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Estimation of Split Renal Function With ^{99m}Tc -DMSA SPECT: Comparison Between 3D Volumetric Assessment and 2D Coronal Projection Imaging

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Abstract

OBJECTIVE—Split renal function (SRF) can be estimated with ^{99m}Tc -labeled dimercaptosuccinic acid (DMSA) SPECT cortical renal scintigraphy on either 2D projected images or 3D images. The purpose of this study was to determine whether there is a significant difference between SRF values calculated with the 2D method and those calculated with the 3D method.

MATERIALS AND METHODS—This retrospective study was performed with ^{99m}Tc -DMSA SPECT images of 316 patients (age range, 1–26 years). All images were reconstructed by filtered back projection. An automated computational method was developed to estimate SRF using both 2D projection images and direct 3D images. A paired t test was used to evaluate the difference between SRFs determined with the two methods and the association between the magnitude of the differences and kidney size, patient age, and SRF.

RESULTS—There was strong correlation between SRFs estimated with the 2D and 3D methods ($r = 0.94$, $p < 0.001$). There was small significant difference ($0.14\% \pm 0.86\%$, $p = 0.003$) in SRFs obtained with the two methods. The difference was clinically negligible and independent of renal length ($p = 0.698$), volume ($p = 0.297$), and patient age ($p = 0.768$) but was associated with SRF ($p = 0.018$).

CONCLUSION—For determination of split renal function, ^{99m}Tc -DMSA SPECT renal scintigraphy 2D coronal projection images perform as well as and are simpler to analyze than 3D images.

Keywords

^{99m}Tc -dimercaptosuccinic acid; DMSA; pediatrics; planar; scintigraphy; SPECT; split renal function

Split renal function (SRF), or differential renal function, is a determination of the relative contribution of each of the two kidneys to total renal function. SRF is helpful for evaluating

and guiding the management of a wide range of renal disorders. SRF can be estimated with renal scintigraphy performed with various radionuclides, including ^{99m}Tc -labeled dimercaptosuccinic acid (^{99m}Tc -DMSA), ^{99m}Tc -labeled mercaptoacetyltriglycine (^{99m}Tc -MAG3), and ^{99m}Tc -labeled diethylenetriaminepentaacetate (^{99m}Tc -DTPA) [1–4]. Other noninvasive modalities and procedures for calculating SRF include CT angiography [3, 5], dynamic contrast-enhanced MR urography [6], and DWI [7]. Among these, ^{99m}Tc -DMSA renal scintigraphy has been considered the most sensitive method for proving the existence of parenchymal damage due to acute or chronic pyelonephritis and acquiring data on differential kidney function [4, 8, 9].

Either planar imaging or SPECT can be used to acquire ^{99m}Tc -DMSA renal cortical images. Although publications comparing the two methods [10–14] have not consistently shown whether SPECT offers a diagnostic advantage over the planar method, SPECT has become the generally preferred method for detecting renal cortical defects because it yields a 3D anatomic image of the renal cortex. Both ^{99m}Tc -DMSA SPECT and ^{99m}Tc -DMSA planar approaches have been used to measure SRF and individual renal function and renal uptake [15–19]. With SPECT, SRF has typically been determined on a 2D coronal projection (sum) image of the reconstructed 3D image. The 3D image is rarely used to estimate SRF, primarily because of the lack of automated and reliable 3D kidney segmentation. Consequently, published data comparing SRFs obtained from 2D kidney regions with background correction and direct 3D kidney volumes are limited. The objective of this study was to compare and characterize SRFs determined from 2D projection images with those determined from direct 3D images.

Materials and Methods

Patients

The study included 316 patients (195 female patients, 121 male patients; age range, 1–26 years; median, 9 years) in whom renal ^{99m}Tc -DMSA SPECT showed two kidneys (632 total kidneys) with no apparent renal cortical abnormalities. Given the absence of anatomic abnormalities, SPECT studies were processed with automated image analysis techniques, including 3D and 2D kidney segmentation and 2D background region generation. All study images were deidentified by removal of personal health information, and the requirement for informed consent was waived by the institutional review board.

Technetium 99m -Labeled Dimercaptosuccinic Acid SPECT

Renal SPECT was performed 3–4 hours after IV administration of 1.85 MBq/kg (minimum, 7.4 MBq; maximum, 111 MBq) ^{99m}Tc -DMSA. All studies were performed with ECAM gamma cameras (Siemens Healthcare) and low-energy ultra-high-resolution collimators. Images were acquired on a 128×128 matrix with both detectors with a noncircular 360° orbit and 120 stops. SPECT images were reconstructed with filtered back projection with a 5-order Butterworth filter (cutoff frequency, 0.35 cycle/cm).

Automated Split Renal Function Measurement

To eliminate interoperator and intraoperator errors caused by manual region and volume delineation, an automated program [20] developed at Boston Children's Hospital was used for calculating renal length, renal volume, 2D SRF, and 3D SRF. Figure 1 is a flowchart that shows the image-processing steps. First, a 2D coronal projection image was created from the reconstructed 3D image. The 2D regions and 3D volumes of kidneys were segmented automatically by use of a pixel-voxel classification [20, 21], which minimized the within-class (kidney and background) variance rather than a fixed threshold. Background regions used for the background correction in 2D SRF estimation were automatically generated by movement of lateral boundaries of kidney regions one pixel (2.4 mm) outward (Fig. 2). Background correction was not required for the estimation of 3D SRF (Fig. 3). The counts inside each kidney 2D ROI or 3D volume of interest were determined. Background correction was applied in calculating counts of the kidney on the 2D image. For each kidney, SRF was calculated as the ratio of the counts in the kidney to the sum of the counts in both kidneys.

Statistical Analysis

Statistical analysis was performed with SPSS 8.0 software (IBM-SPSS). All correlation analyses and regression analyses were performed with the SRF of the left kidney only because SRF is a relative measurement, and the sum of the SRFs of both kidneys is always 100%. SRFs obtained with the 2D and 3D methods were compared by paired two-tailed *t* test, and correlation of the two methods was analyzed with the Pearson correlation coefficient. For each individual, the difference in SRFs calculated with the two methods was determined, and linear regression analysis was used to assess the dependence of this difference on 3D SRF, renal size (volume and length), and patient age. Two-tailed $p < 0.05$ was considered statistically significant for both the *t* test and Pearson correlation coefficient. Both linear regression model equations and scatterplots with 95% prediction intervals were generated for correlation analysis.

Results

The mean SRFs determined from 2D coronal projection images were $50.85\% \pm 2.50\%$ for the left kidney and $49.15\% \pm 2.5\%$ for the right kidney. From 3D reconstruction images the mean SRFs were $50.71\% \pm 2.47\%$ for the left kidney and $49.29\% \pm 2.47\%$ for the right kidney (Table 1). To investigate whether kidney size could affect the accuracy of SRF measurement, the length and volume of the left kidney were also automatically determined with the automated program.

The SRF obtained from 2D projection images was slightly higher ($0.14\% \pm 0.86\%$) in the left kidney than the SRF obtained from 3D images. The paired *t* test showed a small and significant systematic difference ($t = 2.95$, $p = 0.003$) between the two methods. In Pearson correlation analysis, there was high correlation between the two methods ($r = 0.94$, $p < 0.001$). The scatterplot and linear regression analysis results in Figure 4 show the correlation of SRFs estimated between the 2D and 3D methods.

The Pearson correlation coefficients and linear regression models for analysis of 2D-3D SRF difference in relation to 3D SRF, renal volume and length, and patient age are summarized in Table 2. The scatterplots in Figure 5 show the visual representation of SRF difference between 2D and 3D measurements, and the relations to 3D SRF, patient age, and renal volume and length. There was no significant correlation between 2D SRF measure error (3D method as reference standard) and patient age, renal volume, or renal length ($p > 0.05$). There was significant correlation between 2D-3D SRF difference and 3D SRF ($r = -0.133$, $p = 0.018$).

Discussion

Technetium 99m-labeled DMSA SPECT is used primarily for evaluation of cortical anatomy and assessment of renal function, including absolute renal function or individual renal uptake [15–19] and relative renal function or SRF [1–4]. Accurate measurement of percentage individual kidney uptake per injected dose in planar DMSA SPECT depends on the selection of background regions for depth correction. Therefore, selection of the background region, including its size, location, and distance from the kidney, is an important source of measurement errors. For example, selection of a background region too close to or too far from the kidney will result in underestimation or overestimation errors of total kidney counts. However, for SRF, a relative renal function, the background region has limited effect on SRF measurement: it produces similar errors of background correction for both kidneys if left and right background regions have the same properties, such as shape, location, and distance from the kidney.

The results of our study show that SRF estimated from 2D coronal projection images has minimal error (left kidney, $0.14\% \pm 0.86\%$; right kidney, $0.14\% \pm 0.86\%$) in comparison with SRF measured from 3D images. This minimal error is not of clinical significance. The slight 0.14% overestimated left 2D SRF and the underestimated right 2D SRF indicate that the background correction of the left kidney had less compensation for the coronal projection counts below and over the kidney than did the right kidney dose. The lower compensation of background correction in left kidney counts means that there were fewer average counts in the left background region (Fig. 2) than in the right background region. The possible explanation could be related to the liver, which produces a slight asymmetric background to the left and right kidneys.

The results of the correlation analysis ($r = -0.133$, $p = 0.018$) and regression analysis ($y = -0.046x + 2.496$) of the SRF difference between the 3D and 2D methods and 3D SRF (Fig. 5A) indicate that the difference decreases slowly with increased SRF of the left kidney on 3D images. This finding reasonable because the contribution of count error estimated from the 2D method with background correction to SRF decreases with increasing SRF of the left kidney. The correlation between 2D-3D SRF difference and renal volume follows a similar trend, although it is not significant ($r = -0.059$, $p = 0.297$) (Fig. 5B).

Because there is no need for depth correction, ^{99m}Tc -DMSA SPECT has been considered more reliable than the 2D scintigraphic method for estimating individual renal function [22, 23]. To date, however, because of the lack of reliable segmentation of renal volumes, there

have been only a few statistical reports. The fixed threshold (43%) [15–17, 19] of maximum activity has been the single most important factor affecting 3D kidney segmentation because the threshold varies with renal size [24, 25] and patient age. In our previous study [20] and in the current study, we used an optimized thresholding technique based on pixel and voxel classification. Further research on kidney segmentation may take advantage of more sophisticated image-processing techniques, such as iterative triclass thresholding [26] to improve the robustness and accuracy of SRF and individual renal uptake measured with ^{99m}Tc -DMSA SPECT.

To avoid interoperator and intraoperator error and save time and effort required to manually determine 2D regions and 3D volumes of the kidney, the population of our study included only subjects without parenchymal defects, which was a limitation. When a broader clinical population is selected, patients with parenchymal abnormalities should be included for evaluation of the adequacy of 2D measurements of SRF applied to diseased kidneys. Adding subjects with parenchymal defects and known cortical abnormalities may be at the cost of increased measurement errors due to inaccurate drawing of 2D regions and 3D volumes on DMSA SPECT images. It is difficult to draw a region of DMSA tracer on a 2D image with an incomplete renal outline, and this will probably primarily be dependent on the operator's guess as to the limits of the functional renal image. Drawing a 3D renal volume slice by slice on DMSA SPECT images is even more difficult, and the interoperator and intraoperator error may outweigh the real error between 2D and 3D methods. To address this challenge, imaging techniques such as SPECT/CT and image-processing methods are needed to delineate renal regions and volumes with parenchymal defects on fused functional DMSA SPECT and anatomic CT images.

Conclusion

Two-dimensional coronal projection ^{99m}Tc -DMSA SPECT is a simple and effective method for estimating SRF with minimal difference compared with the volumetric method.

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Fig. 1.

Flowchart shows steps in automated measurement of split renal function (SRF). DMSA = ^{99m}Tc -labeled dimercaptosuccinic acid, VOIs = volumes of interest.

Fig. 2.
12-year-old girl with normal kidneys in posterior view. Automated 2D coronal reconstruction of SPECT image shows kidney regions and background regions for split renal function measurement. White lines were used for calculating kidney length.

Fig. 3. 12-year-old girl with normal kidneys in anterior view. Surface rendering of 3D SPECT image shows kidneys segmented with automatic volume segmentation for direct split renal function measurement.

Fig. 4.

Scatterplot shows correlation ($r=0.94$, two-tailed $p<0.001$) between 2D and 3D split renal function and linear regression analysis results ($y=0.927x+3.577$) with 95% prediction interval ($n=316$).

Fig. 5.

Scatterplots show difference between split renal function (SRF) measurements obtained with 2D and 3D methods with 95% prediction interval ($n = 316$).

A, Three-dimensional SRF ($r = -0.133$, two-tailed $p = 0.018$, $y = 0.0464x + 2.496$).

B, Kidney volume ($r = -0.059$, two-tailed $p = 0.297$, $y = -0.0009x + 0.255$).

C, Kidney length ($r = 0.022$, two-tailed $p = 0.698$, $y = 0.0013x + 0.03$).

D, Patient age ($r = -0.017$, two-tailed $p = 0.768$, $y = -0.0026x + 0.116$).

TABLE 1

Split Renal Function (SRF) Values Obtained From 2D Region and 3D Volume of Kidney and Their Differences

Type of Measurement	Left Kidney		Right Kidney	
	Mean $\pm$ SD	Range	Mean $\pm$ SD	Range
2D Region ($n = 316$)	50.85 $\pm$ 2.50	43.74 to 57.04	49.15 $\pm$ 2.50	42.96 to 56.26
3D Volume ($n = 316$)	50.71 $\pm$ 2.47	44.10 to 56.54	49.29 $\pm$ 2.47	43.46 to 55.90
Difference ($n = 316$)	0.14 $\pm$ 0.86	-2.15 to 3.58	-0.14 $\pm$ 0.86	-3.58 to 2.15

Note—Values are percentages.

TABLE 2

Results of Linear Regression and Correlation Analyses of the Dependence of 2D and 3D Split Renal Function (SRF) Difference (y) on 3D SRF, Renal Volume, Renal Length, and Patient Age (x) for Left Kidney ($n = 316$)

Variable (x)	Regression Equation	r	p
SRF (%)	$y = -0.0464x + 2.496$	-0.133	0.018
Kidney volume (cm^3)	$y = -0.0009x + 0.255$	-0.059	0.297
Kidney length (cm)	$y = 0.0013x + 0.03$	0.022	0.698
Patient age (y)	$y = -0.0026x + 0.116$	-0.017	0.768