Low-Dose Computed Tomography in the Evaluation of Urolithiasis

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Introduction

Urolithiasis is common, with the lifetime risk in the United States exceeding 12% in men and 6% in women, and the prevalence appears to have increased in recent years.1,2 In addition, many patients have recurrent stones, with an estimated rate of 30% to 40% within 5 years.1,3 Noncontrast CT is the imaging study of choice in patients with acute flank pain,4 replacing traditionally used radiography, ultrasonography, and excretory urography (EU). CT is highly sensitive for stone detection,5 can be performed rapidly, needs no intravenous iodinated contrast, and is able to identify nonurinary tract pathology.6 Studies have shown a high sensitivity (97%) and high specificity (95%) of CT for stone disease,7 and alternative diagnoses are found in 10% to 24% of patients with acute flank pain.7,8 Unenhanced CT is also increasingly being used for treatment planning and post-treatment surveillance for stone recurrence.6

Medical radiation exposure has increased dramatically from 15% of all radiation to the US population in the early 1980s to 48% by 2006,9 and much of this is attributed to CT scans. Repeated CTs in the diagnosis and follow-up of urolithiasis have raised concerns about excessive radiation exposure and potential radiation-related cancer risk.10 In one study, total radiation dose for examinations within 1 year of an acute stone episode averaged ~30 mSv and exceeded 50 mSv in 20% (the recommended yearly occupational exposure limit).11 The use of CT for flank pain evaluation in the emergency department has increased from 19.6% to 45.5% in the last decade per one report.12 The risk of radiation-induced cancer is highly age-dependent. The estimated mean lifetime cancer risk is 20 cancers per 10,000 single-phase standard dose CT scans of the abdomen and pelvis (median effective dose of 15 mSv) when performed at age 3 compared with only 3/10,000 when performed at age 70.13,14 While techniques have been described to help limit radiation dose to patients, a recent evaluation of the American College of Radiology National Radiology Data Registry found that only 2% of studies performed for renal colic were considered to be “low dose”—i.e., performed with an effective dose of < 3 mSv.15

In this article, we discuss the information provided by CT in the evaluation of urinary stones and strategies to reduce patient radiation dose while maintaining the ability to accurately diagnose and characterize calculi. We also specifically consider the utility of low-dose CT in the obese patient population. There is no precise definition of “low dose” because there is considerable variation between patients and with CT hardware and software improvements leading some to discourage the use of this term.16 The American College of Radiology Appropriateness Criteria considers low-dose CT in the evaluation of stone disease to be <3 mSv,4 while the American Urological Association (AUA) uses 4 mSv as the upper threshold.17

Imaging Features of Urolithiasis

Ultrasonography (US) is an attractive alternative to CT because of the low cost and lack of ionizing radiation and attendant long-term cancer risk. Multiple studies have demonstrated considerably decreased sensitivity and specificity of US compared with CT for detection of both renal and ureteral calculi, particularly for small (<5 mm) stones.18–23 In addition, US has been shown to overestimate stone size, which may have implications for management as discussed further below.21 A 2010 article, however, indicated that a negative renal US for urolithiasis in the emergency department predicts a very low likelihood (0.6%) for urologic intervention, implying that US may miss stones that pass without intervention.24 In addition, a recent trial randomized patients with suspected renal colic presenting to the emergency department to point-of-care US, radiology US, or CT initially. US as a first test was associated with lower cumulative radiation exposure than initial CT without significant differences in high-risk diagnoses with complications, serious adverse events, pain scores, return emergency department visits, or hospitalizations.25 Up to 41% percent of patients who first had US underwent additional examinations during their emergency department visits, however, and overall radiation exposure during the 6 months of the study was 10.1 mSv for patients who first had US and 17.2 mSv for patients who first had CT. These studies suggest that US may be an appropriate preliminary imaging modality in some patients, but more research is needed in this regard.

CT has several advantages over other imaging techniques (i.e., radiography, EU, and US) in the evaluation of urolithiasis, including high speed, no requirement for intravenous contrast material, high sensitivity for the detection of even small stones, and capability to diagnose other extraurinary and urinary abnormalities.4 Not only can CT provide an accurate diagnosis, it can also provide other information that can guide therapeutic decision making, like stone size, stone...

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location, stone composition, and skin-to-stone distance (SSD). Stone burden is most commonly measured linearly, by reporting the greatest dimension of the stone to the closest millimeter, and can be used to plan treatment and predict the rate of spontaneous passage. More recently developed methods of measuring stone volumes, either manually or semiautomatically, are useful for irregularly shaped stones, and are also predictive of outcomes.

Stone composition is an important determinant of appropriate management. For example, urinary alkalization is first-line treatment for patients with uric acid stones, whereas shockwave lithotripsy (SWL) may be difficult with cystine and certain calcium stones. Determination of stone composition can be attempted by CT attenuation measurement, but suffers from overlapping attenuation values between different stone types, particularly those of mixed composition. CT attenuation measurements alone have been most accurate in identifying pure uric acid stones. Dual-energy CT scanners are new equipment that can more accurately differentiate among stone types. While a detailed description is beyond the scope of this article, dual-energy CT involves acquiring CT data at two different x-ray energies (80 and 140 peak kilovoltage [kVp]). Postprocessing software can exploit the variable attenuation properties of stones of diverse chemical compositions at low and high x-ray energies. With dual-energy CT, it is now possible to discriminate between uric acid and other stones, and between struvite stones and cystine stones in vivo.

Finally, SSD is measured from the center of the stone to the skin surface on axial CT images. It has been found to be a reliable predictor of stone-free status after SWL and may suggest the need for alternative treatment strategies, such as ureteroscopic intervention or percutaneous nephrolithotomy.

**Strategies for CT Radiation Dose Reduction**

**Radiation dose measurements and terminology**

A basic knowledge of radiation dose terminology and metrics is needed to understand how CT dose can be optimized. Many scanner settings impact patient radiation exposure. Some of the most important include the product of tube current and time (milliamperes-seconds [mA·s]), peak tube potential (kVp), and pitch (no units). The product of tube current (mA) and time (sec) describes the photon flux and is directly proportional to CT dose. Peak tube potential defines the energy of the x-ray beam; radiation dose is related to approximately the square of tube potential. Therefore, altering kVp has a greater effect on radiation dose than does mAs. Pitch is the ratio of table feed to gantry rotation and is inversely proportional to CT dose. Multiple other scan parameters (i.e., slice collimation) also affect radiation dose but are not often modified for the purpose of reducing dose.

Metrics to quantify patient radiation exposure and dose are many and are not universally reported. CT dose index or CTDI (mGy) is a CT-specific dose measure that is independent of total scan length. The weighted average of CTDI measurements made at the periphery and at the center of a phantom (an object that is scanned to analyze and tune CT performance) is referred to as the CTDIw. Volume CTDI or CTDIvol accounts for different pitch values in helical scanning (CTDIvol/pitch). Finally, the dose length product or DLP (mGy cm) is the product of the CTDIvol and scan length and is a good indicator of the total amount of radiation incident on a patient. Effective dose (mSv) conveys the relative potential for harm or cancer risk from the CT examination. The effective dose can be calculated from DLP by conversion factors (k factors) provided in many reference publications, which have already performed organ-by-organ assessments of dose.

**Modifying scan parameters**

Modifying many CT technical parameters differs from vendor to vendor but, in general, is easily accomplished and can significantly affect radiation dose. Limiting the scan range, particularly on follow-up studies (e.g., scanning only the kidneys to assess residual stone burden after urological intervention), is one of the simplest ways to decrease exposure. Lowering tube potential (kV) reduces dose and improves image contrast, but image quality also decreases, particularly in larger patients, because of an increase in image noise and artifacts. Slice collimation, pitch, table speed, and gantry rotation are all interrelated scan parameters. Keeping other factors (i.e., tube current) constant, thicker collimation, higher pitch, and faster table speed and gantry rotation results in reduced radiation dose. Adjustment to tube current (mA) is the most common strategy to reduce radiation dose and has been the focus of recent literature regarding CT dose reduction in the evaluation of urolithiasis.

Alteration in tube current can be achieved by automated tube current modulation (ATCM) or by using a decreased but fixed tube current. The basic principle of ATCM is that tube current changes based on patient thickness (as determined by the initial CT scout image) as the x-ray tube rotates around the patient and as the patient passes through the CT scanner. ATCM relies on user-defined parameters that differ depending on scanner type, like noise index or a reference tube current-time product (mAs). ATCM is available on all current scanners and is universally used.

Radiation dose savings of up to 40% to 50% can be achieved by using ATCM in adult abdomen-pelvis CT. Elevation the user-defined noise index above the level of 10 to 15 routinely used in CT of the abdomen and pelvis can further reduce radiation dose. In one 2005 study by Kalra and colleagues, the conspicuity of renal stones was evaluated in phantoms and real patients using ATCM with various noise indices vs a fixed tube current. No significant differences in renal stone identification were observed using a noise index of up to 20 to 25 with dose reductions of 56% to 77% in phantoms and 43% to 66% in patients.

Several recent noise simulation studies have demonstrated similar sensitivities and specificities for detection of urolithiasis at doses as low as 25% of conventional CT scans. In these studies, CT raw data was acquired at standard dose, with or without ATCM, and software was used to introduce noise to simulate lower mAs. In a 2009 study by Ciaschini and coworkers, simulated tube current as low as 25% of original tube current (and therefore dose) resulted in no significant difference in sensitivity and specificity for stones >3 mm (Fig. 1). Detection of renal calculi in cadaveric kidneys was also similar with decreased tube current and dose savings of up to a 70% in a 2010 study by Jin and associates.

Finally, several prospective studies enrolled patients with suspected renal colic, and these patients underwent CT
with both decreased tube current (30–100 mAs) and standard (160–260 mAs) protocols. Comparable sensitivity, specificity, and accuracy for diagnosis of urinary tract stones >2–3 mm was demonstrated at a 51% to 81% decreased radiation dose in nonobese patients. Low-dose CT was also similar to standard-dose CT in identifying alternative disease, such as appendicitis and diverticulitis. Accuracy of low-dose CT in the diagnosis of urinary tract stones in obese patients will be specifically discussed later in the article.

**Noise reducing image reconstruction algorithms**

Postprocessing noise reducing solutions include conventional noise reduction filters and iterative reconstruction (IR) based image reconstruction algorithms (Figs. 2–4). These strategies indirectly enable CT dose reduction by enhancing image quality. Noise reduction filters result in a homogenous decrease in image noise across all pixels (picture elements within the image), which reduces image contrast but is less expensive and faster than IR algorithms. Filters can also be used in conjunction with IR synergistically.

IR is an alternative reconstruction algorithm to the traditional filtered back projection (FBP) algorithm. Very long computational times initially limited its utilization, but several generations of IR have been developed by vendors. New partial reconstruction algorithms applied in the projection or image space domain have increased speed enough to make routine use a reality. At a fixed dose, IR improves objective and subjective image quality compared with FBP.

Many recent studies have demonstrated that low-dose CT using IR is comparable to standard-dose CT using FBP. For example, in a 2009 study by May and associates, there was no significant difference in image noise, sharpness, diagnostic acceptability, and lesion conspicuity between full-dose, contrast-enhanced abdominal CT using FBP and half-dose CT using IR. Similar findings of image quality improvement at reduced radiation dose have been shown with low-dose CT using IR in patients with suspected urolithiasis. In a 2014 prospective study by McLaughlin and coworkers, both low-dose and conventional-dose CT were acquired in patients with clinically suspected renal colic.

**FIG. 1.** Axial scans showing increasing image noise with progressive dose reduction. Arrows point to 3 mm and 5 mm anterior mid left renal calyceal calculi. (A) 100% dose; (B) 50% dose reduction; (C) 75% dose reduction. Reprinted from MW Ciaschini, EM Remer, ME Baker, et al. Urinary calculi: Radiation dose reduction of 50% and 75% at CT—effect on sensitivity. *Radiology* 2009 251:105–111, with permission from the Radiological Society of North America (RSNA).

**FIG. 2.** (A) Axial 50% dose scan reconstructed with iterative reconstruction shows no loss in bilateral caliceal calculus detectability compared with B. 100% dose scan reconstructed with filtered back projection.
and data were reconstructed with both FBP and adaptive statistical IR. Low-dose CT with adaptive statistical IR provided a dose savings of nearly 90% of conventional-dose CT and was still able to detect calculi >3 mm with a sensitivity of 87% and specificity of 100%. A study in which seven readers compared 100% exposure CT scans reconstructed with FBP with 50% exposure scans reconstructed with IR in 99 patients found that the lower exposure images were not inferior to the full exposure images for the diagnosis of stones, there was no decrease in reader confidence with lower exposure, there was no significant difference in sensitivity between the two techniques as a function of calculus size, and there was no difference in stone size categorization based on technique.\textsuperscript{51}

Ultra–low-dose CT acquired at an exposure comparable to that of an abdominal radiograph or EU has been shown to be superior in sensitivity and specificity compared with US\textsuperscript{52} and EU\textsuperscript{53} in the detection of urolithiasis. Application of IR-based reconstruction algorithms has enabled CT with a dose of less than 1 mSv to exhibit similar sensitivities and specificities for identification of stones >3 to 4 mm compared with conventional low-dose CT (4.4–6.5 mSv) using FBP.\textsuperscript{49,54} In one study, however, this technique underperformed a low-dose reference standard (3–4 mSv) scans in small (<3 mm) stone detection, detection of secondary signs, and in reader diagnostic confidence.\textsuperscript{55}

A recent meta-analysis included seven studies using low-dose CT (<3 mSv dose applied for entire CT examination) for the diagnosis of urolithiasis. The pooled sensitivity and specificity was 0.966 and 0.949, respectively.\textsuperscript{56} As a result of all the aforementioned research, low-dose (<3 mSv) non-contrast CT is now the preferred imaging modality in patients with acute flank pain and suspicion of stone disease according to the American College of Radiology Appropriateness Criteria.\textsuperscript{4}

At our institution, our low-dose protocol for the evaluation of urolithiasis uses a constant kVp of 120. Automated tube current modulation and a weight-based reference mAs of 0.5 mAs/lb, half that of routine abdominal CT scan, are used. IR is applied when possible but is only available on some scanners at this time.

**Effect of Low-Dose Imaging on Stone Characterization**

The clinical value of characterizing urinary tract stones using low-dose CT has just begun to be studied in the medical literature. In a 2014 study by Alsyouf and colleagues,\textsuperscript{57} low-dose CT at variable mAs resulted in similar attenuation values (as a surrogate for stone composition) compared with conventional-dose CT with only a slight increase in variability. A 2013 study by Sohn and associates\textsuperscript{58} supported this observation, demonstrating no significant difference in measurement of stone size, attenuation, or SSD between low-dose and conventional-dose CT with a marked reduction in radiation dose of 73% (from 23 to 6 mSv).

The new technique for differentiation of urinary calculi with differing compositions, dual-energy CT (Fig. 5), can also be performed at a low dose. In a 2010 study by Thomas and coworkers,\textsuperscript{59} low-dose, dual-energy CT correctly characterized the composition of 38 of 40 urinary calculi with a mean radiation dose of 2.7 mSv, although image quality was decreased in obese patients.
Impact of BMI

Initial studies of decreased dose scanning were limited to patients weighing less than a certain value because of a presumed decrease in image quality in obese patients. Several subsequent studies including a small number of overweight and obese patients (body mass index [BMI] > 30–35) demonstrated decreased sensitivity for detection of ureteral calculi with low-dose CT using fixed tube current, and suggested that conventional CT with higher radiation exposure may be more appropriate in this patient population to achieve adequate image quality. Currently, the AUA suggests a low-dose CT protocol (< 4 mSv) only for patients with a BMI of 30 kg/m² or less.

A few more recent studies that examined low-dose CT using tube current modulation have questioned these findings. Mulkens and colleagues showed that there was no significant difference in sensitivity, specificity, and accuracy.
in standard-dose technique vs low-dose CT applying 4D tube current modulation, even in overweight and obese patients. In a 2014 study by Gervaise and associates, a low-dose CT protocol (using ATCM in addition to IR and low kVp) was used in all included patients with renal colic, including those with a BMI < 25 and BMI ≥ 25. There was no statistically significant difference between accuracy rates of both BMI groups (approximately 96%), but there was a slightly greater exposure for overweight and obese patients (3.7 mGy compared with 2.4 mGy). These studies indicate that it may be possible to obtain adequate diagnostic performance with low-dose CT using ATCM in all patients, including overweight and obese patients.

Conclusion

Low-dose noncontrast CT is the test of choice in identifying and characterizing urinary tract calculi. Decreased exposure is most commonly achieved by modifying tube current and applying new image reconstruction algorithms. Low-dose CT has been shown to maintain diagnostic accuracy compared with standard-dose CT, even in overweight and obese patients when using ATCM.

Disclosure Statement

No competing financial interests exist.

References


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Abbreviations Used
ATCM = automated tube current modulation
AUA = American Urological Association
BMI = body mass index
CT = computed tomography
CTDI = computed tomography dose index
DLP = dose-length product
EU = excretory urography
FBP = filtered back projection
IR = iterative reconstruction
kV = kilovolt
kVp = peak kilovoltage
mA = milliamperes
mAs = milliamperes-seconds
mGy = milligray
mSV = millisievert
SSD = skin-to-stone distance
SWL = shockwave lithotripsy
US = ultrasonography