Material Decomposition Images Generated from Spectral CT:

Detectability of Urinary Calculi and Influencing Factors

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Rationale and Objectives: To evaluate the detectability of urinary calculi on material decomposition (MD) images generated from spectral computed tomography (CT) and identify the influencing factors.

Materials and Methods: Forty-six patients were examined with true nonenhanced (TNE) CT and spectral CT urography in the excretory phase. The contrast medium was removed from excretory phase images using water-based (WB) and calcium-based (CaB) MD analysis. The sensitivity for detection on WB and CaB images was evaluated using TNE results as the reference standard. The signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR) on MD images were evaluated. Using logistic regression, the influences of image noise, attenuation, stone size, and patient's body mass index (BMI) were assessed. Threshold values with maximal sensitivity and specificity were calculated by means of receiver operating characteristic analyses.

Results: One hundred thirty-six calculi were detected on TNE images; 98 calculi were identified on WB images (sensitivity, 72.06%) and 101 calculi on CaB images (sensitivity, 74.26%). Sensitivities were 76.92% for the 3–5-mm stones and 84.51% for the 5-mm or larger stones on both WB and CaB images but reduced to 46.15% on WB images and 53.85% on CaB images for small calculi (<3 mm). Compared to WB images, CaB images showed lower image noise, higher SNR but similar CNR. Larger stone sizes (both >2.71 mm on WB and CaB) and greater CT attenuation (>280 Hounsfield units [HU] on WB, >215 HU on CaB) of the urinary stones were significantly associated with higher stone visibility rates on WB and CaB images ($P \leq .003$). Image noise and BMI showed no impact on the stone detection.

Conclusions: MD images generated from spectral CT showed good reliability for the detection of large (>2.71 mm) and hyperattenuating (>280 HU on WB, >215 HU on CaB) urinary calculi.

Key Words: Spectral CT; urinary calculi; material decomposition; water-based material decomposition; calcium-based material decomposition.

Material characterization with the use of dual-energy computed tomography (DECT) has been described in the late 1970s (1,2). However, DECT was not adopted widely for clinical use until recently because of the limited technology. Currently, the two common approaches to realize DECT scanning are the use of dual-source, dual-detector assembly for the simultaneous generation of low- and high-energy CT images and the use of single-source, single-detector system for the simultaneous acquisition of the low- and high-energy projection sets in a single examination. DECT provides material decomposition (MD) images for material characterization and has been shown to be useful for determining the composition of urinary stones (3,4).

Traditionally, nonenhanced CT is used for the detection of urinary stones because urinary stones are often obscured by high-attenuating iodinated contrast material in the renal parenchyma or collecting system in the contrast-enhanced CT images (5). However, with the use of virtual nonenhanced (VNE) images generated from DECT, iodine can be subtracted from the contrast-enhanced CT images (6–9) and be used to depict urinary stones submerged in iodine solutions (10), and detect urinary stones in the pyelographic phase images (11). Therefore, with the creation of VNE CT scans, nonenhanced CT during CT urography could be achieved without obtaining a true nonenhanced (TNE) scan for the detection of urinary stones to reduce radiation dose and scanning time. However, the accuracy of stone detection on VNE images could not be exactly equivalent to TNE images. Recently, it has been shown that VNE images in the dual-source DECT (dsDECT) generated from the excretory phase enables the depiction of urinary stones larger than 5 mm with high sensitivities; however, there are limitations regarding smaller stone sizes (sensitivity of 16%–29% for <3-mm stones) (12,13). Urinary calculi with a diameter of <3 mm can cause symptoms such as pain and microscopic hematuria. Unfortunately, this cannot be assured in the current state of VNE dsDECT imaging.

The more recently introduced spectral CT imaging mode uses a single-source and single-detector system with rapid

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alternation between 80 kVp and 140 kVp tube voltages for the simultaneous acquisition of precisely registered data sets. This scanning mode allows the generation of accurate MD images using various base material pairs (e.g., water- and iodine-based) to discriminate different materials. With the spectral imaging viewer, iodine subtraction from basis material pair is possible and easy, resulting in water-based (WB) and calcium-based (CaB) data sets similar to VNE data sets in dsDECT. To our best knowledge, MD in spectral CT has not yet been assessed for the detection of urinary stones.

Therefore, the purpose of this study was to evaluate the detectability of urinary calculi with WB and CaB MD images obtained with spectral CT compared to TNE images and to identify factors influencing the stone detection rate.

MATERIALS AND METHODS

Patient Population

This retrospective study was approved by our institutional review board, with a waiver of informed consent. From June 2012 to May 2013, 61 consecutive patients who had undergone the conventional helical CT in the TNE phase and spectral CT urography in the excretory phase for the evaluation of hematuria, work-up of urinary tract malignancy, or known or suspected urinary stone disease were retrospectively identified by reviewing medical records. Fifteen CT studies (in 12 men and three women) were excluded from the evaluation owing to absence of the stones. Finally, 46 consecutive patients (33 men, 13 women; mean age, 51 $\pm$ 15 years) were included in our study. Each patient's body mass index (BMI) was calculated and reported as BMI < 18.5 (underweight), between 18.5 and 23.9 (normal), between 24 and 28.9 (overweight), or $\geq$29 (obese) based on the appropriate BMI for China (14).

CT Protocol

Quadruple-phase CT (nonenhanced, renocortical, nephrographic, and excretory phases) from the kidneys to the bladder was performed using a Discovery CT750 HD system (GE Healthcare, WI). At our institution, single-bolus, quadruple-phase, CT urography is generally used for patients with a relatively high risk of malignancy, with renal insufficiency, and requiring simultaneous evaluation of renal parenchymal or other solid organ lesions. The TNE scanning was initially performed in the conventional helical mode with a tube voltage of 120 kVp, an automatic tube-current control (308–453 mA), a rotation speed of 0.6 seconds, and a helical pitch of 0.984:1; volume CT dose index (CTDIvol) = 18.03 $\pm$ 4.24 mGy.

Patients were then injected with nonionic contrast medium (Ioversol Injection, Optiray 320; Tyco Healthcare, Montreal, Quebec, Canada) through antecubital venous access at a rate of 3–4 mL/s for a total of 90–120 mL (1.5 mL/kg) and followed by 40 mL of saline administered at the same rate using a power injector. Renocortical phase scanning was automatically begun 12 seconds after the trigger attenuation threshold (100 Hounsfield units [HU]) reached the level of the supraceliac abdominal aorta. Nephrographic scanning began 30 seconds after the renocortical phase scanning. The tube voltage and current range of these two phases were 120 kVp and 227–346 mA with the automatic tube-current modulation. Other parameters included: collimation, 64 $\times$ 0.625 mm; rotation speed, 0.6–0.8 second; pitch, 0.984:1; noise index, 9.0; and CTDIvol, 15.80 $\pm$ 4.74 mGy.

After 30-minute delay from the start of contrast material administration, excretory phase scanning was performed in the spectral imaging mode. Other parameters were as follows: collimation, 64 $\times$ 0.625 mm; tube current, 550–640 mA; rotation speed, 0.6–0.8 second; helical pitch, 1.375:1; and CTDIvol, 16.50 $\pm$ 1.08 mGy (comparable with the dose for single-energy CT at our institution, nominally 15.8 mGy). The reconstruction thickness of nonenhanced and excretory phases was both 0.625 mm, at an interval of 0.625 mm to balance image noise and spatial resolution.

Two different types of images with iodine subtraction were reconstructed from the single spectral CT acquisition in the excretory phase for analysis: WB MD (using the water–iodine pair) images and CaB MD (using the calcium–iodine pair) images.

Image Interpretation

Quantitative analysis. An abdominal radiologist with 3 years' experience performed all the measurements using spectral imaging viewer (GSI Viewer; GE Healthcare, WI). Noise levels (SD_{fat}) on WB images, CaB images, and excretory phase images were all determined by measuring the standard deviation of the pixel values from a region of interest drawn in the subcutaneous fat of the anterior abdominal wall.

Signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR) of these stones on WB and CaB images were calculated according to the following equations: SNR = ROI_{stone}/SD_{fat} and CNR = $(ROI_{stone} - ROI_{muscle})/SD_{fat}$, where ROI_{stone} and ROI_{muscle} are the densities of the stones and muscles, respectively, and SD_{fat} is the standard deviation. For each patient, the densities (in milligrams per milliliter) of the stones were derived from WB or CaB images. In addition, the densities of the central parts of latissimus dorsi and the psoas muscles were measured on both sides and averaged (ROI_{muscle}). For the assessment of scanner dose output, the CTDIvol was recorded.

Qualitative analysis. Two radiologists with 13–30 years of experience independently performed a blinded qualitative analysis of CT images in the same workstation. They were blinded to patients' information and evaluated independently. The default display window width and level settings were 200 and 800 HU on WB images, 300 and 1000 HU on CaB images, respectively, but the reviewer was allowed to change the window settings as necessary. The number and