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Consistency of Renal Stone Volume Measurements Across CT Scanner Model and Reconstruction Algorithm Configurations

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Abstract

Objective—The objective of this prospective study is to evaluate the consistency of renal stone volume estimation using dual-energy CT across scanner model and reconstruction algorithm configurations.

Subjects and Methods—Patients underwent scanning with routine kidney stone composition protocols on both second- and third-generation dual-source CT scanners. Images were reconstructed using filtered back projection and iterative reconstruction (IR). In addition, a modified IR kernel on the third-generation CT scanner was evaluated. Individual kidney stone volumes were determined and compared.

Results—No significant difference was noted in measured volumes between filtered back-projection data, IR data from the second-generation scanner, and the modified IR kernel data ($p > 0.05$). The third-generation commercially available IR kernel yielded lower volumes than did the other configurations ($p < 0.0001$).

Conclusion—With the use of a modified kernel for the third-generation scanner, patients being monitored for changes in kidney stone volume can undergo scanning performed with second- or third-generation dual-energy CT scanners, and the images obtained can be reconstructed with either filtered back projection or IR without the introduction of bias into kidney stone volume measurements.

Keywords

CT; iterative reconstruction; nephrolithiasis; stone volume; renal stone

Renal stone disease continues to increase in prevalence globally [1], affecting one in 11 people in the United States and recurring in more than 50% of individuals who have stones develop for the first time [2]. To guide treatment decisions and optimize patient outcomes, several studies have been conducted to identify diagnostically valuable characteristics of kidney stones.

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Stone size, which traditionally has been quantified as the maximum in-plane diameter on a CT image, is consistently identified as a primary predictor of the likelihood of spontaneous stone passage [3], the success of surgical intervention [4, 5], and patient experience and pain levels [6, 7]. However, 1D and 2D measurements are inadequate when describing complex stone shapes [8, 9]. Instead, when compared with stone diameter measurements, stone volume has an equal or greater predictive value for treatment success [10–12] and a higher accuracy in detecting interval changes in stone size [13].

Unenhanced CT is the recommended and most widely used imaging modality for evaluating patients with kidney stones, with dual-energy CT used as the standard protocol at our institution. Various CT-based methods for measuring stone volume have been developed and have been shown to be highly accurate and precise [10, 12, 14, 15]. As a result, electronic calipers are being replaced by 3D visualization software that provides automated stone volume measurements [16]. In parallel, to address concerns about radiation dose, manufacturers of CT scanners have implemented iterative reconstruction (IR) algorithms to reduce image noise and allow the use of lower radiation doses. These IR techniques are becoming more widely used in routine clinical protocols [17, 18]. However, some reports have indicated that IR algorithms can alter quantitative results [19–21]. Because IR is used in renal stone CT, and considering the importance of stone size in disease management, including in serial examinations, there is a need to evaluate the reproducibility of stone volume measurements. We hypothesize that volume should remain constant, independent of the CT scanner model or reconstruction algorithm. Hence, this study aims to assess the consistency of stone volume measurements across two different scanner models and two reconstruction algorithms.

Subjects and Methods

Patient CT Scanning

To examine stone volume in vivo, we conducted a prospective HIPAA-compliant institutional review board–approved study of patients referred for clinically indicated dual-source dual-energy CT performed at Mayo Clinic. Patients underwent scanning on the same day that they provided written informed consent. Both second-generation (Definition Flash, Siemens Healthcare) and third-generation (Somatom Force, Siemens Healthcare) dual-source CT scanners were used. Our clinical renal stone protocol dictated the patient size–dependent low-energy-beam tube voltage (80 or 100 kV... The high-energy-beam tube potential was fixed at 140 kV with a 0.4-mm tin filter for Flash and at 150 kV with a 0.6-mm tin filter for Force. The volume CT dose index ($CTDI_{vol}$) value was matched between the two scans, with a $CTDI_{vol}$ of 18 mGy used for a patient of standard body weight (70–80 kg).

Image Reconstruction and Processing

All images were reconstructed with an FOV diameter of 300 mm², a slice thickness of 1.0 mm, and a slice increment of 0.8 mm. Both a filtered back-projection (FBP) kernel and an IR kernel were used for each scanner, and they were selected on the basis of matching resolution and noise texture between the four configurations. The FBP kernels were D30 for Flash and Qr40 for Force (the vendor has different naming conventions for each scanner,

thus neither the letter nor the number indicates a difference between these kernels). The IR kernels were Q30 for Definition Flash (which uses a sinogram-affirmed IR technique [SAFIRE]) and Qr40 for Somatom Force (which uses an advanced modeled IR technique [ADMIRE]). A modified Qr40 reconstruction kernel for ADMIRE was also evaluated. This kernel is not available on commercial scanners and was recently developed for ADMIRE by the manufacturer for the purpose of removing its visually preferred edge enhancement, which has been shown to alter quantitative accuracy [19, 20]. An IR level of 2 was used for the three IR kernels. All kernels are presented in Table 1.

Individual stone volumes for each of the five reconstructions were determined on a postprocessing workstation (Syngo Via VA30, Siemens Healthcare). After images were loaded to the workstation, stones were automatically detected, and the volume of each stone was calculated. Kidneys with more than seven stones were excluded because of the difficulty in matching individual stones. All pairwise combinations of volume estimations were compared using a paired *t* test. Because no ground truth can be reliably attained for patient stone samples, the mean of the five volume estimations was used as the reference volume for each stone. The mean error was calculated for each configuration and was defined as the difference between the mean volume and the volume estimated by the given configuration. Statistical significance was denoted by $p < 0.05$.

Results

A total of 62 stones from 20 patients were included in the study. Stone volume ranged from 1.6 to 1590.0 mm³, with a median volume of 13.1 mm³ (lower quartile, 8.9 mm³; upper quartile, 57.7 mm³). Volume measurements from the five configurations are shown in Table 2. A paired *t* test found that comparable stone volumes were estimated by images obtained using Flash with FBP, Flash with SAFIRE, Force with FBP, and Force with ADMIRE (with modified Qr40) (mean difference, -1.2 to 1.0 mm³; $p = 0.30$ – 0.99). However, a significant difference was found between volumes estimated using ADMIRE (Qr40) and those estimated using the four other scanner and reconstruction configurations. Specifically, images obtained with ADMIRE (Qr40) underestimated stone volumes, compared with images obtained using the other configurations (mean difference, -5.1 to -3.9 mm³; $p = 0.0001$ – 0.009). Figures 1 and 2 show the magnitude of and trend in differences between reconstruction algorithms.

We also noted a difference in the magnitude of volume underestimation by ADMIRE (Qr40), when comparing uric acid (UA) and non-UA stones. In our patient study, the postprocessing software identified 15 of 62 stones as purely or primarily composed of UA. The mean error for volume estimations of these UA stones by Force with ADMIRE (Qr40) was 9.0 mm³, which represented 73% of the median UA stone volume of 12.4 mm³. A representative stone is shown in Figure 3A. The remaining 47 stones in our study were of pure non-UA composition. The mean error for volume estimations of non-UA stones with ADMIRE (Qr40) was 1.7 mm³, which represented 13% of the median non-UA stone volume of 13.5 mm³ (Fig. 3B). The median volumes of UA and non-UA stones were comparable; therefore, this difference likely is not attributable to size differences between UA and non-UA stone populations. Furthermore, this relationship between stone composition and volume

underestimation was not seen in the ADMIRE (modified Qr40) data. The mean error of volume estimations by ADMIRE (modified Qr40) was 0.5 mm^3 for UA stones and 0.1 mm^3 for non-UA stones.

Discussion

Given the critical value of stone volume in guiding surgical and treatment decisions, it is necessary to evaluate the accuracy and re-producibility of stone volume measurements across CT scanners and reconstruction algorithms. The present study showed discrepancies in volume estimations between FBP and IR techniques when the third-generation CT scanner was used (Fig. 2). ADMIRE (Qr40) estimated significantly lower volumes than did the other configurations.

Several studies have compared FBP with IR techniques in abdominal imaging and have found that IR is associated with superior image quality and equivalent diagnostic accuracy [17, 22, 23]. These IR techniques use an image-based iteration process called regularization in which areas of low contrast are averaged to decrease noise and areas of high contrast are left intact to preserve spatial resolution [24]. However, many of the evaluation metrics used in these studies, such as pixelated or blurry appearances and detectability, are subject to interpretation by a radiologist. In the present study, which investigates the purely quantitative task of volumetric analysis, the ADMIRE technique appears to alter quantitative measurements in a small but consistent fashion from the reference standard of FBP.

In the context of the present study, we hypothesized that the effect of regularization would potentially manifest between the different stone types and contribute to discordant volume estimations. One common type of stone is the UA stone, which has an attenuation value closer to that of soft tissue than to that of non-UA chemicals [25, 26]. The resulting low-contrast boundary between UA stones and surrounding kidney tissue would be averaged across by the SAFIRE and ADMIRE techniques. On the other hand, non-UA stones, which contain compounds such as calcium oxalate and apatite, have an attenuation value that is much higher than that of the surrounding tissue [25, 26]. Thus, in the present study, we found that, on average, the ADMIRE (Qr40) technique reduced the volume of UA stones by 7.3 mm^3 more than the volume of non-UA stones, with respect to mean volumes. This volume difference is greater than 50% of the median volume of all stones (13.1 mm^3). Considering that even a 1- to 2-mm difference in stone size (spherical volume, $> 4.1 \text{ mm}^3$) can alter the therapeutic approach [27], this volume discrepancy may be clinically significant.

The finding that the ADMIRE (mod-Qr40) kernel produced volumes that were insignificantly different from FBP volumes strengthened our suspicion that IR edge effects contributed to the lower volume estimations. The mean difference between volume estimations with the ADMIRE (modified Qr40) technique and mean stone volumes was less than 1 mm^3 for UA and non-UA stones. Thus, we conclude that the ADMIRE (mod-Qr40) kernel had its intended effect of minimizing edge enhancement to improve quantitative accuracy.

We noted no discrepancy between SAFIRE and FBP volume measurements (Fig. 1). SAFIRE uses narrower averaging at object boundaries and, consequently, less edge enhancement than does ADMIRE [28]. We believe that this technical difference improves the quantitative accuracy of SAFIRE relative to FBP. Hence, volume measurements made using SAFIRE data were in significantly different from those made using FBP and ADMIRE (modified Qr40) data.

A limitation of many studies of patients with renal stones, including the present study, is the lack of true measurements of stone volume. For stones that pass spontaneously, we rely on the patient to submit the stones to clinical laboratories for evaluation. Surgically removed stones are often fragmented during the removal procedure, producing samples that cannot be represented by the CT image obtained preoperatively. Moreover, many patients have more than one stone or cluster of stones. Even if the stones are removed intact, it is extremely difficult to match each sample to a stone on the preoperative CT image. Without reference stone volumes for our samples, the absolute accuracy of volume measurements made using the different CT scanner model and reconstruction configurations could not be evaluated. However, the information regarding consistency in stone volume measurements across CT scanner models and reconstruction algorithms provides confidence in the ability to serially evaluate stone growth with the use of these two scanner models and these two types of reconstructions.

A second limitation of the present study is our use of two scanners produced by the same manufacturer and, also, our use of only two reconstruction algorithms, the results for which may not be applicable to other scanner models and reconstruction techniques. However, we believe that our results remain widely applicable because the scanner models used in our study comprise a large share of the dual-energy CT scanners currently used in clinical practice.

In conclusion, after the release of the modified Qr40 kernel with future software versions, clinicians can expect reliable stone volume measurements from both second-and third-generation CT scanners using FBP or IR techniques. Reconstruction kernels that aim to improve object delineation with the use of edge enhancing techniques should be evaluated for quantitative accuracy before they are adopted for quantitative tasks. As CT becomes the standard modality for an increasing number of quantitative clinical tasks, it will become necessary to validate quantitative accuracy for new scanner models and reconstruction algorithms.

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Fig. 1.

Comparison of kidney stone volume estimations. Graph shows stone volume estimations from second-generation dual-source CT scanner (Definition Flash, Siemens Healthcare) using two different reconstruction algorithms: filtered back projection (*black circles*) versus sinogram-affirmed iterative reconstruction (SAFIRE) (*blue circles*). Note the discontinuities in the y-axis scale, indicated by =.

Fig. 2.

Comparison of kidney stone volume estimations. Graph shows stone volume estimations from third-generation dual-source CT scanner (Somatom Force, Siemens Healthcare) using different iterative reconstruction algorithms and kernels: filtered back projection (*black circles*) versus advanced modeled iterative reconstruction (ADMIRE) with Qr40 kernel (*blue circles*) and ADMIRE with modified Qr40 kernel (which reduces edge enhancement effects of ADMIRE) (*pink circles*). Note the discontinuities in the y-axis scale, indicated by =.

Fig. 3.

Comparison of volume estimations of uric acid (UA) kidney stones and non-UA stones, as made using third-generation dual-source CT scanner (Somatom Force, Siemens Healthcare). **A–C**, CT images of UA stones obtained using filtered back projection (FBP) (**A**), advanced modeled iterative reconstruction (ADMIRE) using Qr40 kernel (**B**), and ADMIRE using modified Qr40 kernel (**C**) show volume estimations of 264, 246, and 265 mm³, respectively, indicating that the magnitude of volume underestimation for UA stones was greater than that for non-UA stones.

D–F, CT images of non-UA stones obtained using FBP (**D**), ADMIRE using Qr40 kernel (**E**), and ADMIRE using modified Qr40 kernel (**F**) show volume estimations of 259, 257, and 257 mm³, respectively.

Table 1
Kernels Used for Each Configuration of CT Scanner Model and Reconstruction Type

Scanner Model ^a	Reconstruction Algorithm	Kernel Used
Second generation	FBP	D30
Second generation	SAFIRE	Q30
Third generation	FBP	Qr40
Third generation	ADMIRE	Qr40
Third generation	ADMIRE	Modified Qr40

Note—FBP = filtered back projection, SAFIRE = sinogram-affirmed iterative reconstruction, ADMIRE = advanced modeled iterative reconstruction.

^aThe second-generation CT scanner model was Definition Flash (Siemens Healthcare) and the third-generation model was Somatom Force (Siemens Healthcare).

Table 2
Volume Measurements Obtained Using the Different Configurations of CT Scanner Models and Reconstruction Types

Renal Stone	Second-Generation CT Scanner ^a			Third-Generation CT Scanner ^b		
	FBP D30	SAFIRE Q30	FBP Qr40	ADMIRE Qr40	ADMIRE Modified Qr40	
1	5.8	4.1	6.4	5.4	6.0	
2	5.9	6.0	6.4	5.4	6.0	
3	6.0	5.8	7.7	6.6	7.3	
4	6.1	6.0	3.5	4.8	3.6	
5	6.4	6.1	5.8	4.6	5.3	
6	6.5	5.9	9.8	8.4	9.0	
7	6.7	6.7	6.0	4.7	5.9	
8	6.9	5.8	9.3	7.5	8.6	
9	7.1	7.1	6.8	5.3	6.3	
10	7.2	7.2	7.7	6.5	7.3	
11	7.6	7.6	7.7	6.5	7.5	
12	8.0	7.7	7.2	6.0	6.9	
13	8.6	8.7	9.3	7.1	8.8	
14	9.2	8.3	10.2	9.6	9.8	
15	9.2	8.7	9.6	1.6	12.5	
16	9.3	8.8	9.2	7.8	8.7	
17	9.7	9.3	10.4	8.2	9.9	
18	9.5	7.9	10.3	8.2	9.9	
19	9.6	9.7	10.6	9.0	10.0	
20	10.0	10.0	10.1	8.8	9.8	
21	10.0	9.5	12.8	9.4	11.5	
22	10.5	10.2	10.0	8.7	9.8	
23	10.9	10.7	7.3	6.2	6.7	
24	11.1	11.1	13.5	11.1	12.4	
25	11.1	11.2	11.6	12.2	15.7	
26	11.4	10.4	11.7	2.4	11.0	

Renal Stone	Second-Generation CT Scanner ^a		Third-Generation CT Scanner ^a		
	FBP D30		FBP Qr40	ADMIRE Qr40	ADMIRE Modified Qr40
	SAFIRE Q30	SAFIRE Q30	FBP Qr40	ADMIRE Qr40	ADMIRE Modified Qr40
27	11.8	11.5	11.6	9.5	11.0
28	12.4	12.4	12.3	10.7	11.9
29	12.5	12.4	13.7	11.8	13.3
31	14.0	12.4	13.9	1.6	13.3
32	14.2	14.6	16.1	7.6	9.3
33	15.4	13.2	15.3	13.9	14.9
34	15.5	12.7	15.6	13.0	14.3
35	17.0	16.6	18.1	15.2	17.3
36	18.7	18.3	19.9	17.1	19.1
37	19.7	19.4	21.7	18.7	21.4
38	20.5	20.5	21.4	19.6	21.6
39	20.6	17.5	19.5	17.5	19.3
40	20.8	21.0	22.6	19.9	22.0
41	26.0	26.0	25.6	24.2	25.6
42	31.0	27.1	30.7	27.4	30.6
43	31.8	31.0	29.2	26.3	27.8
44	35.3	35.6	35.5	31.1	35.1
45	25.0	19.0	66.0	57.4	65.5
46	54.9	49.4	51.9	47.4	52.2
47	59.7	60.1	58.7	48.1	58.3
48	68.6	57.6	58.2	53.2	58.4
49	111.0	111.0	109.0	105.0	108.0
50	113.0	109.0	110.0	106.0	110.0
51	120.0	121.0	124.0	109.0	124.0
52	132.0	132.0	127.0	124.0	126.0
53	158.0	162.0	155.0	141.0	155.0
54	158.0	158.0	156.0	155.0	156.0
55	255.0	341.0	302.0	294.0	301.0
56	271.0	269.0	259.0	257.0	257.0
57	275.0	277.0	264.0	246.0	265.0

Renal Stone	Second-Generation CT Scanner ^a		Third-Generation CT Scanner ^b			
	FBP D30	SAFIRE Q30	FBP Qr40	ADMIRE Qr40	ADMIRE Modified Qr40	
58	292.0	297.0	293.0	286.0	295.0	
59	322.0	321.0	318.0	315.0	317.0	
60	377.0	374.0	312.0	291.0	311.0	
61	400.0	402.0	396.0	398.0	395.0	
62	1530.0	1540.0	1580.0	1550.0	1590.0	

Note—Data are volume measurements expressed in cubic millimeters. FBP = filtered back projection, SAFIRE = sinogram-affirmed iterative reconstruction, ADMIRE = advanced modeled iterative reconstruction.

^aDefinition Flash (Siemens Healthcare).

^bSomatom Force (Siemens Healthcare).