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Kidney Stone Volume Estimation from Computerized Tomography Images Using a Model Based Method of Correcting for the Point Spread Function

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Abstract

Purpose—We propose a method to improve the accuracy of volume estimation of kidney stones from computerized tomography images.

Materials and Methods—The proposed method consisted of 2 steps. A threshold equal to the average of the computerized tomography number of the object and the background was first applied to determine full width at half maximum volume. Correction factors were then applied, which were precalculated based on a model of a sphere and a 3-dimensional Gaussian point spread function. The point spread function was measured in a computerized tomography scanner to represent the response of the scanner to a point-like object. Method accuracy was validated using 6 small cylindrical phantoms with 2 volumes of 21.87 and 99.9 mm³, and 3 attenuations, respectively, and 76 kidney stones with a volume range of 6.3 to 317.4 mm³. Volumes estimated by the proposed method were compared with full width at half maximum volumes.

Results—The proposed method was significantly more accurate than full width at half maximum volume ($p < 0.0001$). The magnitude of improvement depended on stone volume with smaller stones benefiting more from the method. For kidney stones 10 to 20 mm³ in volume the average improvement in accuracy was the greatest at 19.6%.

Conclusions—The proposed method achieved significantly improved accuracy compared with threshold methods. This may lead to more accurate stone management.

Keywords

kidney; kidney calculi; tomography, x-ray computed; diagnosis; mathematics

Between 1976 and 1994 nephrolithiasis developed in 5.2% of the American population between ages 20 and 74 years.¹ Nephrolithiasis is a recurrent disease with a relapse rate of about 50% at 5 to 10 years.² Unenhanced CT is a fast, accurate method to diagnose urolithiasis in patients with acute flank pain.^{3,4} It is the diagnostic test of choice for nephrolithiasis. Information on stone size can be extracted from CT images and used as a major consideration when selecting stone treatment.⁵

Kidney stone size is usually quantified as the mean diameter of each stone,^{5,6} which is often measured subjectively using digital calipers. However, this estimation method is not highly accurate or reproducible due to the complex 3-dimensional shape of kidney stones.^{7–9}

Several groups have quantified stone volume from CT images using threshold based methods.^{7,9-12} Demehri et al noted that the variable threshold method provided more accurate results than fixed threshold methods to estimate stone volume.¹⁰ Similar threshold methods were used with CT images to quantify the size or volume of vascular calcifications,^{13,14} pulmonary nodules^{15,16} and the cortical shell of vertebral bones.^{17,18} The general conclusion of these studies was that a threshold equal to half the CT number of the object tended to provide a relatively accurate size or volume. However, a limitation of this method is that the measurement error increases rapidly with decreasing object size.

A major source of error in size or volume measurement is blurring caused by the imaging system, which can be quantified by the PSF. Efforts have been made to improve spatial resolution and measurement accuracy in images using information about the PSF. For PET the PSF is used to correct partial volume averaging and restore pixel values in PET images. A practical method that has been extensively studied and validated is to calculate a recovery coefficient from the PSF.¹⁹⁻²² The recovery coefficient is modeled as a function of the true object diameter, which is estimated in images, eg using registered CT images,^{23,24} the threshold method^{19,25,26} or regions of interest in the PET images.¹⁹ However, since these methods require the true object diameter, the accuracy of the recovery coefficient is limited for small objects, of which the true size is difficult to measure.

We sought to increase the accuracy of volume measurement for small objects to provide an accurate, reproducible method to measure stones of any size. To achieve this goal we propose a volume estimation method, which was developed based on the recovery coefficient method and applied to stone volume measurement.

MATERIALS AND METHODS

Mathematical Theory

We first derived the relationship of object size and FWHM size using the PSF and then defined a correction factor for FWHM size based on this relationship.

Our method is described in 1D first and then generalized to 3D. It was assumed that the CT system meets linear system criteria. When an object $f(x)$ is imaged by a CT system with a PSF of $h(x)$, without considering noise the image $g(x)$ is the convolution between the object function and the PSF according to the equation, $g(x) = \int f(x')h(x - x')dx'$.

Assuming an object $f(x)$ with a constant value of c and a width of a (equation 1),

$$f(x) \begin{cases} c & -a/2 \leq x \leq a/2, \quad a > 0 \\ 0 & \text{others} \end{cases}$$

and a Gaussian PSF $h(x)$ with an SD of σ (equation 2),

$$h(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{x^2}{2\sigma^2}}, \quad \sigma > 0$$

the imaged object can be expressed as

$$g(x) = \frac{c}{\sqrt{2\pi}\sigma} \int_{-a/2}^{a/2} e^{-\frac{(x-x')^2}{2\sigma^2}} dx'.$$

Therefore, $g(0)$ describes the maximum CT number in the image. The FWHM size of the imaged object is $\text{FWHM} = 2t$, where t is the solution to the equation $g(x) = g(0)/2$, $x > 0$. If the object is in a nonzero background, the threshold for FWHM size is equal to the average of the background and the maximum CT number of the object. FWHM size can be derived and calculated for a given object size a and PSF $h(x)$, from which the relationship between FWHM and object size can be established (fig. 1, A).

Since this relationship depends only on the ratio of the size to the SD of the PSF,¹⁹ all data were scaled to σ . When the object is large enough, FWHM is a good estimator of object size. However, as the size of the object decreases, the difference between object size and FWHM size increases dramatically. To achieve an error of less than 5% the object size must be larger than 3.8 for 1D. The object size estimated using this method is referred to as FWHM size and this method is referred to as the FWHM method.

Based on the relationship between object size and FWHM size a correction factor can be defined as (equation 3) correction factor (1D) = a/FWHM . Measured FWHM size is multiplied by this correction factor to provide a more accurate estimation of the true size of the imaged object.

This method can be extended to 3D, which is the scenario for CT imaging. In 3D a uniform sphere with a diameter of d and an isotropic 3-dimensional Gaussian PSF are assumed and the correction factor is defined as (equation 4) correction factor (3D) = d/FWHM .

Based on these assumptions, the correction factor can be calculated for objects with different FWHM sizes. The correction factor was plotted as a function of FWHM size (fig. 1, B). This curve serves as a reference table from which a correction factor can be obtained for a given image object based on FWHM size and the PSF. FWHM size did not always overestimate object size. When object size was larger than a certain threshold (about 3σ), FWHM size underestimated object size, ie the correction factor was greater than 1.

The correction factor acquired in equation 4 is a length correction. When applied to volume estimation, 3 correction factors are required, corresponding to the 3D of the object. They are multiplied together to obtain a volume correction factor.

Scanning Protocol

Validation experiments were performed on a clinical Somatom® Definition FLASH CT system. To investigate the influence of beam energy our routine dual energy protocol for kidney stone analysis was used with tube potentials of 80 and 140 kV. A tin filter was added to the 140 kV tube.²⁷ Since the CT number of stones changes with tube potential, we analyzed data separately at 80 and 140 kV. Collimation was 32×0.6 mm and pitch was 0.6. A reconstruction image slice thickness of 0.6 mm was used, which was the thinnest available, with a medium smooth reconstruction kernel (D30f). All reconstructed images (512×512 matrix) were exported to an external computer. MATLAB® was used for data processing.

Studies

Phantom—The 3-dimensional PSF of the CT scanner was measured using a Catphan® 500 CT image quality phantom with a CPT 528 module (The Phantom Laboratory, Salem, New York). This contained a tungsten carbide bead 0.28 mm in diameter 28 mm away from the center of the phantom. The bead image was fitted to a 3-dimensional Gaussian function to determine the PSF.

To validate that the proposed method would increase the accuracy of volume measurement of small objects a phantom study was done using small solid cylinders made of water and HA. To determine the volume of 2 cylinders diameters and heights were measured. This yielded V1 (21.87 mm³, 3.02 mm diameter, 3.05 mm height) and V2 (99.9 mm³, 5.03 mm, 5.03 mm). These values were used with 3 nominal concentrations of HA (HA200, HA400 and HA800) for a total of 6 cylinders (fig. 2, A).

The cylinders were placed in a water phantom 30 cm in diameter. The described scanning protocol was used. Reconstruction field of view was 30.7 cm and the reconstruction increment was 0.6 mm, resulting in a cubic image voxel with edge length of 0.6 mm.

Kidney stone ex vivo—To determine the accuracy of the proposed method using real kidney stones 76 stones of common types were evaluated, including 30 uric acid, 3 brushite, 13 cystine, 17 calcium oxalate and 13 hydroxyl or carbonate apatite calculi. The reference volume of the stones was measured using the water displacement method. Two graduated cylinders were used to measure the reference volume, including 1 with an inner diameter of 9 mm for stones larger than about 30 mm³ and 1 with an inner diameter of 7 mm for smaller stones. Reference volume measurement was repeated 3 times per stone.

All stones were placed in water filled plastic test tubes (1.5 ml with snap caps). The tubes were placed in a 30 cm diameter water phantom (fig. 2, B). The phantom was scanned using the same scanning and reconstruction parameters as for the described phantom study.

Data Processing

Four steps were performed to determine the volume from the images of the cylinders and the kidney stones, including 1—VOI selection, 2—threshold calculation, 3—FWHM calculation and 4—volume correction. Software was developed at our laboratory to accomplish these procedures. Steps 2 to 4 were totally automatic and step 1 required minimal user interaction.

Step 1—VOI selection—The user selected a cubic volume, such that the VOI contained only 1 object (an HA cylinder or a stone). Voxels in this VOI were processed in the following steps.

Step 2—FWHM volume calculation—To calculate the FWHM volume adaptive threshold the object CT number was estimated by averaging the CT numbers in the interior of the object. An initial internal region was acquired by a threshold equal to 20% of the maximum voxel value without averaging. This region was then eroded by a 3 × 3 × 3 voxel cube to determine the internal region. If the initial region was less than 400 voxels, the maximum voxel value was directly used as the object CT number.

The background CT number was determined by histogram. In each VOI there were usually 2 histogram peaks, including 1 from the background and 1 from the object. The peak with the lower CT number was considered the background CT number.

The mean value of the object and the background CT number was used as the segmentation threshold. The FWHM volume was equal to the total volume of voxels with a CT number larger than the threshold.

Step 3—FWHM size calculation—Object orientation was arbitrary in the image, especially for kidney stones. Thus, 3 principal directions corresponding to object length, width and height, respectively, were calculated by principal component analysis for the surface points of the object.²⁸ FWHM sizes along the 3 principal directions were determined by measuring the distance between the surface points along these directions.

Step 4—volume correction—Since the measured 3-dimensional PSF was anisotropic, as described, 3 σ s corresponding to the 1-dimensional PSFs along the 3 principal directions of the object were calculated from the measured 3-dimensional PSF. FWHMs were then divided by the corresponding σ to obtain FWHM/ σ ratios. The correction factor was obtained by interpolation using these ratios and a curve (fig. 1, *B*). Corrected volume was calculated by multiplying FWHM volume by the 3 correction factors.

Data Analysis

Since FWHM volume was an adapted threshold method with accuracy superior to that of fixed threshold methods of stone volume estimation,¹⁰ we directly compared our method with FWHM volume to demonstrate the improvement vs these threshold methods. Two terms were used to determine the accuracy of the results, including volume error = (measured volume from CT images – reference volume)/reference volume and volume error reduction = volume error of the FWHM method – volume error of the proposed method.

For statistical analysis the Spearman rank correlation was used to analyze the correlation between volume error and the CT number of cylinders. The paired t test was used to compare the volume error of the FWHM and proposed methods, and the volume error using images at 80 and at 140 kV with the tin filter.

A variation that may have affected the final result was VOI selection in data processing step 1. To investigate this influence 3 stones of the smallest, medium and greatest volume (reference volumes 6.3, 84.1 and 317.4 mm³) were measured using 5 VOIs, respectively. We maximized the variation of region of interest selection for size and position, and to ensure that the VOI was large enough to contain the whole stone and only 1 stone.

RESULTS

Phantom Study

Figure 3 shows the results of the phantom study. The volume error of the proposed method strongly correlated with the CT number of the target object (Spearman rank correlation $\rho = 0.88$, $p < 0.001$, fig. 3, *A*). This indicates that for these uniform cylinders contrast was an important factor to accurately estimate volume. Since images at 80 kV usually had better contrast, the volume error at 80 kV was smaller than that at 140 kV with the tin filter ($p = 0.017$). Cylinder volume did not significantly impact the volume error for these 2 sizes (V1 vs V2 $p = 0.15$).

The proposed method significantly decreased volume error compared with the FWHM method ($p = 0.0003$). Figure 3, *B* shows the volume error reduction using the proposed method. Smaller volumes benefited more from the proposed method. Figure 3, *B* shows an exception, which represents the most challenging case, that is HA200 with volume V1 at 140 kV with the tin filter. Figure 4 shows that the cylinder shape was distorted by noise. Excluding this case the average volume error reduction was 16.6% for V1 and 5.5% for V2.

Ex Vivo Kidney Stone Study

Mean $\pm$ SD reference stone volume was 80.1 ± 61.9 mm³ (range 6.3 to 317.4). Figure 5 shows kidney stone volume estimates. The volume error variation greatly increased as stones became smaller (fig. 5, *A*). There was no significant difference between results at 80 kV and at 140 kV with the tin filter ($p = 0.203$). This differed from the phantom study. The probable reason is that most kidney stones had high attenuation, which provided enough contrast for images at 80 kV and at 140 kV with the tin filter. Volume error using the proposed method was significantly decreased compared to that of the FWHM method (p

<0.0001). Figure 5, *B* shows the volume error reduction using the proposed method vs the FWHM method. For the 10 to 20 mm³ volume stone group the average volume error reduction was 19.6%. The relationship of volume error reduction and reference volume was similar to the correction factor curve because the corrected-to-FWHM volume ratio was equal to the correction factor (fig. 1, *B*).

For the influence of VOI selection the volume estimation variation was less than 1% (SD/mean volume) for the largest and medium stones, and 2.2% for the smallest stone using 5 VOIs.

DISCUSSION

We proposed a volume estimation method based on an adaptive threshold segmentation method and a correction for the PSF model. We also determined the accuracy of the method for cylindrical objects and kidney stones. The method showed significant improvement compared with the FWHM method.

The proposed method of measuring stone volume has potential clinical applications. Stone volume is often the major factor directing clinical treatment. Medium to small stones are treated with shock wave lithotripsy or ureteroscopy while percutaneous nephrolithotomy is reserved for larger stones. Precise stone measurement is necessary to direct the patient toward the appropriate treatment modality, specifically when stones are of a size for which different treatment modalities are an option. Precise volume measurement would give the surgeon a better understanding of the true stone burden and provide direction toward a more appropriate treatment modality. Also, an accurate, reproducible volume estimation method would benefit the monitoring of stone growth or shrinkage, which is important to track disease development and treatment effectiveness.

Compared with threshold methods the proposed method improved accuracy by correcting for blurring due to the PSF. The implementation of FWHM volume in our method was superior to that in the previous method¹⁰ since the accuracy of our method was almost independent of the size and position of VOI selection, which made it more convenient and reproducible.

Our method is also more advantageous than the recovery coefficient method used for PET and single photon emission CT. In those methods the recovery coefficient is calculated using true object size, which cannot be directly measured. In our method the correction factor depends on FWHM size, which is directly measurable. Another advantage is that the recovery coefficient method for PET and single photon emission CT does not consider object shape or anisotropic PSF. For volume correction our method uses 3 correction factors, corresponding to the 3D of the object.

A study limitation is that the reference volume measured by water displacement had limited accuracy, particularly for stones with a volume of less than 10 mm³. However, this error did not affect the comparison of the 2 methods.

CONCLUSIONS

We proposed a method to quantify kidney stone volume from CT images that corrected for error due to the PSF. This method was derived from the FWHM method and the PSF based correction, and it significantly improves the accuracy of volume estimates. This method could benefit various tasks of stone management that rely on the accuracy of stone volume estimation using CT.

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Abbreviations and Acronyms

1D	1 dimension
3D	3 dimensions
CT	computerized tomography
FWHM	full width at half maximum
HA	hydroxyapatite
HA200	200 mg HA/cc
HA400	400 mg HA/cc
HA800	800 mg HA/cc
PET	positron emission tomography
PSF	point spread function
V1	volume 1
V2	volume 2
VOI	volume of interest

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Figure 1.

A, relationship between object size and FWHM size in 1D. FWHM size of object equals object size for all sizes (dashed line). Imaged FWHM deviates from object size when object becomes smaller. B, dimensional correction factor curve for sphere as function of FWHM size.

Figure 2.

A, HA cylinders used in phantom study were taped to plastic base with water equivalent x-ray attenuation. B, experimental setup for kidney stone scan. Stone was placed in water filled plastic tube and tubes were placed in 2 plastic racks, which were scanned in water phantom.

Figure 3.

Cylinder phantom study results. *A*, volume error of proposed method vs object CT number. Filled squares indicate V1 at 80 kV. Hollow squares indicate V1 at 40 kV with tin filter. Filled circles indicate V2 at 80 kV. Hollow circles indicate V2 at 140 kV with tin filter. *B*, volume error reduction using proposed method vs FWHM method. Point at lower left represents most challenging case.

Figure 4.
Phantom study image of small V1 size HA cylinders at 140 kV with tin filter, 400/40 display window and width/center CT number.

Figure 5. Kidney stone volume estimation. *A*, volume errors using proposed method. Circles indicate 80 kV. Triangles indicate 140 kV with tin filter. *B*, volume error reduction using proposed and FWHM methods. Bars indicate SE.