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Role of Dual-Energy Computed Tomography in Urolithiasis

Shibani Mehra[1]

[1] Department of Radiodiagnosis, RML Hospital, Atal Bihari Vajpayee Institute of Medical Sciences, New Delhi, India

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Address for correspondence Shibani Mehra, Department of Radiodiagnosis, RML Hospital, Atal Bihari Vajpayee Institute of Medical Sciences, New Delhi 110001, India (e-mail: Shibani.mehra@yahoo.in).

Abstract

Objectives The objectives of this study are to describe the role of dual-energy computed tomography (DECT) in evaluation of renal stones in current practice and elaborate the imaging findings that need to be reported to help surgeons make an appropriate management strategy for renal stones.

Background Nephrolithiasis is a global problem, affecting people across geographical, cultural, and economic boundaries. Renal stones can be accurately diagnosed on computed tomography.

Discussion With the development of DECT, renal stones can now be better characterized in terms of stone burden, stone composition, and stone fragility.

Conclusion These parameters are helpful to treating surgeons in not only planning an appropriate management for patient but also in predicting the success of the various procedures such as extracorporeal shock wave lithotripsy, flexible ureterorenoscopy, or percutaneous nephrolithotomy. Familiarity with recent developments will help radiologists give an apt description of renal stone to meet the requirements of treating surgeon.

Keywords
- dual-energy ratio
- dual-energy computed tomography
- linear attenuation coefficient
- nephrolithiasis
- skin-to-stone distance
- stone attenuation value
- stone burden
- stone fragility

Introduction

Dual-energy computed tomography (DECT) is an exciting upgradation of contrast-enhanced computed tomography (CECT) technology that has given a new advantage to the radiologist in image interpretation. DECT with acquisition of two separate keV utilizes a second X-ray spectrum to decipher the elemental composition of materials in the body part being imaged.[1] Nephrolithiasis is a global problem and is seen to occur irrespective of geographical, cultural, and economic boundaries. There has been a rise in incidence nephrolithiasis worldwide.[2] The accuracy of CT in diagnosing renal stones is very high. However, the challenge faced in differentiating substances that produce significant attenuation of the beam is significant using single-energy CT technology, which relies on linear attenuation coefficient of different materials. Familiarity with recent CT developments will help radiologists to report appropriate findings that have clinical importance, in patients with renal stones, to aid in treatment planning and patient management.

Materials and Methods

This was a prospective cross-sectional study that included 36 patients of renal stones in their preoperative evaluation period. DECT was performed using a dual-energy helical scan mode with a 128-slice dual-source CT (Siemens Somatom Definition Flash) scanner. Initially unenhanced low-

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dose CT scan of the entire abdomen and pelvis in supine position was done. After localizing the renal stone, targeted dual-energy scanning of the anatomic region containing the stone was performed. Concurrent scanning at two different energies (80 and 140 kVp) was done and the resulting data reconstructed with the available software program. The sensitivity, specificity, and diagnostic accuracy of DECT in evaluating renal stones were found to be 95, 96, and 98%, respectively, in our study.

Discussion

Renal Stone Burden is an important parameter that determines how nephrolithiasis will be treated. CT has a high sensitivity in detection of renal stones and has also been useful in diagnosing the complications of renal nephrolithiasis.[3] Indications for surgical intervention include urosepsis, bilateral stones with obstruction, obstructing stone in a single kidney, infection in presence of urinary tract obstruction, impending acute renal failure, or intractable pain and vomiting.[4] The treatment options include medical expulsive therapy, flexible ureteroscopy, percutaneous nephrolithotomy (PCNL), or extracorporeal shock wave lithotripsy (ESWL). PCNL results in higher stone-free rates and lower retreatment rates than shock wave lithotripsy that is relatively noninvasive.[5] However, because it is more invasive, PCNL is usually reserved for patients in whom shock wave lithotripsy fails or those who are unsuitable for lithotripsy.

Knowledge of the composition of urinary tract stones is also a fundamental part of the preoperative patient evaluation, as this information influences treatment strategy, as well as prevention of recurrence. Mass density of the material is used to characterize various tissues on CT. The disadvantage of single-energy monoenergetic CT technology is that linear attenuation coefficient of materials is used to differentiate among different materials. As different materials can have the same linear attenuation, this unit is not unique for any element, and therefore not useful in detecting the exact composition of materials. Moreover, it varies with the power and kilovoltage of interacting photons.[6] CT

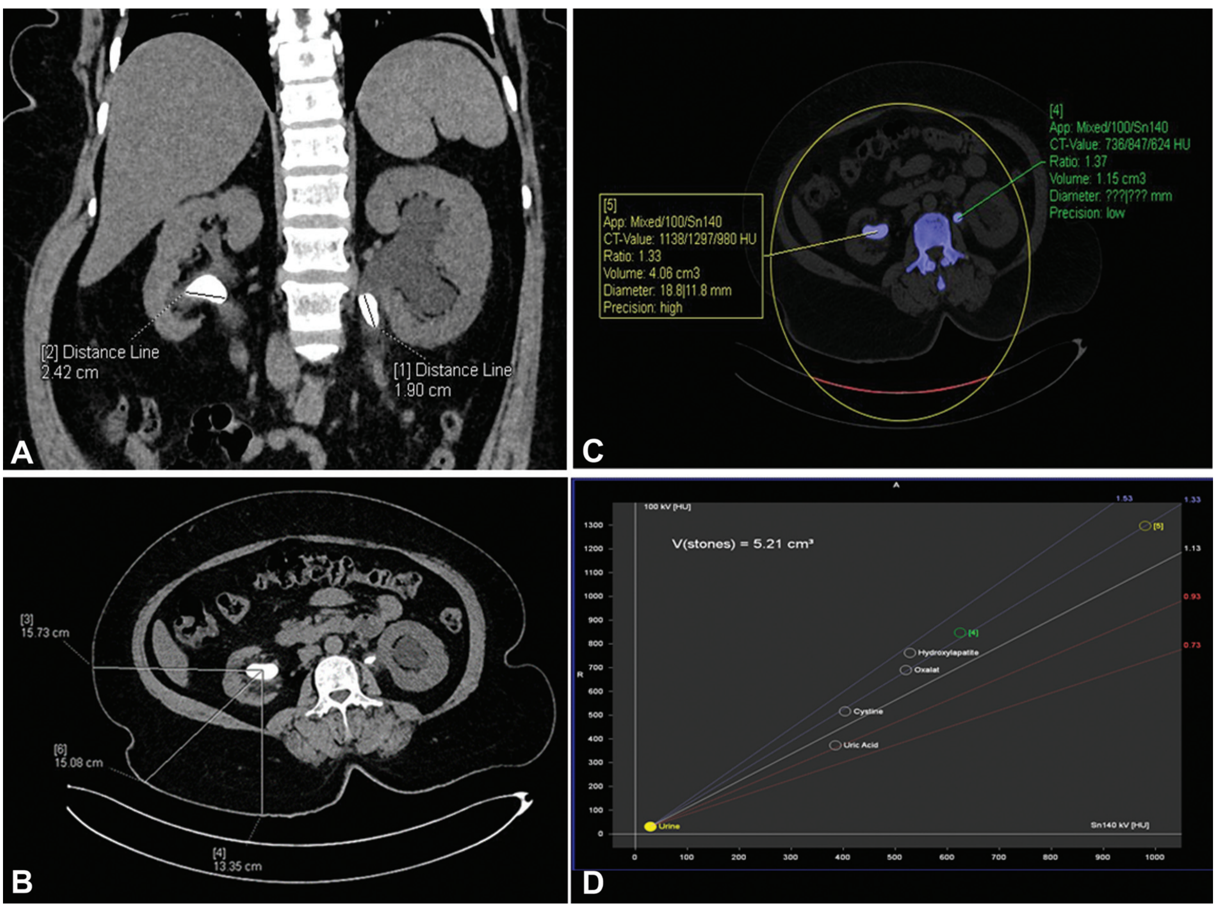

Fig. 1 (**A**) Stone burden assessment—measurement of size of the calculus by including the maximum dimension in the horizontal or vertical plane. Calculus in the right pelvis measures 2.42 cm, while calculus in the left proximal ureter measures 1.9 cm. The right renal calculus is located at upper border of L3 vertebral body, while left ureteric calculus is extending from slightly below the upper border to lower border of L3 vertebra. Hydronephrosis is seen in left pelvicalyceal system, while the calculus in the right renal pelvis is causing caliectasis. (**B**) Assessment of exact location of the stone—the calculus in right kidney is seen contouring the pelvicalyceal system, while calculus in proximal left ureter is associated with hydronephrosis upstream. Left periureteric fat stranding can be appreciated, indicating inflammation of ureteric wall by the obstructing calculus (a sign of pelvicalyceal obstruction). (**C** and **D**) Dual-energy computed tomography (DECT) color overlay image and DECT ratio graph analyzing the stone composition—DECT ratio of 1.33 (right kidney) and 1.37 (left proximal ureter) deciphers the chemical composition and shows these to be calcium oxalate calculi.

scanners that use monochromatic radiation are thus unable to provide the structure and density of materials encountered.

Of all the technologies available, DECT is currently the most successful for achieving element decomposition. Since DECT acquisitions are at two different energy levels, the second attenuation measurement is made at a differing tube potential, in fact at a lower energy spectrum, which enables quantification of composition of elements that have similar electron densities but varying photon absorption, thereby providing differentiation between materials.[7] This is especially useful for materials with similar beam attenuation but different atomic numbers, such as iodinated contrast material and calcium. In renal stone evaluation, this ability of DECT is again extremely useful to identify chemical composition of stones and give preoperative analysis differentiating calcium containing stones, separate from cystine stones.[8]

Element decomposition capability of DECT is useful in renal stone characterization. The elements contributing to formation of renal stones are calcium, oxalate, urate, cystine, xanthine, and phosphate, with maximum renal stones being of calcium oxalate/phosphate composition (80%); 5 to 10% are uric acid stones, 5 to 15% are struvite, that is, magnesium ammonium phosphate stones; 1% are cystine stones; and xanthine, guaifenesin contribute 1% of chemical composition of urinary stones.[4] Dual-source CT uses two independent X-ray tubes, mounted in the same gantry positioned orthogonal to each other, each X-ray source having its own detectors and own high voltage generator. Each X-ray source is operated at a different tube potential and tube current value. The key technical aspect of DECT is simultaneous acquisition at different tube potentials, prior to table incrementation to reduce motion artifacts. The dual source enables superior image quality due to spectral separation by spectral filtration for each tube detector pair. This allows for higher signal to noise ratio and better image quality. Another advantage of dual-source CT is effective utilization of scatter generated from one tube being detected by the orthogonally placed second tube and reduction in spectral separation. Thus, material decomposition is achieved with little loss of temporal or spatial resolution.[9] Beam hardening artifact reduction is achieved by use of projection data acquired at two tube energies. Composition of renal stone can be assessed on DECT to differentiate between calcium-containing stones and uric acid stones, as for both types of stones different management principles are followed.

The characteristics of renal stone that are considered before selecting a treatment approach for renal calculi by the urologist are the stone size, number, location in the calyx, and composition, along with renal anatomy and the clinical factors. These parameters are helpful for treating surgeons in not only planning an appropriate management for patient but also in predicting the success of the various procedures like ESWL, flexible ureterorenoscopy, or PCNL.[10]

DECT enables better characterization of renal stones in terms of stone burden, stone composition, and stone fragility. On DECT, we begin with assessing the stone burden. The simplest and most common method of assessing stone burden is measurement of stone size. The greatest dimension of the stone is measured to the closest millimeter at CT (►**Fig. 1A–C**). Measurement of stone size at CT helps to accurately predict the rate of spontaneous passage of renal and ureteral stones. Symptomatic or asymptomatic small renal stones that are 6 to 8 mm in diameter can either be treated by ESWL or retrograde flexible ureteroscopy, if medical management does not work.[11] Most simple renal calculi (80–85%) with a stone burden of <1.1 cm (aggregate diameter) and normal renal anatomy can be treated successfully with shock wave lithotripsy. However, lithotripsy may fail or be less effective when stones are larger; stones are located in dependent or obstructed parts of the collecting system; stones are made up of calcium oxalate monohydrate, brushite, or cystine; the patient is obese or has a body build that inhibits proper imaging; or it is difficult to target the stone for shock wave delivery and subsequent fragmentation.[12] Smaller stones and those with lower mean Hounsfield unit (HU) levels are more successfully fragmented with ESWL. Patients with larger stones should preferentially be treated with PCNL or ureteroscopy.

The location of stone in the pelvicalyceal system is equally important to assess. One of the essential steps for successful percutaneous access while performing PCNL is localization of the posterior calyx. Stones located in posterior calyces are more amenable to removal by PCNL. CT assists in the preintervention selection of an appropriate calyx for percutaneous access and helps ascertain a safe path for puncture by depicting the relationship of the kidney to various surrounding organs such as the spleen, liver, and colon. Location of the stones should be reported both at the lumbar spine level, the stone is located at, and the calyx it is involving (►**Fig. 2A, B**). Renal pelvic/ureteropelvic junction stones have a better clearance than calyceal stones on ESWL. Similarly, upper or middle calyceal stones are fragmented and cleared better than those in lower pole calyces.[13] Coronal reformatted images are useful to differentiate between calculi and other calcium containing structures such as calcified lymph nodes.

DECT assists in analyzing the stone composition as knowledge of the composition of renal stone beforehand is crucial for planning management strategy for the patient.[14] Uric acid calculi are amenable to medical management (►**Fig. 2C–E**). Uric acid stones can be dissolved medically with urinary alkalinization therapy using oral potassium citrate solution or allopurinol.[15] Success of ESWL depends on stone composition that affects the type of fragments produced on decomposition of the calculus. Denser calculi made of calcium phosphate or cysteine are resistant to breakage by ESWL and require surgery. Calcium-based stones include calcium oxalate monohydrate, calcium oxalate dihydrate, and calcium phosphate stones. Calcium oxalate monohydrate, struvite, calcium oxalate dihydrate, and uric acid stones have a firm composition that may limit the success of ESWL. Cystine and calcium oxalate monohydrate calculi are resistant to fragmentation and are treated by ESWL only when the stone burden is smaller than <1.5 cm.[16] Stones composed of brushite and cystine are the most resistant to ESWL and

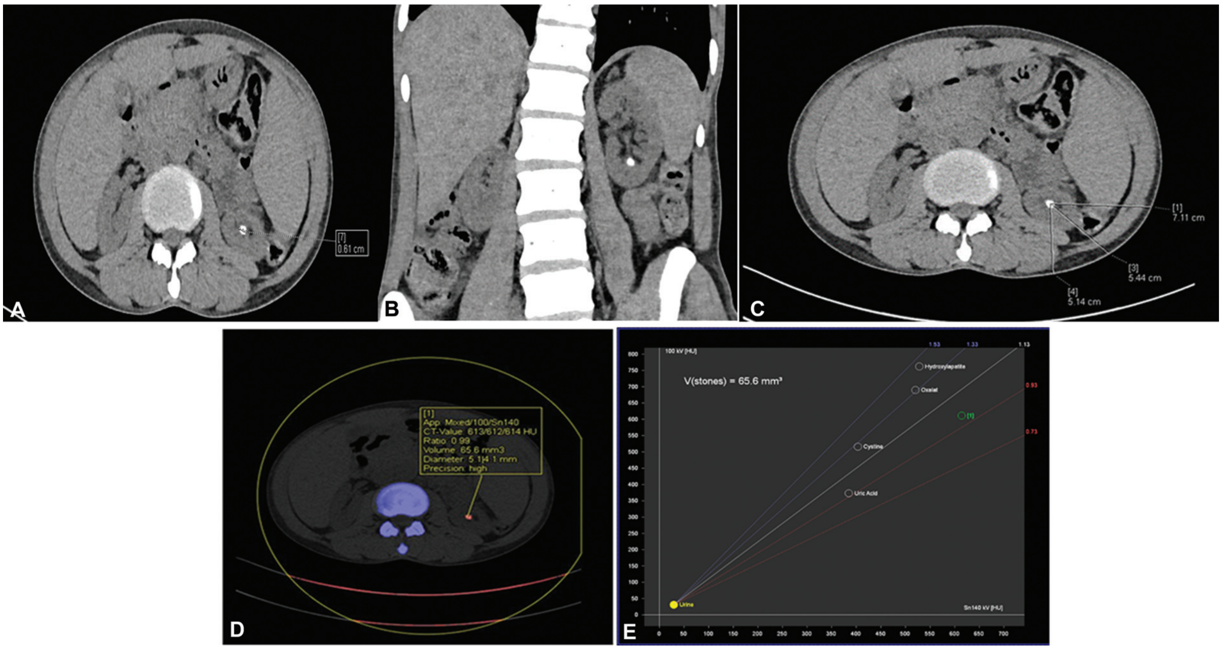

Fig. 2 (**A** and **B**) Measurement of stone burden and assessment of location of calculus—A 0.81 cm calculus is seen in the lower pole calyx of left kidney. The calculus lies at L3 lower body level, adjacent to the L3-L4 disc. There is no hydronephrosis. (**C**) Stone to skin distance—measurement is obtained at three different angles, both, up to the lateral abdominal wall and posteriorly as this information is useful in therapeutic management. (**D** and **E**) Stone composition analysis using dual-energy (DE) ratio—this is a uric acid stone with DE ratio of 0.99. Ratios below 1.1 are characteristic of uric acid stones.

warrant alternate treatment options. Patients with larger stones should preferentially be treated with PCNL or ureteroscopy and not ESWL.[17]

Dual-energy ratios (DE ratios) are used to differentiate between calcium-based stones and uric acid stones. DE ratios obtained in a graphical format are the highlight of DECT equipment in urolithiasis imaging. The DE ratios are obtained by dividing the attenuation value of the calculus at 80 kV by its attenuation value at 140 kV. DE ratio greater than 1.24 is characteristic for calcium containing stones[18] (►**Fig. 1D** and E). Pure calcium oxalate monohydrate calculi have significantly lower DE ratio compared with mixed calcium calculi. The ratio is 1.1 or less for uric acid stones (►**Fig. 2D** and E). Calcium monohydrate and dihydrate calculi show DE ratios above 1.4 (►**Fig. 3A–D**). DE ratio for cysteine stone ranges between 1.1 and 1.24 (►**Fig. 4A–C**). Calcium oxalate monohydrate and dihydrate calculi cannot be differentiated from each other as the DE ratios of these two minerals are almost similar in the 1.5 range.[19] Of the calcium containing calculi, calcium apatite stones have the highest DE ratios that remain at 1.6 and above. Struvite stones have DE ratios of 1.2 to 1.3 that overlap somewhat with those reported for calcium containing stones. DE ratios with cutoff values of 1.12 for uric acid, 1.34 for struvite, and 1.66 for calcium oxalate, and carbonate apatite calculi have >80% sensitivity and specificity to differentiate among these calculi ($p < 0.001$).[20] DECT at low energy is thus very useful to get the mineral composition in urolithiasis. The DECT color

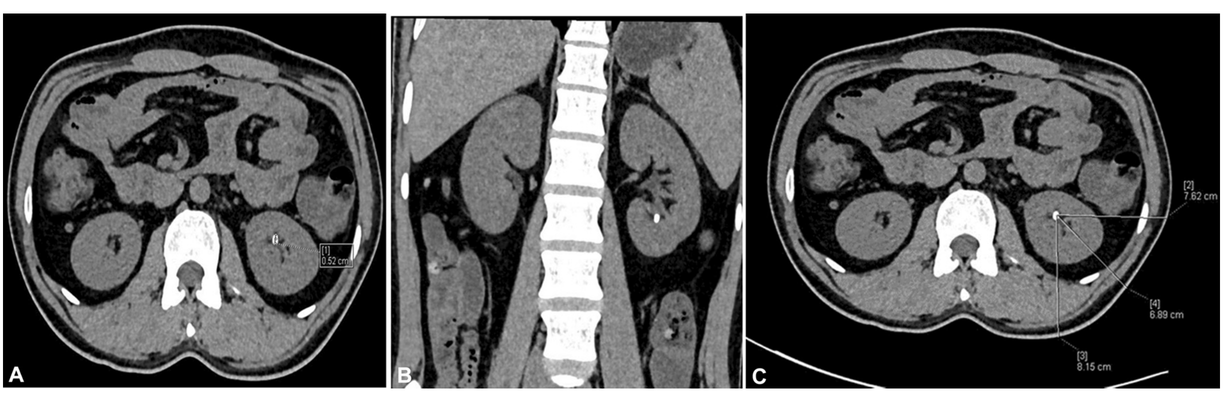

Fig. 3 (**A** and **B**) Stone size measurement using radiographic calipers and location assessment in a patient of renal colic—the coronal image is essential to show the vertebral body level corresponding with the calculus. (**C**) Skin to stone distance measurement—this is an essential part of the radiology report being a highly specific factor in determining success of both extracorporeal shock wave lithotripsy and percutaneous nephrolithotomy. (**D** and **E**) Stone composition analysis—using dual-energy (DE) ratio, this calculus is found to be of calcium hydroxyapatite composition, with a DE ratio of 1.43.

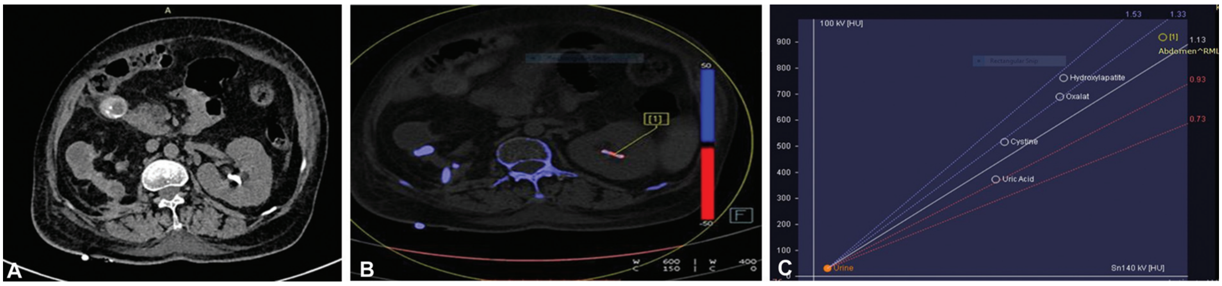

Fig. 4 (A–C) Dual-energy computed tomography (DECT) plain and color overlay image with DECT ratio graph of left renal calculus—DE ratio of 1.13 helps to analyze the chemical composition of this calculus and diagnoses it to be a cystine calculus.

overlay is also useful in coloring stones of varying composition with different color hues. The DECT ratio graph displays the mean attenuation value of calculi on the right-hand side, while the ratio is reflected on the left side. Higher attenuation values of the order of 900 and above are seen with calcium containing calculi, while uric acid calculi show attenuations of 400 HU (►**Fig. 1E**).

Identifying uric acid calculi with the help of DE ratios can change patient management. Patients with familial metabolic diseases tend to benefit from DECT. This is especially so for patients suffering from cystinuria, who develop renal calculi that are composed of cystine. These can be treated medically using captopril, and more invasive treatments such as ESWL or PCNL, which are both expensive and have potential complications including renal hemorrhage, fibrosis, or hypertension, can be avoided in these patients.[21]

Stone fragility is another important parameter that a urologist needs to know before planning the therapeutic technique.[22] Stone fragility can be determined on DECT by measuring the attenuation value of stone in terms of HU.[23] This stone attenuation value is an independent predictor of the success of ESWL. Stone attenuation values (SAV) > 900 HU is a significant predictor of the failure of ESWL. Patients with a SAV 956 HU are not ideal candidates for ESWL.[24] In patients with a SAV of 500 to 1000 HU, factors like a body mass index of $>30\,kg/m^2$ and a lower calyceal location further contribute to making them unfit candidates for ESWL.[25] The worst outcomes of ESWL are seen with a SAV >750 HU and a stone diameter >1.1 cm.[26]

The next step for the radiologist is to assess on DECT maps is whether the stones are homogenous or heterogenous in composition. Heterogeneity in stone composition renders a stone susceptible to fragmentation with treatment and hence warrants a mention in report, so that the urologist can target these stones with ESWL. Homogeneous stones, cystine stones as well as calcium-stones of certain attenuation, are extremely difficult to fragment with ESWL.[27]

The final aspect of relevance in therapeutic planning of urolithiasis that must be mentioned is the "skin to stone distance" (SSD).[28] Measurements are taken at 0 degree, 45 degrees, and 90 degrees using standard calipers from the toolbox (►**Figs. 1C**, **2C**, **3C**). Higher stone free rates and ESWL success rates are found with a shorter SSD among calyceal stones. Median SSD (125 mm; range: 81–165 mm) is associated with successful ESWL treatment, whereas a mean SSD (141 mm; range: 108–172 mm) is associated with ESWL treatment failure. SSD is a parameter that correlates better with treatment outcome ($p < 0.001$), like body mass index which correlates with a ($p = 0.008$), unlike mean attenuation value of the stone that has shown ($p = 0.37$).[29] It is important to know that SSD greater than 10 cm often results in failure of ESWL.

After describing the stone characteristics, the radiologist must proceed to assess and determine signs of obstruction namely hydroureter, hydronephrosis, perinephric stranding, or unilateral renal enlargement (►**Fig. 1A, B**). Stones greater than 6 mm in diameter in the proximal ureter accompanied by more than five secondary signs of obstruction are more likely to necessitate intervention such as endoscopic removal or lithotripsy than are those with fewer secondary signs.

Image space reconstruction is a special advantage with DECT. Monoenergy images acquired from each X-ray source can be used to get conventional poly energetic images (like those acquired by single-source CT). Another dataset that can be achieved is virtual noncontrast images obtained after removing the CT numbers of iodine, to simultaneously get noncontrast images without exposing patient to radiation dose of an additional noncontrast CT scan. These virtual noncontrast-enhanced images are useful for genitourinary kidneys, ureters, bladder scans. Iodine voxels are identified and removed from the images obtained after injecting iodinated contrast to get noncontrast scans, which allow stone identification as well as contrast-enhanced scans that allow evaluation of pelvicalyceal system.[30]

Conclusion

DECT as a modality has the potential to revolutionize the surgical approach to renal stones. It is essential for radiologists to know the benefits of DECT technology so that they can provide adequate information to the treating surgeons for a holistic treatment plan to be formulated for the patient, since stone size, mean HU, composition, and location are all predictors of ESWL fragmentation success, and in deciding whether PCNL or flexible ureteroscopy ought to be the therapeutic choice.

Conflict of Interest
None declared.

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