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Radiation Dose Reduction in Dual-Energy CT: Does It Affect the Accuracy of Urinary Stone Characterization?

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Abstract

OBJECTIVE—The purpose of this article is to assess the effect of radiation dose reduction in dual-energy CT (DECT) on the performance of renal stone characterization using a patient cohort.

MATERIALS AND METHODS—CT data from 39 unenhanced DECT examinations performed for stone characterization were retrospectively analyzed in this study. Reduced-dose images were simulated at 75%, 50%, and 25% of the routine dose using a previously validated noise-insertion algorithm. Differentiation between uric acid (UA) and non-UA stones was performed using a fixed cutoff value for the dual-energy ratio. ROC analysis was performed to determine optimal cutoff values and the associated sensitivity and specificity.

RESULTS—Of the 206 stones found, 43 were UA and 163 were non-UA. The mean ($\pm$ SD) volume CT dose index (CTDI_{vol}) was 16.0 ± 4.0 mGy at the 100% dose level. The mean noise in 100-kV images increased from 40.9 ± 6.8 HU at 100% dose to 46.8 ± 8.8 HU, 57.7 ± 12.5 HU, and 85.4 ± 22.9 HU at 75%, 50%, and 25% dose levels, respectively. Using the default cutoff value, for stones 10 mm^3 or larger, the sensitivity/specificity were 100.0%/98.8%, 82.8%/98.8%, and 89.3%/98.7%, at 75%, 50%, and 25% dose levels, respectively. ROC analysis showed varying optimal cutoff values at different dose levels. The sensitivity and specificity improved with use of these optimal cutoff values. Differentiation capability decreased for stones smaller than 10 mm^3 .

CONCLUSION—At 75% of the 16-mGy routine dose, the sensitivity and specificity for differentiating UA from non-UA stones were minimally affected for stones 10 mm^3 or larger. The use of optimal cutoff values for dual-energy ratio as dose decreased (and noise increased) provided improved performance.

Keywords

dual-energy CT; dual-energy ratio; radiation dose reduction; renal stone composition; uric acid stones; urinary stones

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CT is the modality of choice for assessing kidney stone disease [1]. The recent development of dual-energy CT (DECT) technology has further extended the application of CT to noninvasive characterization of stone composition [2–4]. Accurate differentiation between uric-acid (UA) and non-UA stones has been shown using both phantom [3, 4] and clinical studies [5]. The potential to characterize more than two stone types has also been explored recently [6, 7].

Despite the consensus that CT benefits the patient in appropriate clinical settings, public health concerns have arisen because of the potential risk of cancer induction from radiation exposure [8]. This widespread concern about CT will have a major negative effect on the treatment of patients with kidney stone disease, because many patients may become unwilling to receive CT examinations and physicians may become hesitant about recommending CT as an imaging tool to monitor the changes of stone burdens. Therefore, minimizing the radiation dose of CT for the diagnosis of stone diseases has become one of the top priorities in order to fully utilize the benefit provided by state-of-the-art CT technology. The mean radiation dose in a routine-dose DECT examination for stone composition analysis ranges from 6.0 to 26.2 mGy [2, 3, 6, 7, 9–14]. Efforts have been made to minimize the x-ray radiation dose in CT examinations using dual-energy technologies for kidney stone characterization purposes, including using a low-dose scan technique with the volume CT dose index ($CTDI_{vol}$) as low as 8.3 mGy [12], and a stone-targeted scan strategy to reduce the DECT scan range after a full-range single-energy scan [13–15].

In this study, we aimed to assess the effect of radiation dose reduction on the accuracy of stone characterization using DECT in a cohort of patients. A validated software tool was used to simulate several levels of reduced-dose images.

Materials and Methods

Study Population

This HIPAA-compliant study was reviewed and approved by the Mayo Clinic institutional board with a waiver of informed consent.

CT projection data were collected from patients with kidney stones who underwent clinically indicated unenhanced DECT examinations on a second-generation dual-source CT scanner (Definition Flash, Siemens Healthcare) from January 2012 through July 2013. If a patient underwent multiple examinations, only data from the first examination were included. Cases were excluded from subsequent analysis if foreign objects were present (e.g., tubes, stents, or metal). Patient sizes represented by the lateral width through the transpyloric plane were measured in the localizer scan (topogram).

Image Acquisition and Dose Simulation

A clinical routine DECT kidney stone protocol was used for all patients: 100 kV on tube A at a quality reference mAs of 240 and 140 kV with an added tin filter on tube B at a quality reference mAs of 185, rotation time 0.5 second; detector configuration 32×0.6 mm. These settings were used as the reference 100% dose level. Automatic exposure control

(CareDose4D, Siemens Health-care) was used to adjust the tube current for each patient according to their body shape and size.

Raw CT data were exported from the scanner to a separate workstation and were processed using a previously validated software tool developed in our laboratory to simulate projection data at lower scanner output levels [16]. The simulation software inserted noise onto each projection frame. The amount of noise inserted was based on a noise model that incorporated the effects of the bowtie filter, automatic exposure control, and electronic noise. The accuracy of noise insertion was validated by comparing the noise level and noise power spectrum with those in the acquired images at each radiation dose level. Three sets of lower-CTDI_{vol} data were created at 75%, 50%, and 25% of the original level. Images were reconstructed using a dual-energy kernel (D30f) for all datasets, a 1.0-mm slice thickness, and a 0.8 slice interval.

Image Analysis

A clinically validated dual-energy software tool (Syngo Via, Siemens Healthcare) was used to postprocess the images. It identified the presence of the stones, determined the composition of the stones by labeling with red color for UA and blue for non-UA, and measured the volume, all performed in a fully automated fashion. In principle, the software characterized stones according to the dual-energy ratio, which was calculated by dividing the CT number of the stone at low tube voltage by that at high tube voltage. When the dual-energy ratio was above a predetermined cutoff value, the stone was labeled as non-UA; otherwise, the stone was labeled as UA. For determining the compositions, the manufacturer-recommended default settings were used (thresholds, 200 HU; range, 3; cutoff, 1.13).

Statistical Analysis

Sensitivity and specificity for differentiating UA and non-UA stones were calculated at each dose level. The stone type determined according to the 100%-dose images was used as the reference standard. Stones identified in the 100%-dose images for analysis but not in the lower-dose images were excluded from the calculation of sensitivity and specificity. Overall accuracy was also calculated, with unidentified stones at lower dose levels counted as a misdiagnosis. ROC analysis was performed for each reduced dose level to determine the optimal cutoff value, which was the point on the ROC curve closest to the upper left corner, approximately corresponding to the maximum sum of sensitivity and specificity for differentiation. The paired Student *t* test was used to compare the volume measurements in images at 100% dose level with those in the three reduced-dose images.

Results

Examination and Patient Information

A total of 39 sets of DECT data were included in this study. The study cohort included 25 men (64.1%) and 14 women (35.9%). The mean ($\pm$ SD) age was 61.6 ± 10.7 years (range, 38–83 years). The mean body size (abdominal width at the transpyloric plane measured in topogram) was 41.4 ± 5.2 cm (range, 29.7–52.0 cm). A total of 206 stones were found with

an mean of 5.3 ± 3.3 stones per patient (range, 1–14 stones per patient), including 43 (20.9%) UA and 163 (79.1%) non-UA stones (Table 1).

The mean CTDI_{vol} was 16.0 ± 4.0 mGy (range, 7.9–26.7 mGy). Figure 1 shows example images of reduced-dose simulation. The average image noise in 100- and 140-kV images was 40.9 ± 6.8 HU and 38.2 ± 6.4 HU, respectively, at the 100% dose level and increased to 46.8 ± 8.8 HU and 44.2 ± 9.1 HU at the 75% dose level, 57.7 ± 12.5 HU and 54.8 ± 12.8 HU at the 50% dose level, and 85.4 ± 22.9 HU and 81.5 ± 23.8 HU at the 25% dose level (Fig. 2). Compared with theoretically predicted noise levels at 75%, 50%, and 25% dose levels, the simulated noise levels were within 0.1%, 1.5%, and 6.8%, respectively.

Stone Characterization With Default Dual-Energy Ratio Cutoff Values

Among the 206 stones identified in images at the 100% dose level, 203 (98.5%), 202 (98.1%) and 186 (90.3%) were identified by the software for further composition analysis at each of the respective reduced-dose levels. Figure 3 shows an example case where a stone was characterized in the original full-dose image as UA but was unidentified in the image obtained at the 50% dose level. The unidentified stones were removed from the subsequent composition analysis. Using the default cutoff value for the dual-energy ratio of 1.13 to differentiate between UA and non-UA stones, the overall sensitivity and specificity were 95.1% and 97.5%, 75.0% and 96.3%, and 79.5% and 93.9% at the 75%, 50%, and 25% dose levels, respectively (Table 2). For stones 10 mm^3 or larger ($n = 109$, including 29 UA and 80 non-UA stones), the sensitivity and specificity were 100.0% and 98.8%, 82.8% and 98.8%, and 89.3% and 98.7% at each respective dose level (Table 3). For stones smaller than 10 mm^3 ($n = 97$, including 14 UA and 83 non-UA stones), the sensitivity and specificity were 83.3% and 96.3%, and 54.5% and 93.9%, and 54.5% and 88.6%, at each respective dose level (Table 4).

Use of Variable Cutoff Value to Improve Performance on Stone Characterization

For stones 10 mm^3 or larger, the optimal cutoff values for the dual-energy ratio to differentiate between UA and non-UA stones varied from 1.13 to 1.20 at different dose levels. The sensitivity and specificity improved with use of these cutoff values (Table 5). (The manufacturer's default value is 1.13, regardless of the level of image noise.)

Stone Volumes at Different Dose Levels

The mean stone volumes were $46.5 \pm 120.9 \text{ mm}^3$ (range, 1.4–955.0 mm^3) measured automatically using the Syngo Via software tool. At 75%, 50%, and 25% dose levels, stone volumes were $46.8 \pm 121.5 \text{ mm}^3$ (range, 1.4–957.0 mm^3), $44.4 \pm 120.8 \text{ mm}^3$ (range, 1.4–961 mm^3), and $58.4 \pm 149.8 \text{ mm}^3$ (range, 1.4–1170 mm^3), respectively. Volume measurements at the 75% dose level were not statistically significantly different from those at full-dose levels ($p = 0.10$), but were statistically significantly different at the 50% and 25% dose levels ($p < 0.05$ for both).

Discussion

Using patient DECT image data and a validated noise-insertion algorithm to simulate three different lower dose levels, this study found that the performance of differentiation between UA and non-UA stones was minimally affected at 75% of the routine dose level, especially for bigger stones. With a further decrease of dose level to 50% and 25%, the performance was substantially reduced, with the sensitivity decreasing to less than 80%. It can also be observed that the effect of radiation dose on performance differed substantially for different stone sizes. For stones 10 mm³ or larger, the sensitivity and specificity were maintained to be above 89.3% and 98.7%, respectively, at dose levels as low as 25%. However, for stones smaller than 10 mm³, the sensitivity and specificity decreased to 83.3% and 96.3%, respectively, even at dose levels as high as 75%.

The mean CTDI_{vol} in routine-dose DECT examinations for stone characterization that used similar scan parameters have been reported to range from 6.0 to 26.2 mGy in phantom studies [3, 6, 7, 9–11] and from 8.2 to 14.6 mGy in patient studies [2, 10, 12–14], with the CTDI_{vol} value depending on the size of the phantom or patient. In comparison, the routine-dose protocol in this study resulted in an mean CTDI_{vol} value of 16.0 ± 4.0 mGy, which is above the reported values in patient studies but within the range of reported phantom studies. If a 25% dose reduction is allowed on the basis of the results in this study, then the mean CTDI_{vol} of the scanning technique can be reduced to 12 mGy. Further dose reduction will lead to a decrease in the accuracy in stone characterization. This study is clinically significant because it establishes how low the radiation dose can be reduced in a DECT examination while maintaining the accuracy of stone characterization.

One interesting finding in this study is that, when the default cutoff value of the dual-energy ratio was increased as the dose levels decreased, improved sensitivity and specificity for detecting UA were obtained (96.4% and 97.4% at 25% dose level for stones 10 mm³). This is an important consideration for ensuring that efforts to decrease patient dose levels do not decrease the diagnostic accuracy of the examination.

In a previous study evaluating stone composition analysis in a cohort of patients with different body sizes, cutoff values specific to each patient were determined on the basis of the patient's abdominal size using a linear regression model created from the measurements in five standard-size phantoms [10]. In the current study, patient size was not a study parameter. Because the automatic exposure control was turned on, the tube current was automatically adjusted according to the patient's size. All patients in the study cohort (mean lateral width, 41.4 ± 5.2 cm, range: 29.7–52.0 cm) were included at each dose level. The accuracy of stone characterization at each dose level represents the overall performance for all patient sizes, given a specific automatic exposure control setting, which is directly relevant to clinical practice.

In addition, in the current study, the scanner was equipped with a different detector type that uses an integrated detector electronics design [17, 18], compared with that used by Qu et al. [10]. This difference is very relevant in the case of large patients or low dose levels because the newer detector has much lower levels of electronic noise [17, 18]. Further work to

determine the cutoff values that provide the best diagnostic performance appears merited, especially because patient size varies and equipment models and software versions change.

This study has the following limitations. First, the stone detection accuracy was not assessed here, even though an increase in image noise could decrease the ability of human observers to detect some stones, particularly small ones. We did observe a small decrease in the number of stones that were characterized by the analysis software. When stones were smaller than 10 mm³, 3.1%, 5.1%, and 16.5% of stones were not identified as UA or non-UA at 75%, 50%, and 25% dose levels, respectively. For example, the numbers of stones that were color-coded as UA or non-UA decreased from 206 at the routine dose level to 186 at the 25% dose level. The reason for the software to exclude those stones from analysis remains unknown, but was likely caused by excessive noise and small stone sizes. However, this does not mean that those stones cannot be detected at all. A multireader multicase observer performance study would be required to assess the potential consequences of decreasing radiation dose. Second, the number of UA stones ($n = 43$) was much smaller than the number of non-UA stones ($n = 163$). This reflects the prevalence of UA stones, which is estimated to range from 5% to 10% of the population [19, 20]. Thus, using data from all eligible patients scanned during the study period, a comparable number of UA and non-UA stones would not be expected.

Conclusion

In summary, this study found that, for stones 10 mm³ or larger, the diagnostic performance for the task of differentiating UA and non-UA urinary stones using DECT was minimally reduced as the amount of radiation was decreased by 25%. For small stones (< 10 mm³), radiation dose reduction by as small as 25% may result in decreased performance. The use of optimal cutoff values for dual-energy ratio as the dose decreased provided improved performance. Stone volume estimates were statistically significantly different ($p < 0.05$) from reference values at the 50% and 25% dose levels, suggesting that when quantitative volume measurements are important for patient management decisions or for assessing longitudinal changes in stone volume, caution should be exercised in how much the radiation dose is reduced.

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References

1. Reddy S. State of the art trends in imaging renal of colic. *Emerg Radiol.* 2008; 15:217–225. [PubMed: 18386086]
2. Graser A, Johnson TR, Bader M, et al. Dual energy CT characterization of urinary calculi: initial in vitro and clinical experience. *Invest Radiol.* 2008; 43:112–119. [PubMed: 18197063]
3. Primak AN, Fletcher JG, Vrtiska TJ, et al. Noninvasive differentiation of uric acid versus non-uric acid kidney stones using dual-energy CT. *Acad Radiol.* 2007; 14:1441–1447. [PubMed: 18035274]

4. Stolzmann P, Scheffel H, Rentsch K, et al. Dual-energy computed tomography for the differentiation of uric acid stones: ex vivo performance evaluation. *Urol Res.* 2008; 36:133–138. [PubMed: 18545993]
5. Stolzmann P, Kozomara M, Chuck N, et al. In vivo identification of uric acid stones with dual-energy CT: diagnostic performance evaluation in patients. *Abdom Imaging.* 2010; 35:629–635. [PubMed: 19727931]
6. Boll DT, Patil NA, Paulson EK, et al. Renal stone assessment with dual-energy multidetector CT and advanced postprocessing techniques: improved characterization of renal stone composition—pilot study. *Radiology.* 2009; 250:813–820. [PubMed: 19244048]
7. Qu M, Ramirez-Giraldo JC, Leng S, et al. Dual-energy dual-source CT with additional spectral filtration can improve the differentiation of non-uric acid renal stones: an ex vivo phantom study. *AJR.* 2011; 196:1279–1287. [PubMed: 21606290]
8. Brenner DJ, Hall EJ. Computed tomography: an increasing source of radiation exposure. *N Engl J Med.* 2007; 357:2277–2284. [PubMed: 18046031]
9. Stolzmann P, Leschka S, Scheffel H, et al. Characterization of urinary stones with dual-energy CT: improved differentiation using a tin filter. *Invest Radiol.* 2010; 45:1–6. [PubMed: 19996763]
10. Qu M, Jaramillo-Alvarez G, Ramirez-Giraldo JC, et al. Urinary stone differentiation in patients with large body size using dual-energy dual-source computed tomography. *Eur Radiol.* 2013; 23:1408–1414. [PubMed: 23263603]
11. Morsbach F, Wurnig MC, Muller D, Krauss B, Korporaal JG, Alkadhi H. Feasibility of single-source dual-energy computed tomography for urinary stone characterization and value of iterative reconstructions. *Invest Radiol.* 2014; 49:125–130. [PubMed: 24141741]
12. Thomas C, Patschan O, Ketelsen D, et al. Dual-energy CT for the characterization of urinary calculi: in vitro and in vivo evaluation of a low-dose scanning protocol. *Eur Radiol.* 2009; 19:1553–1559. [PubMed: 19205704]
13. Ascenti G, Siragusa C, Racchiusa S, et al. Stone-targeted dual-energy CT: a new diagnostic approach to urinary calculosis. *AJR.* 2010; 195:953–958. [PubMed: 20858824]
14. Eiber M, Holzapfel K, Frimberger M, et al. Targeted dual-energy single-source CT for characterisation of urinary calculi: experimental and clinical experience. *Eur Radiol.* 2012; 22:251–258. [PubMed: 21847542]
15. Manglaviti G, Tresoldi S, Guerrer CS, et al. In vivo evaluation of the chemical composition of urinary stones using dual-energy CT. *AJR.* 2011; 197:[web]W76–W83.
16. Yu L, Shiung M, Jondal D, McCollough CH. Development and validation of a practical lower-dose-simulation tool for optimizing computed tomography scan protocols. *J Comput Assist Tomogr.* 2012; 36:477–487. [PubMed: 22805680]
17. Duan X, Wang J, Leng S, et al. Electronic noise in CT detectors: impact on image noise and artifacts. *AJR.* 2013; 201:[web]W626–W632.
18. Liu Y, Leng S, Michalak GJ, et al. Reducing image noise in CT colonography: effect of an integrated circuit CT detector. *J Comput Assist Tomogr.* 2014; 38:398–403. [PubMed: 24651744]
19. Schubert G. Stone analysis. *Urol Res.* 2006; 34:146–150. [PubMed: 16477427]
20. Daudon M, Donsimoni R, Hennequin C, et al. Sex- and age-related composition of 10,617 calculi analyzed by infrared spectroscopy. *Urol Res.* 1995; 23:319–326. [PubMed: 8839389]

Fig. 1.
Example dual-energy CT images at different dose levels simulated using noise insertion tool.

A–H, 100kV images at 100% (**A**), 75% (**B**), 50% (**C**), and 25% (**D**) dose levels; 140 kV images at 100% (**E**), 75% (**F**), 50% (**G**), and 25% (**H**) dose levels.

Fig. 2.

Validation of noise-insertion algorithm to simulate three lower dose levels from full-dose raw data for both 100 kV and 140 kV (with tin filter). Percentages on top of bars indicate difference between simulated noise level and theoretically predicted noise level (calculated using inverse square root law between dose and noise level).

Fig. 3.
66-year-old man with renal stones.
A and B, On original full-dose image (**A**), a small stone was characterized as uric acid (*green arrow*), but it was unidentified on image obtained at 50% dose level (**B**).

TABLE 1

Stones Identified for Characterization at the Original 100% Dose Level

Stone Size (mm ³)	Uric Acid	Non-Uric Acid	Total
10	29	80	109
< 10	14	83	97
Total	43	163	206

Note—Data are number of stones.

TABLE 2 Sensitivity and Specificity for Detecting Uric-Acid Stones Using the Default Cutoff Dual-Energy Ratio of 1.13 for All Stones

Parameter	75% Dose Level	50% Dose Level	25% Dose Level
No. of identified stones ^a	203	202	186
Sensitivity (%)	95.1	75.0	79.5
Specificity (%)	97.5	96.3	93.9
Accuracy (%) ^b	95.6	90.3	82.0

^a Some stones were not identified for characterization using the dual-energy software (Syngo Via, Siemens Healthcare) and were excluded from sensitivity and specificity calculations.

^b When calculating accuracy, the unidentified stones were counted as missing stones, using 100% dose images as reference.

TABLE 3

Sensitivity and Specificity for Detecting Uric-Acid Stones Using the Default Cutoff Dual-Energy Ratio of 1.13 for Stones $\geq 10 \text{ mm}^3$

Parameter	75% Dose Level	50% Dose Level	25% Dose Level
No. of identified stones	109	109	105 ^a
Sensitivity (%)	100.0	82.8	89.3
Specificity (%)	98.8	98.8	98.7
Accuracy (%) ^b	99.1	94.5	92.7

^aNote that four stones were not identified for characterization using the dual-energy software (Syngo Via, Siemens Healthcare) at 25% dose level and were excluded when calculating sensitivity and specificity.

^bWhen calculating accuracy, the unidentified stones were counted as missing stones, using 100% dose images as reference.

TABLE 4

Sensitivity and Specificity for Detecting Uric-Acid Stones Using the Default Cutoff Dual-Energy Ratio of 1.13 for Stones < 10 mm³

Parameter	75% Dose Level	50% Dose Level	25% Dose Level
No. of identified stones ^a	94	93	81
Sensitivity (%)	83.3	54.5	54.5
Specificity (%)	96.3	93.9	88.6
Accuracy (%) ^b	91.8	85.6	70.1

^a Some stones were not identified for characterization using Syngo Via software (Siemens Healthcare). They were excluded from sensitivity and specificity calculation.

^b When calculating accuracy, the unidentified stones were counted as missing stones, using 100% dose images as reference.

TABLE 5ROC Analysis of Characterizing Uric-Acid Stones at Different Dose Levels for Stones $\geq 10 \text{ mm}^3$

Parameter	75% Dose Level	50% Dose Level	25% Dose Level
No. of stones	109	109	105 ^a
AUC (95% CI)	1.0000 (1.00-1.00)	0.9924 (0.9848-1.00)	0.9861 (0.9804-1.00)
Dual-energy ratio cutoff	1.13	1.19	1.20
Sensitivity (%)	100.0	89.7	96.4
Specificity (%)	100.0	97.5	97.4
Accuracy (%) ^b	100.0	95.4	93.6

^a Note that four stones were not identified for characterization using dual-energy software (Syngo Via, Siemens Healthcare) at 25% dose level and were excluded from the calculation of sensitivity and specificity.

^b When calculating accuracy, the unidentified stones were counted as missing stones, using 100% dose images as reference.