Characterization of Human Renal Stones with MDCT: Advantage of Dual Energy and Limitations Due to Respiratory Motion

Romain Grosjean¹
 Benoît Sauer^{1,2}
 Rui Matias Guerra^{1,3}
 Michel Daudon⁴
 Alain Blum²
 Jacques Felblinger¹
 Jacques Hubert^{1,5}

Keywords: chemical composition, CT attenuation value, nephrolithiasis, renal stones, respiration motion

DOI:10.2214/AJR.07.2466

Received August 25, 2007; accepted after revision October 3, 2007.

¹Interventional and Diagnostic Adaptive Imaging, INSERM ERI 13, Nancy University, Centre Hospitalier Universitaire Nancy (TD4), Rue du Morvan, 54511 Vandœuvre-les-Nancy CEDEX, France. Address correspondence to R. Grosjean (r.grosjean@chu-nancy.fr).

²Department of Radiology, Service d'Imagerie Guilloz, Centre Hospitalier Universitaire, Nancy, France.

³Siemens Medical Solutions, Saint Denis, France.

⁴Cristal Laboratory, Necker Hospital, Paris, France.

⁵Department of Urology, Centre Hospitalier Universitaire, Nancy, France.

AJR 2008; 190:720–728

0361–803X/08/1903–720

© American Roentgen Ray Society

OBJECTIVE. Our aim was to determine, using CT attenuation values, the chemical composition of 241 human renal stones placed in a jelly phantom and to analyze the influence of respiratory motion on the classification.

MATERIALS AND METHODS. The stones were placed in a jelly simulating the X-ray attenuation of the kidneys. A dynamic platform was used to apply to the phantom free-breathing motion (sinusoidal motion in z-axis) and motion due to lack of maintenance of a breath-hold (5 mm·s⁻¹ in z-axis). Determination of the chemical composition was performed with mean CT attenuation values obtained at 80 and 120 kV and with dual-energy CT attenuation values.

RESULTS. Two hundred forty-one human urinary stones were classified into six groups: uric acid, cystine, struvite, weddellite (calcium oxalate dihydrate), whewellite (calcium oxalate monohydrate), and brushite. With no motion, the use of dual energy enabled differentiation of all of the types of stones with statistically significant differences. Uric acid (-20 ± 22 H), cystine (106 ± 19 H), struvite (271 ± 16 H), weddellite (323 ± 5 H), brushite (415 ± 30 H), and whewellite (510 ± 17 H) were identified as distinct groups. Motion-induced mean CT attenuation values were significantly different from those obtained with no motion. With motion, dual-energy CT attenuation values did not allow differentiation of all stone types.

CONCLUSION. Dual-energy CT attenuation values can be used to predict the chemical composition of stones in vitro. However, when slight motion is applied to renal stones during image acquisition, the values become significantly different from those obtained with no motion. Consequently, confusion arises in differentiating stone types. A perfect breath-hold has to be performed for in vivo use of attenuation value to discern stone type.

Since the early 1990s, the use of unenhanced CT has gained widespread acceptance in the evaluation of nephrolithiasis. Because studies have shown that helical CT can depict urinary stones more precisely than do radiography [1], sonography [2], nephrotomography [3], and excretory urography [4], MDCT has become the technique most used for rapid and accurate determination of the presence of stones in evaluations for urinary lithiasis treatment [5–10].

Precise determination of the symptoms, localization, size, and chemical composition of stones is key to diagnosis and choice of therapy [11]. Extracorporeal shock wave lithotripsy is the most commonly used technique in the management of urinary stones, but the success of this treatment depends on the chemical composition of the stone and its corresponding fragility [12–15]. For example, brushite, cystine, and calcium oxalate

monohydrate stones are more resistant to extracorporeal lithotripsy [16] than are the other types of stones we describe. Failure of extracorporeal shock wave lithotripsy increases medical costs, necessitates alternative treatment, and results in undesirable exposure of the renal parenchyma to shock waves. For these reasons, pretreatment determination of the composition of stones is essential. Since the early 1980s, studies have been conducted to determine stone composition on the basis of X-ray attenuation of stones in vitro [17–22] and in vivo [23–25].

Organs in the upper part of the abdomen, including the liver, kidneys, and spleen, move considerably as a result of respiration [26]. McCollough et al. [27], Alfidi et al. [28], and Ritchie et al. [29] have proved that physiologic motion decreases the quality of CT images. To our knowledge, no studies have been conducted to evaluate the influence of residual respiratory motion on the

MDCT of Renal Stones

CT attenuation values of stones. The aim of our study was to determine with CT attenuation values the chemical composition of human renal stones in a jelly phantom and to analyze the influence of respiratory motion on stone classification.

Materials and Methods

Urinary Stones

Data on 241 urinary stones from humans were obtained from the database of a stone analysis laboratory. The stones had been collected through surgical and endoscopic intervention. The biochemical composition had been determined with stereomicroscopy and infrared spectrophotometry, which generated the percentages of the predominant components. The percentages of pure and mixed stones were not equal. On average, two thirds of calculi were polycrystalline. The stones were classified according to the main component, and only stones containing at least 85% of one component were used for our study. According to the predominant component, the stones were divided into six groups: uric acid, cystine, magnesium ammonium phosphate hexahydrate (struvite), calcium oxalate dihydrate (weddellite), calcium oxalate monohydrate (whewellite), and calcium hydrogen phosphate dihydrate (brushite) (Table 1). All of these stones had low content of a secondary component. The diameter of the stones varied from 7 to 25 mm (mean size, 12 mm).

Phantom and Dynamic Platform

The stones were placed in a jelly made of water, iodine, and animal proteins (Fig. 1). The iodine and protein concentrations were empirically chosen to ensure the jelly had an X-ray attenuation similar to that of human kidney (30 H at 120 kV). To 1 L of water, we added 21.6 g of animal protein and 0.01 mg of iodine. Each layer of jelly, containing all the stones of one type, was successively settled in a plastic container (280 × 210 × 110 mm). The jelly phantom was homogeneous (30 ± 3 H). Stones were embedded in a layer 3 cm thick. The jelly phantom had six layers, for a total thickness of 18 cm. The plastic container was placed in a water tank. This water tank containing the six layers of jelly and the 241 stones was placed on a dynamic platform designed to accurately simulate respiratory motion in the z-axis [30].

Applied Motion

Two motions were used: a simulation of free-breathing motion and a simulation of motion due to lack of maintenance of a breath-hold. For free breathing, a sinusoidal motion, described by Lujan et al. [31], was applied with an amplitude of 35 mm

TABLE 1: Repartition of Calculi Used for In Vitro Study

Stone Type	n
Brushite (calcium hydrogen phosphate dihydrate)	12
Cystine	64
Struvite (magnesium ammonium phosphate hexahydrate)	29
Uric acid	38
Whewellite (calcium oxalate monohydrate)	63
Weddellite (calcium oxalate dihydrate)	35
Total	241

and a period of 5 seconds, as proposed by Moerland et al. [32] and proved by Pasquier et al. [33]. To achieve independence from the phase of free-breathing motion, we performed three acquisitions with free-breathing motion and averaged the data obtained. For breath-hold motion due to lack of maintenance of a breath-hold, the phantom was translated in the longitudinal axis (z-axis) with a speed of 5 mm/s. To simulate a perfect breath-hold, the platform was kept at rest.

CT Parameters

MDCT (Somatom Sensation 16, Siemens Medical Solutions) was performed at 80 and 120 kV, 200 mAs, 0.5-second gantry rotation time, 0.75-mm collimation, and 0.7-mm index of reconstruction. These parameters were those used in a typical abdominal examination protocol.

Image Analysis

For measurement of CT attenuation values at image analysis, we devised an interface based on Matlab (Mathworks). Stones were segmented from multiplanar reformation by use of standard

morphologic image-processing operations (global threshold of 155 H, opening to remove pixel inferior in relation to three pixels and closing to gather the contiguous zones separated by the thresholding). For each acquisition and for each stone, the largest region of interest (ROI) was set closest to the largest area of the stone (Fig. 2). The size and the position of the ROIs had been validated twice by an experienced radiologist using a conventional soft-tissue window. A conventional soft-tissue window (width, 350 H; level, 40 H) was used to record the mean ± CT attenuation values within the ROI.

Data and Statistical Analysis

Determination of chemical composition was performed with mean CT attenuation value at 80 kV, mean CT attenuation value at 120 kV, and dual-energy CT attenuation value. Dual-energy CT attenuation value was assessed by subtracting the mean CT attenuation value obtained at 120 kV from the mean CT attenuation value obtained at 80 kV. The 95% CI (lowest to highest) was computed. The 95% CI obtained with no motion was considered the reference for the rest of the study. To compare mean CT attenuation values for the different types of motion (perfect breath-hold vs nonmaintained breath-hold, perfect breath-hold vs free breathing, nonmaintained breath-hold vs free breathing), a paired Student's *t* test for two sets of unpaired data with unequal variance assumed was used. The same test was performed to compare the dual-energy CT attenuation values of the different types of stones.

Results

Static Acquisitions (Perfect Breath-Hold)

At 80 kV, according to the mean CT attenuation values from most to least dense, the stone types were as follows: brushite, weddellite, whewellite, struvite, cystine, and

Fig. 1—Photograph shows stones that were placed in jelly phantom.

Fig. 2—Diagram shows regions of interest placed within largest area of stones (120 kV; 200 mAs; soft-tissue window width, 350 H; soft-tissue window length, 40 H).

(Fig. 4). Uric acid (-20 ± 22 H), cystine (106 ± 19 H), struvite (271 ± 16 H), weddellite (323 ± 5 H), brushite (415 ± 30 H), and whewellite (510 ± 17 H) were identified as distinct groups.

Difference Between Nonmaintained Breath-Hold and Perfect Breath-Hold

When motion due to lack of maintenance of a breath-hold was applied to the phantom, the CT attenuation values were significantly different (with 95% CI) from the CT attenuation values obtained with no motion, except for uric acid at 80 kV (Fig. 5A) and brushite at 120 kV (Fig. 5B). In addition, the CT attenuation values were lower than in the static case except for struvite at 120 kV and whewellite at 120 kV. Nevertheless, the classification did not change, and for nonmaintained breath-hold, the classification of stones was similar to the classification obtained with no motion. With nonmaintained breath-hold motion, the overlap was not the same as for the other situations. For example, at 120 kV with no motion, the CI computed for cystine stones (602–648 H) had no overlap with that for the other types of stones. However, when nonmaintained breath-hold motion was applied, the CI of cystine stones (448–526 H) had considerable overlap with that of struvite stones obtained with no motion (344–579 H) (Fig. 5B). Even the dual-energy CT attenuation values did not allow distinction of struvite from uric acid stones or of struvite from weddellite stones (Fig. 6). Only brushite and whewellite were differentiated from the other stones with the dual-energy CT attenuation values.

Difference Between Free-Breathing Motion and Perfect Breath-Hold

With sinusoidal motion applied to the phantom, the mean CT attenuation values were significantly different (with 95% CI) from the mean CT attenuation values obtained with no motion, except for struvite at 120 kV (Fig. 5B) and uric acid at 80 kV (Fig. 5A). CT attenuation values were always lower than without motion. The classification of stones was similar to that at rest. Overlap was not the same as that at rest. For example, at 80 kV with no motion, the CI for whewellite stones (1,190–1,424 H) had no overlap with that of struvite stones (599–865 H). When free-breathing motion was simulated, the CI for whewellite (763–1,100 H) had considerable overlap with that of struvite stones obtained with no motion (599–865 H) (Fig. 5A). With free-breathing motion, the dual-energy CT attenuation

TABLE 2: Mean and 95% Confidence Limits of CT Attenuation Values (H) at Rest of Six Types of Calculi

Stone Type	n	Attenuation at 80 kV			Attenuation at 120 kV		
		Lowest	Mean	Highest	Lowest	Mean	Highest
Brushite (calcium hydrogen phosphate dihydrate)	12	1,451	1,631	1,810	1,066	1,216	1,366
Cystine	64	689	731	773	602	625	648
Struvite (magnesium ammonium phosphate hexahydrate)	29	578	732	865	344	461	578
Uric acid	38	350	417	484	392	437	482
Weddellite (calcium oxalate dihydrate)	35	1,235	1,341	1,547	816	1,017	1,218
Whewellite (calcium oxalate monohydrate)	63	1,190	1,307	1,424	703	797	891

uric acid. At 120 kV, according to the mean CT attenuation values from most to least dense, the stone types were as follows: brushite, weddellite, whewellite, cystine, struvite, and uric acid. The global sort was identical except for the switch between cystine and struvite. The means and 95% confidence limits for the CT attenuation values obtained at 80 and 120 kV are reported in Table 2. When the classification of the various types of stones was arranged according to mean CT attenuation value and 95% CI, substantial overlap between types was found (Fig. 3).

At 80 kV, only uric acid stones were identified as a distinct group on the basis of CI. Struvite and cystine stones were not differentiated, but these two groups were differentiated from uric acid, calcium oxalate, and brushite stones. It was difficult to separate whewellite from weddellite and brushite

stones (Fig. 3A). At 120 kV, cystine stones were clearly identified, but with this energy, uric acid stones were not differentiated from struvite stones. For whewellite, weddellite, and brushite stones, overlap was present but less important than at 80 kV (Fig. 3B).

CT attenuation values were lower at 120 kV than at 80 kV (Table 2). On average, the CT attenuation values at 120 kV were equal to 75% (± 17 kV) of the value at 80 kV. The differences between mean CT attenuation values were particularly high for whewellite stones (61%) and struvite stones (63%). Despite a larger spread of CT attenuation values at 80 kV, there was less overlap at 120 kV (Fig. 3). Only cystine stones at 120 kV and uric acid stones at 80 kV were identified with statistical significance. However, the dual-energy CT attenuation values obtained at 80 and at 120 kV allowed statistically significant differentiation of all types of stones

TABLE 3: Comparison of Techniques and of Mean Absolute Attenuation Values In Vitro and In Vivo Studies

Parameter	Mitcheson et al. [17], 1983	Hillman et al. [18], 1983	Newhouse et al. [19], 1984	Mostafavi et al. [20], 1997	Saw et al. [21], 1999	Nakada et al. [24], 2000	Motley et al. [23], 2001	Pareek et al. [25], 2003	Bellin et al. [22], 2003	Grosjean et al., 2006
CT scanner	Somatoma ^a	GE 8800 ^b	EMI 7070 ^c	HiSpeed ^b	Somatoma Plus 4 ^a	HiSpeed ^b	HiSpeed ^b	GE ^b	Somatoma ^a	Somatoma ^a
Energy setting	125	120	120	120	120	120	120	120	120	120
Kilovoltage	460 mA	100 mA	90 mA	240 mA	240 mA	200 mA	200 mA	—	200 mAs	200 mAs
Tube current or tube current–time product	2	5	2	1	1	3, 5	5	5	3	0.75
Section thickness (mm)	Water	Water	Water	Air	Water	In vivo	In vivo	In vivo	Pig kidney	Jelly
Surrounding medium	80	63	35	102	127	99	100	50	100	241
Number of stones										
Mean attenuation $\pm \sigma$ (H)										
Brushite	> 1,023	—	1,211 $\pm$ 195	1,703 $\pm$ 161	1,913 $\pm$ 43	648 $\pm$ 149	—	—	837 $\pm$ 220	1,216 $\pm$ 150
Calcium oxalate	—	1,273 $\pm$ 193	948 $\pm$ 67	1,620 $\pm$ 232	1,639 $\pm$ 25	484 $\pm$ 60	440 $\pm$ 262	605 $\pm$ 340	—	—
Monohydrate (whewellite)	—	—	—	1,645 $\pm$ 238	—	—	—	—	—	797 $\pm$ 94
Dihydrate (weddellite)	—	—	—	1,417 $\pm$ 234	—	—	—	—	723 $\pm$ 131	1,017 $\pm$ 201
Cystine	703 $\pm$ 69	625 $\pm$ 247	540 $\pm$ 49	711 $\pm$ 228	860 $\pm$ 26	232 $\pm$ 31	248 $\pm$ 0	—	527 $\pm$ 110	625 $\pm$ 23
Struvite	651 $\pm$ 108	943 $\pm$ 259	725 $\pm$ 118	666 $\pm$ 87	1,087 $\pm$ 100	454 $\pm$ 63	401 $\pm$ 198	—	563 $\pm$ 169	461 $\pm$ 117
Uric acid	540 $\pm$ 107	448 $\pm$ 108	426 $\pm$ 51	409 $\pm$ 118	567 $\pm$ 40	136 $\pm$ 19	270 $\pm$ 134	300 $\pm$ 150	386 $\pm$ 154	437 $\pm$ 45

Note.—Dash (—) indicates type of stone not taken into account.

^aSiemens Medical Solutions.^bGE Healthcare.^cEMI.

values allowed differentiation of uric acid, struvite, and cystine stones. Brushite, whewellite, and weddellite were not differentiated from one another (Fig. 7).

Difference Between Simulated Free-Breathing Motion and Nonmaintained Breath-Hold

Except for whewellite at 120 kV, when nonmaintained breath-hold was simulated (5 mm/s), the CT attenuation values were significantly equal (with 95% CI) to the CT attenuation values obtained when free-breathing motion was simulated (Fig. 5B).

Discussion

Since the early 1980s, several studies have been conducted in an attempt to determine the chemical composition of stones on the basis of X-ray attenuation in vitro and in vivo. For our study, we used the largest number ($n = 241$) of stones so far described, to our knowledge, and found that chemical characterization is possible with dual-energy CT attenuation values.

In 1998, Mostafavi et al. [20] asserted, having studied only 102 stones, that the best CT parameter for accurately determining the chemical composition of stones was the mean CT attenuation value obtained at 120 kV. This affirmation was in accord with our results. At 120 kV the overlap between types of stones was less, and it was easier to differentiate the stone groups. Despite the overlap problem, it was possible to classify the types of stones according to mean CT attenuation value and 95% CI. At 120 kV, from least to most dense, the stones types were as follows: uric acid (437 ± 45 H), struvite (461 ± 117 H), cystine (625 ± 23 H), whewellite (797 ± 94 H), weddellite ($1,017 \pm 201$ H), and brushite ($1,216 \pm 150$ H). In most of the previous studies, the chemical composition of the stones had been assessed only at 120 kV. This kilovoltage is the one most commonly used for clinical abdominal imaging. Consequently, only our results obtained at 120 kV can be compared with those of others. Our classification is similar to those of Mitcheson et al. [17], Bachmann et al. [34], and Mostafavi et al. [20]. Hillman et al. [18], Newhouse et al. [19], Saw et al. [21], Bellin et al. [22], and Motley et al. [23] switched cystine and struvite (Table 3). This difference can be explained by the fact that there is often a large overlap between the CI of struvite and the CI of cystine in these studies. Deveci et al. [35] switched whewellite and weddellite, but they used only one weddellite stone, opening the finding to statistical criticism.

Fig. 3—Graphs show overlap of 95% CIs (200 mAs; gantry rotation time, 0.5 second; collimation, 0.75 at 80 kV [A] and 120 kV [B]). UA = uric acid, STR = struvite, CYS = cystine, COM = calcium oxalate monohydrate (whewellite), COD = calcium oxalate dihydrate (weddelite), BRU = brushite.

Fig. 4—Graph shows dual-kilovoltage CT attenuation values (attenuation at 80 kV minus attenuation at 120 kV) obtained with no motion. UA = uric acid, STR = struvite, CYS = cystine, COM = calcium oxalate monohydrate (whewellite), COD = calcium oxalate dihydrate (weddelite), BRU = brushite.

CT attenuation values were 75% higher at 80 kV than at 120 kV, and the classification obtained at 80 kV was not the same as that at 120 kV, cystine and struvite being switched. This variation in CT attenuation value determination according to kilovoltage has been described by McKetty [36] and Bushberg [37]. Without motion, for all stones, findings on single-energy scanning (80 or 120 kV) did not allow accurate differentiation of the chemical composition of stones. Dual-energy scanning, however, provided additional information on chemical characterization. As shown by Mostafavi et al. [20], dual-energy CT attenuation values are extremely reliable in differentiating all stones. Even if Mostafavi et al. had been the only investigators to study the six most frequent types of stones (Table 3), they conducted their study without consider-

ing renal X-ray attenuation, and the number of stones used could not guarantee the statistical significance of the results.

In our study, the use of the dual-energy CT attenuation values made it possible to characterize all renal stones with statistical significance. In clinical use, imaging for nephrolithiasis is generally performed at 120 kV. Because the received dose is proportional to the square of the kilovoltage, use of this technique can lead to an approximately 40% increase in received dose, possibly less. The second acquisition thus can be minimal (centered on the stone without acquisition of images of the rest of the abdomen) and performed with low energy (80 kV) [38–40]. This additional dose can be a problem for children but can be justified for adult patients because accurate and fast determination of the chemical

characterization of renal stones can lead to quicker and more accurate treatment. This new protocol can be facilitated with the dual-source CT (Somatom Definition, Siemens AG Medical Solutions).

Several studies have been conducted in the attempt to determine the chemical composition of renal stones on the basis of in vitro and in vivo X-ray attenuation of the stones (Table 3). The in vitro studies, however, did not reproduce normal abdominal wall and fat, perinephric fat, or the spine, causing uncertainty about standardization of the values obtained. For example, Bellin et al. [22] used excised pig kidney placed in water, Mostafavi et al. [20] and Deveci et al. [35] placed stones in air, and Saw et al. [21] placed stones in water. The influence of the surrounding media on CT attenuation values has been proved by Grosjean et al. [41], who found the mean CT attenuation values of stones vary with the surrounding media tested (air, water, and jelly). This finding can be explained by the beam-hardening effect and insufficient correction of the effect with CT algorithms [42]. In our study, we used a jelly made of water, iodine, and animal proteins and surrounded it with water. The CT attenuation value of the jelly (30 ± 6 H at 120 kV) allowed us to reproduce renal attenuation as accurately as possible, but the phantom did not reproduce exactly normal abdominal wall and fat.

The influence of the surrounding media on mean CT attenuation value explains the difference between our values and those obtained in the other studies [20, 21, 35], which did not respect the normal absorption of the abdomen because the stones were scanned within an

MDCT of Renal Stones

Fig. 5—Graphs show influence of motion on CT attenuation values (attenuation at 80 kV minus attenuation at 120 kV). UA = uric acid, STR = struvite, CYS = cystine, COM = calcium oxalate monohydrate (whewellite), COD = calcium oxalate dihydrate (weddellite), BRU = brushite.
A, Acquisition at 80 kV.
B, Acquisition at 120 kV.

Fig. 6—Graph shows dual-kilovoltage CT attenuation (attenuation at 80 kV minus attenuation at 120 kV) obtained with simulated lack of maintenance of breath-hold. UA = uric acid, STR = struvite, CYS = cystine, COM = calcium oxalate monohydrate (whewellite), COD = calcium oxalate dihydrate (weddellite), BRU = brushite.

air-filled environment or in water. For example, to prevent overlapping densities and to avoid the absorption of X-ray beams by water or fat, Deveci et al. [35] used an air-filled environment instead of phantoms containing water or fat. Thus the density differences increased, and overlap did not occur. Consequently, because the in vitro conditions were too far from the in vivo conditions, the results cannot be considered a reference for in vivo determination of chemical composition.

Because our study had, to our knowledge, the largest number of stones described in the literature to date, the results have statistical significance for the six most frequent types of stones. Only stones containing at least 85% of

one component and having low content of a secondary component were used. These stones can legitimately be considered to reflect the behavior of the principal component and in consequence can be considered pure. Overrepresentation of some components (for example, calcium oxalate monohydrate and brushite) was deliberate because of their particular resistance to extracorporeal shock wave lithotripsy. Carapatite stones were not included in our study because they are rarely pure and almost always are multiphasic with high content of a secondary component. It was also difficult to collect enough pure carapatite stones to obtain significant results. Pure carapatite stones are, in practice, less

frequent than cystine stones. Our stones were selected from the purest possible stones. Even though most stones are polycrystalline, it was necessary to work with pure stones or stones considered pure. Because differentiation of pure stones has not been proved, study of mixed stones would not be realistic.

Our phantom was closer to in vivo conditions than phantoms used in in vitro studies of the X-ray attenuation of the kidney. With this phantom and the large number of stones, we attempted to prove that dual-energy CT attenuation values can be clinically useful for determining the chemical composition of pure renal stones. However, even if a breath-hold can generally be maintained over the acquisition time, for some patients (e.g., those with sharp pain due to renal colic, children, and dyspneic patients), a breath-hold is particularly difficult [43]. To analyze the influence of motion on the X-ray attenuation of stones, two types of motion were applied to the phantom: free-breathing motion and motion due to lack of maintenance of a breath-hold. We found that CT attenuation values depend on motion. With the two types of movement, CT attenuation values generally decreased. With either type of motion, the mean CT attenuation values were significantly different from those obtained at rest. Therefore, even dual-energy CT attenuation values cannot be used to determine the chemical composition of renal stones in the presence of motion.

Fig. 7—Graph shows dual-kilovoltage CT attenuation values (attenuation at 80 kV minus attenuation at 120 kV) obtained with simulated free-breathing motion. UA = uric acid, STR = struvite, CYS = cystine, COM = calcium oxalate monohydrate (whewellite), COD = calcium oxalate dihydrate (weddellite), BRU = brushite.

The explanation for the influence of motion is the partial volume effect due to motion. With 16×0.75 mm collimation and a gantry rotation time of 0.5 second, 24 mm are scanned per second, but in that time, the stones have moved at least 5 mm with lack of maintenance of a breath-hold. The partial volume effect occurs during imaging of any part of the body in which the anatomic relations are changing rapidly in the z direction [44]. To keep the partial volume effect at a minimum, the thinnest available slice thickness has to be used. In addition, acquisition time generally increases when slice thickness is decreased. The longer the acquisition time, the greater is the partial volume effect due to the presence of motion. Because of this partial volume effect paradox, a compromise between slice thickness and acquisition time is needed. To minimize the acquisition time, gantry rotation time can be decreased. It is noteworthy that the gantry rotation time of 500 milliseconds did not allow minimization of motion artifacts but corresponds to the abdominal imaging protocol in current clinical use. Even with the fastest available gantry rotation time (420 milliseconds), it is impossible to remove motion artifacts. Ritchie et al. [29] found that the gantry rotation time necessary to eliminate motion artifacts caused by quiet breathing was 93.5 milliseconds.

Our results indicate that determination of the chemical composition of renal stones has to be done with images obtained during a perfect breath-hold. We can never be sure, however, that a patient has realized a perfect breath-hold. Imprecision due to motion is a limitation of CT determination of the chemical composition of renal stones. Without motion, prediction of renal stone composition

with dual-energy CT attenuation values is reliable. When motion is applied, the technique becomes unusable.

Saw et al. [21] scanned 127 urinary stones of known composition placed in a water bath (120 kV, 240 mA). By referring to the model of Hu and Fox [45], which showed that measurement of the CT attenuation value of an object with helical CT is affected by collimation width and pitch, Saw et al. found that the measured attenuation of stones declined with increasing collimation width owing to the partial volume effect. In addition, scanning 63 stones in a waterbath (120 kV, 100 mA), Hillman et al. [18] found that even if it is clear that small stones will be subject to partial volume inaccuracies in measurement of CT attenuation and that this source of inaccuracy can be further accentuated by the respiratory movement of a patient, CT may prove a valuable adjunct to traditional laboratory and clinical methods of establishing the chemical composition of stones. To avoid partial volume inaccuracies, we chose the thinnest possible slice thickness for our study (0.75 mm). It is essential to use a narrow slice width to ensure the accuracy of attenuation values in helical CT [46]. But decreasing the slice thickness has two opposing effects. Stone detection can be improved with a decrease in partial volume effect, but it can be hampered by an increase in noise [47–49]. In addition, choosing table feed values greater than the nominal section thickness increases degradation of the slice sensitivity profile [50]. For lesions smaller than the section thickness, a reduction in contrast enhancement due to the partial volume effect can be observed.

There may be variability in CT attenuation values of scans obtained with different CT

scanners manufactured by different companies and even among different scanners made by the same manufacturer and of the same model [51, 52]. This phenomenon may explain the slight variations in CT reports of attenuation values. In addition, most renal stones in humans are not pure. Heterogeneity can be very important, and the proportion of constituents can vary considerably [46, 53, 54]. To determine absolute CT attenuation values, Mostafavi et al. [20] used 1-pixel ROIs to measure CT attenuation. Deveci et al. [35] used three 0.01-cm^2 ROIs. In applying these methods, the investigators did not take into account the structural heterogeneity of mixed calculi. Because of this structural heterogeneity, we used the largest ROI within a stone to obtain a reliable mean CT attenuation value for each stone, as did Motley et al. [23]. When motion is applied, however, the larger the ROI, the more pixels from the environment of the stone can be included and lead to an increase in partial volume effect.

A limitation of our study was that only stones with a diameter between 7 and 25 mm were assessed. The influence of stone size on CT attenuation values was not studied. The results can be degraded when the diameter of the stones approaches the slice thickness. The effect of stone size will be the subject of future work.

In conclusion, with single-energy CT, overlap between types of renal stones makes it difficult to reliably determine the chemical composition. Dual-energy CT attenuation values can be used for accurate prediction of stone composition in vitro. When slight motion is applied to renal stones during acquisition, however, CT attenuation values and even dual-energy CT attenuation values became significantly different from those obtained at rest and consequently can lead to confusion between stone types. Therefore, for in vivo application of this technique, a perfect breath-hold has to be performed by the patient, even during MDCT.

References

1. Levine JA, Neitlich J, Verga M, Dalrymple N, Smith RC. Ureteral calculi in patients with flank pain: correlation of plain radiography with unenhanced helical CT. *Radiology* 1997; 204:27–31
2. Sommer FG, Jeffrey RB Jr, Rubin GD, et al. Detection of ureteral calculi in patients with suspected renal colic: value of reformatted noncontrast helical CT. *AJR* 1995; 165:509–513
3. Olcott EW, Sommer FG, Napel S. Accuracy of detection and measurement of renal calculi: in

MDCT of Renal Stones

- vitro comparison of three-dimensional spiral CT, radiography, and nephrotomography. *Radiology* 1997; 204:19–25
4. Smith RC, Rosenfield AT, Choe KA, et al. Acute flank pain: comparison of non-contrast-enhanced CT and intravenous urography. *Radiology* 1995; 194:789–794
5. Fielding JR, Steele G, Fox LA, Heller H, Loughlin KR. Spiral computerized tomography in the evaluation of acute flank pain: a replacement for excretory urography. *J Urol* 1997; 157:2071–2073
6. Yilmaz S, Sindel T, Arslan G, et al. Renal colic: comparison of spiral CT, US and IVU in the detection of ureteral calculi. *Eur Radiol* 1998; 8:212–217
7. Dalla Palma L, Pozzi-Mucelli R, Stacul F. Present-day imaging of patients with renal colic. *Eur Radiol* 2001; 11:4–17
8. Hubert J, Blum A, Cormier L, Claudon M, Regent D, Mangin P. Three-dimensional CT-scan reconstruction of renal calculi: a new tool for mapping-out staghorn calculi and follow-up of radiolucent stones. *Eur Urol* 1997; 31:297–301
9. Katz DS, Lane MJ, Sommer FG. Non-contrast spiral CT for patients with suspected renal colic. *Eur Radiol* 1997; 7:680–685
10. Preminger GM, Vieweg J, Leder RA, Nelson RC. Urolithiasis: detection and management with unenhanced spiral CT—a urologic perspective. *Radiology* 1998; 207:308–309
11. Wang LJ, Wong YC, Chuang CK, et al. Predictions of outcomes of renal stones after extracorporeal shock wave lithotripsy from stone characteristics determined by unenhanced helical computed tomography: a multivariate analysis. *Eur Radiol* 2005; 15:2238–2243
12. Dretler SP, Spencer BA. CT and stone fragility. *J Endourol* 2001; 15:31–36
13. Zhong P, Preminger GM. Mechanisms of differing stone fragility in extracorporeal shockwave lithotripsy. *J Endourol* 1994; 8:263–268
14. Renner C, Rassweiler J. Treatment of renal stones by extracorporeal shock wave lithotripsy. *Nephron* 1999; 81[suppl 1]:71–81
15. Rassweiler JJ, Renner C, Chaussy C, Thuroff S. Treatment of renal stones by extracorporeal shockwave lithotripsy: an update. *Eur Urol* 2001; 39:187–199
16. Williams JC Jr, Saw KC, Paterson RF, Hatt EK, McAteer JA, Lingeman JE. Variability of renal stone fragility in shock wave lithotripsy. *Urology* 2003; 61: 1092–1096
17. Mitcheson HD, Zamenhof RG, Bankoff MS, Prien EL. Determination of the chemical composition of urinary calculi by computerized tomography. *J Urol* 1983; 130:814–819
18. Hillman BJ, Drach GW, Tracey P, Gaines JA. Computed tomographic analysis of renal calculi. *AJR* 1984; 142:549–552
19. Newhouse JH, Prien EL, Amis ES Jr, Dretler SP, Pfister RC. Computed tomographic analysis of urinary calculi. *AJR* 1984; 142:545–548
20. Mostafavi MR, Ernst RD, Saltzman B. Accurate determination of chemical composition of urinary calculi by spiral computerized tomography. *J Urol* 1998; 159:673–675
21. Saw KC, McAteer JA, Monga AG, Chua GT, Lingeman JE, Williams JC Jr. Helical CT of urinary calculi: effect of stone composition, stone size, and scan collimation. *AJR* 2000; 175:329–332
22. Bellin MF, Renard-Penna R, Conort P, et al. Helical CT evaluation of the chemical composition of urinary tract calculi with a discriminant analysis of CT attenuation values and density. *Eur Radiol* 2004; 14:2134–2140
23. Motley G, Dalrymple N, Keesling C, Fischer J, Harmon W. Hounsfield unit density in the determination of urinary stone composition. *Urology* 2001; 58:170–173
24. Nakada SY, Hoff DG, Attai S, Heisey D, Blankenbaker D, Pozniak M. Determination of stone composition by noncontrast spiral computed tomography in the clinical setting. *Urology* 2000; 55:816–819
25. Pareek G, Armenakas NA, Fracchia JA. Hounsfield units on computerized tomography predict stone-free rates after extracorporeal shock wave lithotripsy. *J Urol* 2003; 169:1679–1681
26. Brandner ED, Wu A, Chen H, et al. Abdominal organ motion measured using 4D CT. *Int J Radiat Oncol Biol Phys* 2006; 65:554–560
27. McCollough CH, Bruesewitz MR, Daly TR, Zink FE. Motion artifacts in subsecond conventional CT and electron-beam CT: pictorial demonstration of temporal resolution. *RadioGraphics* 2000; 20:1675–1681
28. Alfidi RJ, MacIntyre WJ, Haaga JR. The effects of biological motion on CT resolution. *AJR* 1976; 127:11–15
29. Ritchie CJ, Godwin JD, Crawford CR, Stanford W, Anno H, Kim Y. Minimum scan speeds for suppression of motion artifacts in CT. *Radiology* 1992; 185:37–42
30. Grosjean R, Guerra RM, Lorentz C, et al. Dynamic platform for moving organ moving. *Progress in biomedical optics and imaging 2006: proceedings of SPIE medical imaging 2006—physics of medical imaging*, vol. 6142. Bellingham, WA: SPIE, 2006:1137–1147
31. Lujan AE, Ten Haken RK, Larsen EW, Balter JM. Quantization of setup uncertainties in 3-D dose calculations. *Med Phys* 1999; 26:2397–2402
32. Moerland MA, van den Bergh AC, Bhagwandien R, et al. The influence of respiration induced motion of the kidneys on the accuracy of radiotherapy treatment planning, a magnetic resonance imaging study. *Radiother Oncol* 1994; 30:150–154
33. Pasquier C, Odille F, Abaecherli R, Vuissoz PA, Felblinger J. Modeling of organ's motion using external sensors. *Proceedings of the ISMRM 14th scientific meeting and exhibition*. Berkeley, CA: International Society for Magnetic Resonance in Medicine, 2006
34. Bachmann R, Heimbach D, Kersjes W, Jacobs D, Schild H, Hesse A. A new type of artificial urinary calculi: in vitro study by spiral CT. *Invest Radiol* 2000; 35:672–675
35. Deveci S, Coskun M, Tekin MI, Peskircioglu L, Tarhan NC, Ozkardes H. Spiral computed tomography: role in determination of chemical compositions of pure and mixed urinary stones—an in vitro study. *Urology* 2004; 64:237–240
36. McKetty MH. The AAPM/RSNA physics tutorial for residents: X-ray attenuation. *RadioGraphics* 1998; 18:151–163
37. Bushberg JT. The AAPM/RSNA physics tutorial for residents: X-ray interactions. *RadioGraphics* 1998; 18:457–468
38. Liu W, Esler SJ, Kenny BJ, Goh RH, Rainbow AJ, Stevenson GW. Low-dose nonenhanced helical CT of renal colic: assessment of ureteric stone detection and measurement of effective dose equivalent. *Radiology* 2000; 215:51–54
39. Spielmann AL, Heneghan JP, Lee LJ, Yoshizumi T, Nelson RC. Decreasing the radiation dose for renal stone CT: a feasibility study of single- and multidetector CT. *AJR* 2002; 178:1058–1062
40. Kalra MK, Maher MM, Toth TL, et al. Strategies for CT radiation dose optimization. *Radiology* 2004; 230:619–628
41. Grosjean R, Kermarrec I, Sauer B, et al. Determination of the chemical composition of human renal stones with MDCT: influence of the surrounding media. *Progress in biomedical optics and imaging: proceedings of SPIE medical imaging 2007—physiology, function, and structure from medical images*, vol. 6511. Bellingham, WA: SPIE, 2007:1228–1236
42. Maki DD, Birnbaum BA, Chakraborty DP, Jacobs JE, Carvalho BM, Herman GT. Renal cyst pseudoenhancement: beam-hardening effects on CT numbers. *Radiology* 1999; 213:468–472
43. Remy-Jardin M, Tillie-Leblond I, Szapiro D, et al. CT angiography of pulmonary embolism in patients with underlying respiratory disease: impact of multislice CT on image quality and negative predictive value. *Eur Radiol* 2002; 12:1971–1978
44. Barrett JF, Keat N. Artifacts in CT: recognition and avoidance. *RadioGraphics* 2004; 24:1679–1691
45. Hu H, Fox SH. The effect of helical pitch and beam collimation on the lesion contrast and slice profile in helical CT imaging. *Med Phys* 1996; 23:1943–1954
46. Zarse CA, McAteer JA, Tann M, et al. Helical

- computed tomography accurately reports urinary stone composition using attenuation values: in vitro verification using high-resolution micro-computed tomography calibrated to Fourier transform infrared microspectroscopy. *Urology* 2004; 63:828–833
47. Scheck RJ, Coppenrath EM, Kellner MW, et al. Radiation dose and image quality in spiral computed tomography: multicentre evaluation at six institutions. *Br J Radiol* 1998; 71:734–744
48. Shin HO, Falck CV, Galanski M. Low-contrast detectability in volume rendering: a phantom study on multidetector-row spiral CT data. *Eur Radiol* 2004; 14:341–349
49. Ketelslegers E, Van Beers BE. Urinary calculi: improved detection and characterization with thin-slice multidetector CT. *Eur Radiol* 2006; 16:161–165
50. Polacin A, Kalender WA, Marchal G. Evaluation of section sensitivity profiles and image noise in spiral CT. *Radiology* 1992; 185:29–35
51. Groell R, Rienmueller R, Schaffler GJ, Portugaller HR, Graif E, Willfurth P. CT number variations due to different image acquisition and reconstruction parameters: a thorax phantom study. *Comput Med Imaging Graph* 2000; 24:53–58
52. Levi, C, Gray JE, McCullough EC, Hattery RR. The unreliability of CT numbers as absolute values. *AJR* 1982; 139:443–447
53. 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
54. Daudon M, Lacour B, Jungers P. Influence of body size on urinary stone composition in men and women. *Urol Res* 2006; 34:193–199