic images had the lowest mean CT number shift (Table 2).

(3) The BHA index in dual-energy spectral CT and conventional CT

The BHA index in conventional CT image sets range from 3.50 ± 1.38 to 5.32 ± 1.14 under WBH with no significant

TABLE 2. The Mean CT Number Shifts of Monochromatic Images in Dual-Energy Spectral CT and Polychromatic Images in Conventional CT Under WBH and SBH Conditions

		Mean CT Number Shifts	
		WBH	SBH
Monochromatic images	40 keV	3.7 ± 4.0	64.0 ± 24.0
	50 keV	0.9 ± 2.8	38.0 ± 4.4
	60 keV	1.3 ± 2.2	17.1 ± 2.5
	70 keV	2.6 ± 2.0	3.2 ± 2.0
	80 keV	3.7 ± 1.9	5.9 ± 2.4
	90 keV	4.3 ± 1.9	11.2 ± 3.1
	100 keV	4.7 ± 1.8	15.2 ± 3.5
	110 keV	5.0 ± 1.8	18.0 ± 3.7
	120 keV	5.2 ± 1.9	19.9 ± 3.94
	130 keV	5.4 ± 1.9	21.4 ± 4.1
	140 keV	5.5 ± 1.8	22.6 ± 4.3
Polychromatic imaging	80 kVp	39.1 ± 19.9	163.8 ± 42.2
	100 kVp	33.1 ± 15.8	130.0 ± 35.3
	120 kVp	28.8 ± 14.1	112.4 ± 31.4
	140 kVp	25.9 ± 12.8	100.1 ± 28.3
	F	281.7	424.1
	P	<0.001	<0.001

TABLE 1. The CT Number Shifts of Polychromatic Images of Conventional CT Under WBH and SBH Conditions

	CT Number Shifts							
	80 kVp		100 kVp		120 kVp		140 kVp	
Iodine Concentration of Test Tube(mg/ml)	WBH	SBH	WBH	SBH	WBH	SBH	WBH	SBH
0	26.7	134.2	21.2	104.9	18.3	90.5	16.2	79.8
0.1	26.5	135	21.5	105.6	19.1	90.5	16.2	81.2
0.5	28.2	136.6	22.2	108.1	19.4	91.6	16.5	81.5
1	27.5	134.4	23.1	105.5	19.8	93.1	18.7	82.5
2	29.9	142.5	24.4	111.6	19.8	95.6	19.3	85.5
5	35.4	153.1	31.2	121.8	25.5	103.9	23.9	93.6
10	41.8	169.8	35.9	134.6	32.3	116.7	28.6	103
20	56.6	201.3	47.2	160.8	42.9	140.1	36.3	122.7
50	79	267.6	71.5	216.8	62.1	189.6	57.3	170.7
Mean	39.1	163.8	33.1	130	28.8	112.4	25.9	100.1
SD	17.9	44.8	16.8	37.4	14.9	33.3	13.6	30
T	13.865		14.034		13.613		13.542	
P	<0.001		<0.001		<0.001		<0.001	

TABLE 3. The Mean BHA Index of Monochromatic Images of Dual-Energy Spectral CT Under WBH and SBH Conditions Compared with the Mean BHA Index of Polychromatic Images in Conventional CT Under WBH and SBH Conditions

		BHA Index	
		WBH	SBH
Monochromatic images	40 keV	6.26 ± 0.21	5.48 ± 1.36
	50 keV	4.56 ± 0.30	3.65 ± 0.61
	60 keV	2.58 ± 0.51	2.31 ± 0.92
	70 keV	2.09 ± 0.48	1.73 ± 1.13
	80 keV	2.33 ± 0.53	2.14 ± 0.98
	90 keV	2.13 ± 0.49	2.18 ± 1.06
	100 keV	1.70 ± 0.65	2.26 ± 0.96
	110 keV	1.58 ± 0.66	2.28 ± 0.86
	120 keV	1.32 ± 0.66	2.17 ± 0.86
	130 keV	1.24 ± 0.78	2.22 ± 081
	140 keV	1.27 ± 0.75	2.11 ± 0.87
Polychromatic imaging	80 kVp	5.32 ± 1.14	29.79 ± 1.35
	100 kVp	4.37 ± 0.99	24.00 ± 2.06
	120 kVp	3.50 ± 1.38	22.68 ± 1.97
	140 kVp	4.22 ± 0.10	17.89 ± 0.34
	F	13.19	536.8
	P	0.001	<0.001

difference. The BHA index in conventional CT image sets range from 17.89 ± 0.34 to 29.79 ± 1.35 under SBH, reduced by increasing the kilovoltage. The BHA index of each monochromatic image set (ranging from 1.27 ± 0.75 to 6.26 ± 0.21) was lower than that of conventional CT image under WBH ($P < 0.001$). The BHA index of each monochromatic image set (ranging from 1.73 ± 1.13 to 5.48 ± 1.36) was lower than that of conventional CT image under SBH ($P < 0.001$) (Table 3).

DISCUSSION

The CT attenuation values are quantized for materials according to X-ray attenuation. In the past few decades, identification of lesions versus normal tissue mainly depended on their CT attenuation values, but for conventional CT, take a 120-kVp scan, for example, the emission polychromatic X-ray also contains a broad-energy spectrum ranging from 0 to 120 keV.[15] Polychromaticity of the X-rays causes beam hardening artifacts and averaging attenuation effect in the image and leads to CT attenuation value shifts in obese patients and tissues in the central region of body.[13] Clinically, the CT attenuation value shift of small simple renal cysts on contrast-enhanced CT is reported as "pseudo-enhancement," which may affect differential diagnosis of tumors and benign cysts, in which criterion relies on enhancement of a renal mass on contrast-enhanced CT.[6] Dual-energy spectral CT obtained with the single-source dual tube voltage fast switching technique provides 40-keV to 140-keV monochromatic images depicting how the imaged object would appear under single energy X-ray photons. Wang et al[15] reported that monochromatic images obtained with this method have better correlation coefficients between CT attenuation values and iodine concentration than polychromatic images. Matsuda et al[16] found that dual-energy spectral CT provides better CT number consistency than by conventional CT, regardless of the phantom shape. In this study, we have extended the scopes of previous works to simulate lesions of different activity levels and under different beam hardening conditions using a phantom and evaluated the performance of dual energy spectral CT in terms of CT number measurement consistency and beam hardening artifacts reduction, in comparison with the traditional polychromatic X-ray imaging.

Our results showed that under both WBH and SBH conditions, the CT number shifts decreased as the kVp increased, low kVp had larger CT number shifts than high kVp, which implied that the lower the polychromatic X-ray energy level, the more susceptible to beam hardening effect. Under SBH condition, the CT number shifts corresponding to each kVp were larger than those under WBH condition, which implied that in clinical applications, more SBH effect would occur if the background tissues had strong enhancement or there were high attenuation objects in the X-ray paths that would create SBH condition. On the other hand, under both WBH and SBH conditions, monochromatic images of dual-energy spectral CT had lower CT number shifts than polychromatic images of conventional CT. Under WBH condition, the mean CT number shifts for each keV monochromatic images were less than 6 HU, and the energy level for the lowest shift was at 50 keV. Under SBH conditions, the mean CT number shifts in the 70-keV and 80-keV monochromatic images were less than 6 HU, with the lowest happened at 70 keV.

Comparison of Optimal keV Level of Monochromatic Images Under Different Beam Hardening Conditions

Our results showed that under WBH condition, the CT number shifts of 40 to 140 keV monochromatic images were less than 6 HU, which indicate that under this condition, each keV level monochromatic images can provide accurate CT attenuation value with little beam hardening effect. However under SBH condition, only 70 keV and 80 keV monochromatic images had CT number shifts less than 6 HU, which indicate that under SBH condition, 70 keV and 80 keV monochromatic images provide the most accurate CT attenuation value among different keV levels. Meanwhile, the mean CT number shifts for low keV levels (40 keV and 50 keV) were larger than those at high keV levels (60 keV to 140 keV), which implied low keV levels monochromatic images were more susceptible to beam hardening effect.

The present study has some limitations. First, this study was conducted as a phantom study, 20 and 50 mg/mL iodine were used to simulate WBH and SBH conditions, respectively, the clinical feasibility was not investigated. Second, under the SBH condition with 50 mg/mL iodine in periphery cells of the phantom, 70 keV and 80 keV monochromatic images provide the most accurate CT attenuation value among different keV levels, which was different from the optimal 50 keV energy level under the WBH condition. How the optimal energy level changes with the severity of beam hardening condition was not investigated.

The present results demonstrate that dual-energy spectral CT imaging provides more accurate CT number measurements than conventional CT under both weak and SBH conditions, which will enable more accurate comparison of the densities of lesions of interest in clinical diagnosis. The best monochromatic energy levels in spectral CT vary, depending on the severity of beam hardening conditions.

REFERENCES

1. Levi C, Gray JE, McCullough EC, et al. The unreliability of CT numbers as absolute values. *AJR Am J Roentgenol*. 1982;139:443–447.

2. McCullough EC, Morin RL. CT-number variability in thoracic geometry. *AJR Am J Roentgenol*. 1983;141:135–140.
3. Zerhouni EA, Spivey JF, Morgan RH, et al. Factors influencing quantitative CT measurements of solitary pulmonary nodules. *J Comput Assist Tomogr*. 1982;6:1075–1087.
4. Birnbaum BA, Hindman N, Lee J, et al. Multi-detector row CT attenuation measurements: assessment of intra- and interscanner variability with an anthropomorphic body CT phantom. *Radiology*. 2007;242:109–119.
5. Yu L, Bruesewitz MR, Thomas KB, et al. Optimal tube potential for radiation dose reduction in pediatric CT: principles, clinical implementations, and pitfalls. *Radiographics*. 2011;31:835–848.
6. Maki DD, Birnbaum BA, Chakraborty DP, et al. Renal cyst pseudoenhancement: beam-hardening effects on CT numbers. *Radiology*. 1999;213:468–472.
7. Coulam CH, Sheafor DH, Leder RA, et al. Evaluation of pseudoenhancement of renal cysts during contrast-enhanced CT. *AJR Am J Roentgenol*. 2000;174:493–498.
8. Bae KT, Heiken JP, Siegel CL, et al. Renal cysts: is attenuation artifactually increased on contrast-enhanced CT images? *Radiology*. 2000;216:792–796.
9. Birnbaum BA, Maki DD, Chakraborty DP, et al. Renal cyst pseudoenhancement: evaluation with an anthropomorphic body CT phantom. *Radiology*. 2002;225:83–90.
10. Abdulla C, Kalra MK, Saini S, et al. Pseudoenhancement of simulated renal cysts in a phantom using different multidetector CT scanners. *AJR Am J Roentgenol*. 2002;179:1473–1476.
11. Israel GM, Bosniak MA. Pitfalls in renal mass evaluation and how to avoid them. *Radiographics*. 2008;28:1325–1338.
12. Subhas N, Primak AN, Obuchowski NA, et al. Iterative metal artifact reduction: evaluation and optimization of technique. *Skeletal Radiol*. 2014;43:1729–1735.
13. Zhao LQ, He W, Li JY, et al. Improving image quality in portal venography with spectral CT imaging. *Eur J Radiol*. 2012;81:1677–1681.
14. Elbakri IA, Fessler JA. Statistical image reconstruction for polyenergetic X-ray computed tomography. *IEEE Trans Med Imaging*. 2002;21:89–99.
15. Wang L, Liu B, Wu XW, et al. Correlation between CT attenuation value and iodine concentration in vitro: discrepancy between gemstone spectral imaging on single-source dual-energy CT and traditional polychromatic X-ray imaging. *J Med Imaging Radiat Oncol*. 2012;56:379–383.
16. Matsuda I, Akahane M, Sato J, et al. Precision of the measurement of CT numbers: comparison of dual-energy CT spectral imaging with fast kVp switching and conventional CT with phantoms. *Jpn J Radiol*. 2012;30:34–39.