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ORIGINAL PAPER

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Determination of the chemical composition of urinary calculi by noncontrast spiral computerized tomography

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Abstract Various techniques for noncontrast spiral computerized tomography (NCCT) were utilized for the determination of the Hounsefield unit (HU) values of various types of urinary calculi with the aim of determining the best technique for distinguishing various stones compositions. A total of 130 urinary stones, obtained from patients who underwent open surgery, were scanned with a multidetector row scanner using 1.25 mm collimation at two energy levels of 100 and 120 kV at 240 mA. Two post-scanning protocols were used for the HU value assignment, tissue and bone windows, for both kV values. In both protocols, three transverse planes were defined in each stone, one near the top, one in the middle, and one near the bottom. Three regions of interest (ROI) were obtained in each plane. The absolute HU value was determined by three methods: the mean of the nine ROI, the mean of the central three ROI, and the central ROI in the middle plane. Determination of the stones' composition was performed using the absolute HU value measured at 120 kV, the dual CT values (HU values at 100 kV−HU values at 120 kV), and HU values/stone volume ratio (HU density). All stones were analyzed by x-ray diffraction to determine their chemical composition. After the exclusion of groups with few calculi, 47 pure stones [25 uric acid (UA), 15 calcium oxalate monohydrate (COM), seven struvite], and 60 mixed stones [15 COM 60–90% + hydroxyl apatite (HA), 14 COM 40–90% + UA, 21 UA + COM <40%, ten mixed struvite + COM + hydroxyl apatite] were included in the statistical analysis. From the least to the most dense, the pure stone types were UA, struvite, COM. Mixed UA + COM <40% calculi were less dense but insignificantly different from pure UA, while when the COM ratio was ≥40% their density became higher than and significantly different from pure UA, and less than but not significantly differentiated from pure COM. Mixed COM + HA were the most dense stones. Using the absolute HU values at 120 kV and HU density, we could distinguish, with statistical significance, all pure types from each other, pure UA from all mixed calculi except UA + COM <40%, pure COM from mixed UA + COM <40%, and pure struvite from all mixed stones except mixed struvite stones. Dual CT values were not as good as absolute HU values and HU density in the determination of stone composition. These results demonstrate that absolute HU values and HU density derived from CT scanning using a small collimation size could uncover statistically significant differences among all pure and most of the mixed urinary stones. This permits more accuracy in the prediction of stone composition. Moreover, this technique permits diagnostic conclusions on the basis of single CT evaluation.

Keywords Calculi · Tomography · X-ray computed · Urinary tract · Composition

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Introduction

Recently, the use of noncontrast spiral computerized tomography (NCCT) has gained widespread acceptance in the evaluation of urinary stone patients. It has long been used clinically to evaluate the causes of radiolucent filling defects using Hounsfield units (HU) to distinguish calculi from tumor or blood clots, and to identify nonurologic causes of flank pain [1, 2, 3]. Urinary stones have a significantly higher CT attenuation than the surrounding soft tissues and are virtually always visible on NCCT [2, 3, 4, 5].

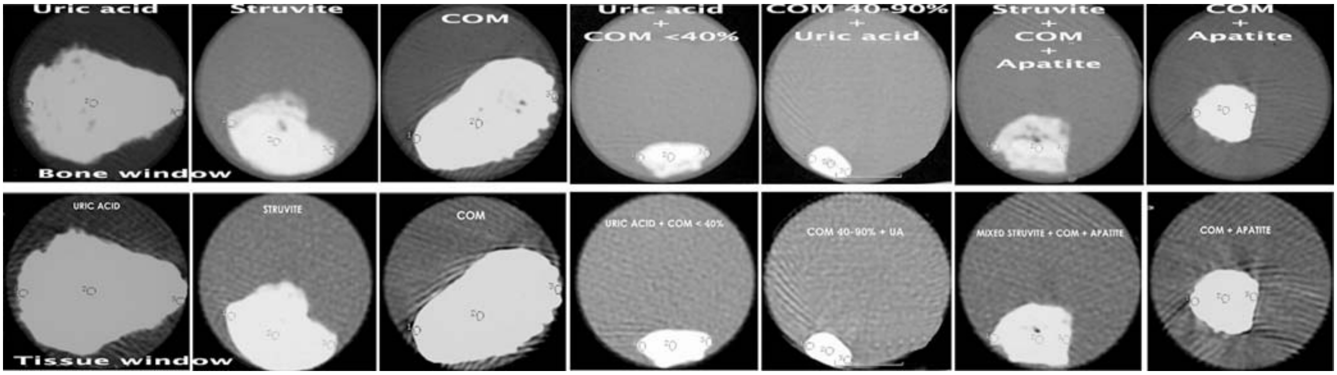

Fig. 1 Helical CT of the stones showing the plane passing through the widest transverse diameter of the stone with the selected three ROI, and viewed with two window settings, bone window (upper row) and tissue window (lower row)

Knowing the composition of a urinary calculus is frequently a key factor in determining its most appropriate management. Should the urine be alkalinized? Will the stone be amenable to extracorporeal shock wave lithotripsy (ESWL), or should ureteroscopy or percutaneous lithotripsy be attempted? Different techniques have been used to assist in determining the correct chemical composition of calculi. Urine pH, urinary crystals, prior stone history, the presence of urea-splitting organisms, and plain radiography are tools which might be used to infer stone composition [6]. Several in vitro studies have suggested that NCCT can demonstrate measured differences in radiodensity among different urinary stones [7, 8, 9]. With these clinical problems in mind, we sought to determine whether the composition of urinary calculi could be predicted by their in vitro CT characteristics in an attempt to find out the best technique for distinguishing the various stones' compositions, provided that it is clinically practical and would not require repeated imaging of the patients.

Materials and methods

A total of 130 renal stones obtained from patients who had undergone pyelolithotomy or nephrolithotomy at our center were included in the current study. Each calculus was immersed in distilled water in a 60 ml hypodermic tube and held firmly at the middle of the tube by two plungers, one above and one below. Every three tubes were fixed to the CT scanner table with the axial position was adjusted such that a single transverse plane passed through the widest part of the stones.

The calculi were scanned with a multidetector row scanner (light speed plus; GE Medical Systems, Milwaukee, Wis.) using 1.25 mm collimation at two energy levels of 100 and 120 kV. The mA were kept constant at 240. All images were reconstructed on a 512×512 matrix using a zoom factor of two, and stored for subsequent evaluation by the staff radiologist who was blinded to the chemical composition of the calculi. Two post-scanning protocols were used for HU value assignment, tissue window (width 350, level 50) and bone window (width 1,200, level 200), for both kV values. Three transverse planes were defined in each stone, near the top, near the bottom, and a plane passed through the widest transverse diameter of the stone. Three regions of interest (ROI) were obtained for each plane (one central and two at the periphery) for tissue and bone windows at 100 and 120 kV (Fig. 1). The mean size for the ROI was 1.3 ± 0.3 mm^2. The absolute HU value of each stone is presented by three methods; the mean of the nine ROI, the mean of the central three ROI, and the central ROI of the plane that passed through the maximum transverse diameter. Distinguishing the chemical composition of the various stones was performed using the absolute HU value measured at 120 kV, and the dual CT values measured by subtracting the corresponding HU values at 120 kV from the HU values at 100 kV, in tissue and bone windows separately.

All stones were analyzed by the Central Laboratories of the Egyptian Geological Survey and Mining Authority (Cairo, Egypt) using a Philips x-ray diffraction apparatus (PW/1710) with Ni-filter, Cu-radiation ($\lambda = 1{,}054.2$ nm at 40 kV, 30 mA and scanning speed 0.02 s. The analysis reported an inner and outer stone composition as a fraction of the components present and then identified the composition of any nidus. Then, all were averaged to determine the overall stone composition. Stones composed of 97% or more single component were considered pure.

Statistical analysis

Independent sample Student's *t*-test was used for comparison of the absolute and dual HU values of the different types of calculi in both post-scanning protocols. Pearson correlation was used to determine the correlations between different HU values and stone volume. Results were considered significant when $P < 0.05$.

Results

The calculi were classified into groups according to their chemical composition. The groups with few calculi were excluded from the statistical analysis. There were two calcium oxalate dihydrate stones, three calcium carbonate, two cystine, three mixed uric acid and apatite, three mixed struvite and apatite, five with a mixture of three components with variable ratios, and five with a mixture of four components with variable ratios.

A total of 107 calculi were included in the statistical analysis. There were 47 pure stones [25 uric acid (UA), 15 calcium oxalate monohydrate (COM), seven struvite], 60 mixed stones composed of two components [15 COM 60–90% + hydroxyl apatite (HA), 14 COM 40–90% + UA, 21 UA + COM < 40%], and ten mixed struvite + COM + apatite stones.

The stone volume ranged from 47 to 10,597 mm^3. However, there were no significant differences in stone volume among the different groups except between pure struvite (3,341 ± 1,007 mm) and each of the following: pure UA (1,670 ± 1,971 mm) ($P = 0.006$), mixed COM 60–90% + UA (1,159 ± 1,783 mm) ($P = 0.008$), and mixed UA + COM < 40% (1,332 ± 1,201 mm) ($P = 0.001$).

The HU values for different types of calculi are shown in Table 1. From the least to the most dense, the pure stone types were UA, struvite and COM. We observed that mixed UA + COM stones in which COM was less than 40% had HU values slightly less than those of pure UA stones, yet this was not significant. As the COM ratio increased, the HU values increased to become significantly more than that of pure UA, but were still lower than, but not significantly different from, those of pure COM. Mixed struvite + COM + HA stones had HU values higher than pure COM or struvite. Mixed COM + HA had the highest HU values.

The highest absolute HU values at 120 kV were those derived from the mean of the ROI at the center of each plane. The highest of these were those at the center of the plane passing through the widest diameter of the stone (center of the stone). Also, the absolute HU values of the bone window protocol were higher than those of the tissue window protocol.

Table 2 represents the P values for the differentiation of stone composition using the absolute HU values at 120 kV in both tissue and bone window protocols. Using both protocols, UA based calculi (UA and mixed UA + COM < 40%) could be differentiated from all other types ($P < 0.05$), regardless the stone volume, but not from each other ($P > 0.05$). Using the bone window protocol, COM based calculi (pure COM, COM + HA, COM ≥40% + UA) and pure struvite calculi were differentiated from UA based calculi ($P < 0.05$) but not from each other or mixed struvite + COM + HA calculi ($P > 0.05$). Using the tissue window, the results were similar to those of the bone window but we could differentiate between COM + HA and COM ≥40% + UA ($P = 0.007$).

Dual CT values could differentiate pure UA from mixed COM + HA ($P = 0.01$), and pure struvite from mixed COM + HA in the bone window only, and pure struvite from mixed UA + COM < 40% ($P = 0.009$) in the tissue window only. It could differentiate mixed

Table 1 Absolute HU values of stones at 120 kV

Type	n	Tissue window			Bone window		
		All nine, ROI	Central three ROI	ROI of the stone center	All nine, ROI	Central three ROI	ROI of the stone center
Pure UA	25	443.5 ± 192	548 ± 348	688 ± 377	704 ± 351	695 ± 376	810 ± 457
Pure COM	15	530 ± 202	809 ± 288	1,235 ± 442	857 ± 310	1,130 ± 413	1,375 ± 468
Pure struvite	7	586 ± 206	804 ± 364	1,152 ± 369	1,015 ± 298	1,008 ± 381	1,301 ± 410
COM + HA	15	614 ± 238	980 ± 272	1,544 ± 507	973 ± 388	1,273 ± 468	1,534 ± 590
COM ≥40% + UA	14	540 ± 129	724 ± 201	1,100 ± 390	975 ± 340	971 ± 325	1,163 ± 541
UA + COM < 40%	21	429 ± 202	490 ± 259	671 ± 334	641 ± 286	661 ± 331	759 ± 338
Mixed struvite + COM + HA	10	595 ± 165	861 ± 196	1,350 ± 482	874 ± 108	1,250 ± 390	1,459 ± 467

Table 2 Stone determination by absolute HU values of the stone center ROI at 120 kV. The P values for the independent sample t-test are given. $P < 0.05$ indicates a significant difference

		Tissue window						
		UA	COM	Struvite	COM + Apatite	COM 40–90% + UA	UA + COM < 40%	Mixed struvite + COM + apatite
Bone window	UA		0.000	0.01	0.000	0.003	0.8	0.000
	COM	0.001		0.7	0.09	0.4	0.000	0.6
	Struvite	0.02	0.7		0.06	0.7	0.003	0.3
	COM + HA	0.000	0.4	0.3		0.01	0.000	0.3
	COM ≥40% + UA	0.04	0.3	0.5	0.09		0.002	0.2
	UA + COM < 40%	0.7	0.000	0.002	0.000	0.01		0.001
	Mixed struvite + COM + HA	0.002	0.7	0.4	0.7	0.2	0.001	

COM + HA from mixed UA + COM < 40% in both windows. All of these types could be differentiated by absolute HU values at 120 kV. However, other types could not be differentiated using the dual CT values.

The best absolute HU values for differentiation are those derived from ROI in the center of the stone and those derived from the average of the three central ROI. Both of these were better at distinguishing different chemical compositions of calculi than either the mean of the nine ROI or the dual CT value.

Aiming at the differentiation of more types, we repeated the statistical analysis factoring in the effect of stone volume on radiodensity. Nevertheless, there were no significant differences in stone volume between most of the undifferentiated types. In addition, there were no significant correlations between the stone volume and HU values except for UA + COM < 40% calculi in both the bone and tissue windows ($r=0.8$, $P=0.000$), which were differentiated from most types regardless the stone volume, and pure struvite calculi in the bone window only ($r=0.8$, $P=0.04$). The ratio of the mean HU values of the three central ROI to the stone volume was used for differentiation and termed HU density. Using this method, pure struvite calculi could be differentiated from all other types ($P<0.05$) except for mixed struvite + COM + HA ($P>0.05$) as shown in Table 3.

Discussion

Upper urinary tract calculi are a common problem in daily urological practice, and ESWL is now considered the treatment of choice for most of them. However, ESWL may not be a cost-effective option compared with other available treatments, as, in some cases, the optimum fragmentation of the stones is not possible even after three or four sessions, and an alternative treatment is required. Stone fragmentation is difficult to assess prior to treatment. Thus there appears to be a need for a method which could help to predict stone fragility at the beginning of the treatment plan.

There is considerable interest in using radiologic imaging to predict kidney stone fragility before treatment. NCCT is currently the preferred method for investigating suspected renal colic, and may be used to identify stone composition [2, 3, 5, 7, 8, 9, 10]. The technique of CT scanning plays a role in measuring the HU values of urinary stones, specifically the size of collimation [11]. Saw et al. [11] found that scanning stones that were smaller than the size of collimation subjected them to partial volume inaccuracies which had an impact on the measured HU values. They concluded that using a smaller collimation size permitted better accuracy in the prediction of stone composition. Another parameter in the CT technique is dual energy scanning in which the differences in radiodensity observed by scanning stones at different energies are used for determination of their compositions [7, 8].

In the present study, various CT techniques were utilized in an attempt to determine the best method for distinguishing various compositions, provided that it was clinically practical and would not require repeated imaging of the patients. The stones were scanned at 1.25 mm collimation. In other in vitro studies, 1 mm [8], 2 mm [5, 7], and 5 mm collimations [12] were used. Using the absolute HU values at 120 kV, we could differentiate UA based stones from all other types (in both tissue and bone windows), and pure COM from mixed COM + HA stones (in the tissue window only), regardless the stone volume. Other types could not be differentiated from each other. Mitcheson et al. [7] reported the same results for pure stones only; they did not include mixed stones. Hillman et al. [12] could differentiate pure COM, UA, and struvite calculi using absolute HU values. Newhouse et al. [5] reported the results of scanning calculi including a few mixed stones; they could not distinguish calcium based and struvite stones from each other. Mostafavi et al. [8], using the absolute HU values at 120 kV, could differentiate the three pure types (UA, COM and struvite). Determination of stone composition by NCCT in clinical settings has also been reported [9, 10]. Nakada et al. [10] differentiated pure COM from pure UA using the absolute HU values, while Motley et al. [9] did not. All of these studies, as well as the present study, showed the same trend from the least to the most dense calculi. Table 4 shows the parameters and HU values for the above studies in comparison to the present study.

Table 3 Stone determination by HU density (P value). Independent sample t-test. $P<0.05$ indicates a statistically significant difference

		Tissue window						
		UA	COM	Struvite	COM + Apatite	COM 40–90% + UA	UA + COM < 40%	Mixed struvite + COM + apatite
Bone window	UA		0.5	0.04	0.09	0.07	0.9	0.7
	COM	0.3		0.03	0.4	0.4	0.6	0.8
	Struvite	0.04	0.03		0.04	0.007	0.01	0.1
	COM + HA	0.09	0.6	0.03		0.9	0.2	0.4
	COM ≥40% + UA	0.08	0.6	0.01	0.9		0.2	0.4
	UA + COM < 40%	0.6	0.8	0.04	0.5	0.5		0.9
	Mixed struvite + COM + HA	0.4	0.9	0.09	0.7	0.7	0.8	

Table 4 Review of studies

	Mitcheson et al. [7], in vitro	Newhouse et al. [5], in vitro	Hillman et al. [12], in vitro	Mostafavi et al. [8], in vitro	Nakada et al. [11], in vivo	Motley et al. [9], in vivo	Present study, in vitro	
CT scanner	Siemens somatom-2	EMI 7070	GE 8800	GE Hispeed	GE Hispeed	GE Hispeed	GE Light speed	
Energy settings	460 mA at 125 kV, 747 mA at 77 kV	90 mA at 120 kV	100 mA at 120 kV	240 mA at 80, 120 kV	200 mA at 120 kV	200 mA at 120 kV	240 mA at 100, 120 kV	
Collimation	2	2	5	1	3–5	5	1.25	
Surrounding media	Water	Water	Water	Air	In patients	In patients	Water	
Absolute HU values							Tissue window	Bone window
Uric acid	540 ± 107	426 ± 51	448 ± 108	409 ± 118	344 ± 152	270 ± 134	548 ± 348	695 ± 376
Struvite	651 ± 108	725 ± 118	943 ± 259	666 ± 87	NA	401 ± 198	804 ± 364	1,008 ± 381
Calcium oxalate	> 1,023	948 ± 67	1,273 ± 193	1,620 ± 232	652 ± 490	440 ± 262	809 ± 288	1,130 ± 413

As Saw et al. [11] concluded that stone composition and size independently influenced CT attenuation. Despite finding no significant correlations between stone volume and absolute HU values for most of the stones in our study, we derived HU density in an attempt to improve the differentiation of stone types. Using HU density, we could differentiate pure struvite calculi from all other types except mixed struvite + COM + HA calculi. These findings are in agreement with those of Motley et al. [9] and Nakada et al. [10], who used the attenuation/stone length (in mm) ratio. They found statistically significant differences between pure UA and COM, but Motley et al. [9] could not differentiate between pure UA and pure struvite stones.

Using dual energy scanning, Mitcheson et al. [7] could differentiate pure COM, UA, and struvite stones while Mostafavi et al. [8] could not. In our study, dual CT values could not differentiate pure calculi from each other, while differentiated UA based stones from pure struvite and mixed COM + HA were well differentiated using absolute HU values. The only compositions that could be differentiated by dual CT (but not by absolute HU values) value only were pure struvite and mixed COM + apatite, which were differentiated by HU density.

Thus, in our study the use of absolute HU values derived from either the central three ROI or ROI of the center of the stone, and HU density (in both tissue and bone windows) uncovered statistically significant differences among all pure and most of the mixed urinary stones. Differentiation of pure COM and mixed COM + HA was possible only in the tissue window. Moreover, this technique permitted diagnostic conclusions on the basis of a single CT evaluation, whereas the use of dual energy scanning requires the acquisition of additional CT images.

Our findings suggest that the measurement of absolute HU values and HU density at a single energy level utilizing CT scanning with a small collimation size can uncover significant differences among all pure and most of the mixed urinary stones. Moreover, this technique permits diagnostic conclusions on the basis of a single CT evaluation in a clinical setting, and will assist the urologist in the appropriate selection of treatment to optimize success.

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