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: ΔCT_{WBH} = CT_{WBH} - CT_{NBH} and ΔCT_{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

ORIGINAL ARTICLE

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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...
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 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.

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 $\Delta$CTWBH and $\Delta$CTSBH 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 $\Delta$CTWBH and $\Delta$CTSBH were 1.77 HU and 4.20 HU, respectively.
difference (ΔCT) with and without beam hardening effect, with the formulas: ΔCTWBH = |CTWBH - CTNBH|, ΔCTSBH = |CTSBH - CTNBH|. 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 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 ± 42.2 (134.2–267.6) HU, 130.0 ± 35.3 (104.9–216.8) HU, 112.4 ± 31.4 (95.9–189.6) HU, and 100.1 ± 28.3 (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 1. The CT Number Shifts of Polychromatic Images of Conventional CT Under WBH and SBH Conditions |
|--------------------------------------------------------|--------------------------------------------------------|
| Iodine Concentration of Test Tube(mg/ml) | 80 kVp | 100 kVp | 120 kVp | 140 kVp |
| | 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 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 ± 3.9 |
| | 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 |
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 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 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.

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. 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 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. How the optimal energy level changes with the severity of beam hardening condition was not investigated.

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. 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.

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