

7-1-2017

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Recommended Citation

Sontrapornpol, Tanawat; Chaiwatanarat, Tawatchai; Kawinhammasak, Chiramet; Kamklon, Narongsak; and Rattanamonrot, Rinlaphat (2017) "Kidney depth calculation by anterior and posterior renal scintigraphy using attenuation – related techniques," *Chulalongkorn Medical Journal*: Vol. 61: Iss. 4, Article 3.

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Kidney depth calculation by anterior and posterior renal scintigraphy using attenuation – related techniques

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Sontrapornpol T, Chaiwatanarat T, Kawinhammasak C, Kamklon N, Rattanamonrot R. Kidney depth calculation by anterior and posterior renal scintigraphy using attenuation – related techniques. Chula Med J 2017 Jul – Aug;61(4): 425 - 38

Background : *Attenuation correction is one of important steps in calculation of renal function, either glomerular filtration rate (GFR) or effective renal plasma flow (ERPF), from nuclear medicine procedure. To do this correctly, depth of the kidney must be known. Generally, depth of the kidney can be calculated by some equation pre-installed in the machine's computer using patient's weight and height information. This technique will only result in estimated kidney depth values of the patients with the same equation-derived population and will not be valid in patients from other population such as kidney transplanted patients.*

Objective : *To evaluate a more generalized and practical technique in calculation of kidney depth using attenuation-related technique.*

Methods : *By using anterior and posterior images of the body phantom with known width, the kidney depth is calculated using attenuation-related technique and compared with the actual value. The intra- and inter-operator variations are determined. The technique is applied in 98 patients of age 32.75 ± 23.20 (average \pm SD) years old, including 30 children and 68 adults. The results on kidney depth are compared with other technique using lateral view images measurements and equation-derived kidney depth values.*

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Results : *The phantom studies showed no significant intra-operator variations (deviation < 5%, $P \geq 0.99$) and inter-operator variations ($P = 0.9995$). The relationship of calculated kidney phantom depth and the actual value is close to the ideal straight line ($r > 0.99$). The studies in patients show good correlation with other techniques ($r^2 > 0.8099$) and no significant different values of the kidney depth calculated by this technique as compared to lateral view technique ($P = 0.4414$). However, when compared to equation-derived values, there is no significant difference in the adult patients only, but significant difference in pediatric patients.*

Conclusion : *The kidney depth calculation using attenuation related technique is accurate, practical and can be used in most patient groups.*

Keywords : *Kidney depth, renal scintigraphy, attenuation-related technique.*

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Received for publication. February 3, 2017.

ธนวัฒน์ สันทราพรพล, ธวัชชัย ชัยวัฒนรัตน์, จิรเมศร์ กวินธรรมศักดิ์, ณรงค์ศักดิ์ คำกลอน, รินทร์ลภัส รัตนอมรโรจน์. การคำนวณความลึกของไตจากภาพรังสีแกมมาด้านหน้าและหลังของไตด้วยเทคนิคที่เกี่ยวข้องกับหลักการลดทอนของรังสี. จุฬาลงกรณ์เวชสาร 2560 ก.ค. - ส.ค.;61(4):425 - 38

- เหตุผลของการทำวิจัย** : การแก้ไขการลดทอนรังสีภายในร่างกายเป็นหนึ่งในขั้นตอนที่สำคัญในการคำนวณการทำงานของไต ทั้งอัตราการกรองของไต และอัตราการไหลของพลาสมาเข้าสู่ไตด้วยวิธีการตรวจทางเวชศาสตร์นิวเคลียร์ ซึ่งการแก้ปัญหาดังกล่าวอย่างถูกต้องมีความจำเป็นต้องทราบความลึกของไต โดยทั่วไปความลึกของไตสามารถคำนวณได้โดยสมการที่ติดตั้งในเครื่องคอมพิวเตอร์โดยใช้น้ำหนักและส่วนสูงของผู้ป่วย การประมาณค่าความลึกไตด้วยเทคนิคนี้จะทำได้เฉพาะกับผู้ป่วยที่มีลักษณะเดียวกับกลุ่มประชากรที่มีพยาธิสภาพเหมาะสมกับสมการดังกล่าว แต่อาจจะไม่ถูกต้องในผู้ป่วยกลุ่มอื่นที่มีพยาธิสภาพต่างกัน เช่นผู้ป่วยปลูกถ่ายไต เป็นต้น
- วัตถุประสงค์** : เพื่อประเมินเทคนิคที่ง่ายและสามารถใช้ได้กับผู้ป่วยทั่วไป ในการคำนวณความลึกของไตโดยใช้เทคนิคที่เกี่ยวข้องกับการลดทอนรังสีแกมมา ด้วยวิธีการตรวจทางเวชศาสตร์นิวเคลียร์
- วิธีการทำวิจัย** : โดยใช้ภาพถ่ายรังสีแกมมาด้านหน้าและหลังของแบบจำลองร่างกายที่ทราบความหนาและความลึกของไต ความลึกของไตคำนวณโดยใช้เทคนิคที่เกี่ยวข้องกับการลดทอนรังสีแกมมา โดยเทียบกับค่าความลึกที่แท้จริงในแบบจำลอง ความผันแปรภายในและระหว่างผู้คำนวณได้รับการประเมินด้วย จากนั้นนำเทคนิคนี้ไปใช้กับผู้ป่วย 98 ราย อายุ 32.75 ± 23.20 ปี (ค่าเฉลี่ย \pm ค่าเบี่ยงเบนมาตรฐาน) โดยเป็นเด็ก 30 ราย และผู้ใหญ่ 68 ราย ผลความลึกของไตที่คำนวณได้นำมาเทียบกับวิธีวัดระยะความลึกจากภาพด้านข้างของไต และ กับสมการที่ใช้ในการหาความลึกของไต

- ผลการศึกษา** : จากการศึกษานี้ในแบบจำลอง ไม่พบความผันแปรอย่างมีนัยสำคัญ ทั้งภายในผู้ประเมิน (ค่าเบี่ยงเบน <5%, $P \geq 0.99$) และระหว่างผู้คำนวณ ($P = 0.9995$) ความสัมพันธ์ของความลึกของแบบจำลองไตที่คำนวณด้วยวิธีนี้กับค่าความลึกที่แท้จริงใกล้เคียงกันเป็นเส้นตรงในอุดมคติ ($r > 0.99$) การศึกษาในผู้ป่วยพบว่าผลของวิธีการนี้มี ความสัมพันธ์ที่ดีกับเทคนิคอื่น ๆ ($r^2 > 0.8099$) และมีค่าที่ไม่แตกต่างกันของความลึกของไตที่คำนวณได้ เมื่อเทียบกับความลึกของไตที่วัดจากภาพด้านข้าง ($P = 0.4414$) อย่างไรก็ตามเมื่อเทียบกับค่าที่ได้จากสมการไม่มีความแตกต่างกันเฉพาะในผู้ป่วยผู้ใหญ่ แต่แตกต่างกันอย่างมีนัยสำคัญในผู้ป่วยเด็ก
- สรุป** : การคำนวณความลึกของไตด้วยเทคนิคที่เกี่ยวข้องกับหลักการลดทอนของรังสีมีความถูกต้อง กระทำได้ง่ายและสามารถนำมาใช้ได้กับผู้ป่วยเป็นส่วนใหญ่
- คำสำคัญ** : ความลึกของไต, ภาพถ่ายรังสีแกมมาของไต, เทคนิคที่เกี่ยวข้องกับการลดทอนรังสี.

Dynamic images of radionuclide renography provide a rapid and useful quantitative assessment of both absolute and differential kidney function. Fractional uptake methods, based on the accumulation phase of the technetium-99m-diethylenetriaminepentaacetic acid (Tc99m-DTPA) and iodine-131-hippuran (I-131-OIH) renogram, have been reported to correlate with independent measures of glomerular filtration rate (GFR) and effective renal plasma flow (ERPF), respectively.^(1,2) Conventionally, the renal dynamic study is done in the supine position and the camera detector set posterior to the patient. Renogram curves are generated at post-acquisition processing and used to compute the GFR, ERPF and other quantitative parameters.

The accuracy of renal scintigraphy for estimation of GFR or ERPF depends on number of factors including the definition of region of interest, background subtraction, counting statistics, and the tissue attenuation. Variations of skin to kidney center distance without correction for attenuation have been shown to introduce errors in absolute quantification of kidney activity.^(3,4) Considering only the attenuation by soft tissue and assuming a linear attenuation coefficient of 0.153 cm^{-1} for Tc99m, a 1 cm variation in kidney depth will result in a 14 percent change in GFR estimation by the gamma camera.⁽⁵⁾ Correction for tissue attenuation has, therefore, been encouraged by many investigators in the attempt to quantify of renography. Direct measurements of kidney depth, using ultrasound or lateral scintigraphy have been

used by some investigators.^(1,6) For convenience in routine practice use, empirical formulae have been developed to estimate kidney depth from the patient's age and other parameters such as height (cm) and weight (kg). This method will be accurate only when it is applied to the patients of the same population groups that had been used to determine the formula. For example, formula derived from the adult group will not provide accurate kidney depth in children.^(7,8) Base on the same reason, formula derived from the Caucasian group may not provide accurate kidney depth in Asian patients due to the different body structure, as there had been reported of different renal sizes in different ethnic groups.⁽⁹⁾ Theoretically kidney depth can be determined mathematically by attenuation-related formula provided that anterior and posterior images are available with the known antero-posterior diameter of the body. This technique will be a convenience and robust method for kidney depth estimation that may be applied to any population and may even be more accurate than measuring kidney depth from either lateral scintigraphic or diagnostic images alone.

The aim of this study was to evaluate the more generalized and practical technique in calculation of kidney depth using the attenuation-related technique from both anterior and posterior renal scintigraphy in phantom and patients, by comparing the results with the commercial formulae package and direct measurement of kidney depth in lateral renal scintigraphy.

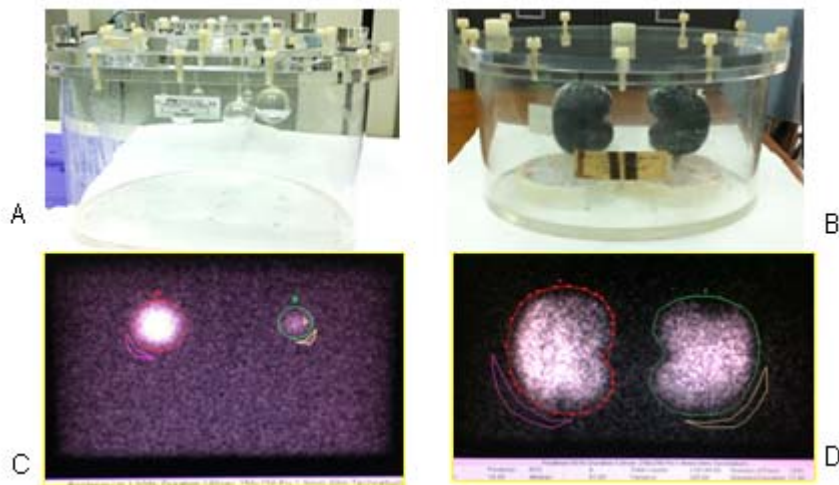


Figure 1. (A) Body phantom and two hollow sphere phantoms with radioactivity inside at activity concentration ratio of 1:4. (B) Home-made kidney phantoms with radioactivity inside body phantom. (C) The scintigraphy of 2 sphere phantoms of different diameters and count density. (D) Scintigraphy of kidney phantoms.

Materials and Methods

Phantom study

Phantom studies were performed to evaluate the feasibility, accuracy and operator variation of the method. Two hollow spheres of different diameter (PET NEMA image quality phantom, PTW, Freiburg, Germany) and home-made kidney phantoms made of absorbent materials, as shown in Figure 1A and 1B, were used. To determine the target to background radioactive activity to be filled in the phantom, 10 clinical renal study images were randomly retrieved from PACS. The first 3 minutes images were added together and the ratio of kidney to background activity was determined in each study. The average of kidney to background activity of these 10 cases was calculated and the result was approximately 4:1. Tc99m-pertechnetate solution was filled in the sphere, soaked in the kidney phantoms and filled in the background solution using 4:1 activity concentration was similar to study of Tc99m-MAG3 in the ten patients, i.e. 55.5 MBq/350cc (1.5 mCi/350 cc) for the sphere lesions and kidney phantoms and 148

MBq/9000 cc (4 mCi/9000 cc) for the background. Simultaneous 3-minute static anterior and posterior scintigraph were acquired using Siemens SPECT ECAM model (Siemens Medical Systems, IL, USA) equipped with a low-energy high-resolution parallel-hole collimator, 256 × 256 matrices size. Image analysis to determine the sphere or kidney phantoms depth was performed step wise as follows:

1. Draw Regions of interest (ROIs) over each sphere, kidney and related background in posterior images as shown in Figure 1C and 1D.
2. Flip posterior ROIs horizontally with some manual adjustment to cover sphere, kidneys and related background in anterior images.
3. Count radioactivity and record area of each ROI. Sphere or kidney depth was then calculated using radiation attenuation techniques as shown in Figure 2 and equation 1 - 3. The net kidney counts were calculated by subtraction of area-normalized background counts from sphere or kidney phantom counts.

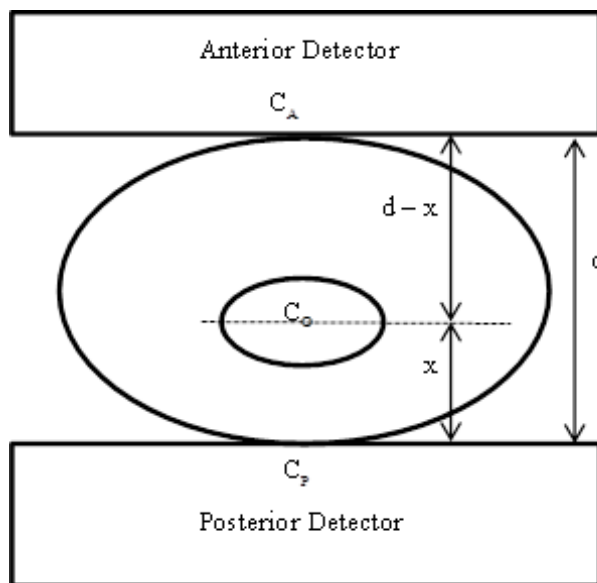


Figure 2. Diagram of the phantom, anterior and posterior detectors and related parameters used to calculate kidney depth in equation 1 - 3.

$$C_A = C_O e^{-\mu(d-x)}$$

$$C_O = \frac{C_A}{e^{-\mu(d-x)}} = C_A e^{\mu(d-x)} \quad \text{_____ (1)}$$

$$C_P = C_O e^{-\mu x}$$

$$C_O = \frac{C_P}{e^{-\mu x}} = C_P e^{\mu x} \quad \text{_____ (2)}$$

(1) = (2)

$$C_A e^{\mu(d-x)} = C_P e^{\mu x}$$

$$x = \frac{1}{2} \left(d - \frac{\ln\left(\frac{C_P}{C_A}\right)}{\mu} \right) \quad \text{_____ (3)}$$

Where

- C_A = net kidney counts from anterior image
- C_P = net kidney counts from posterior image
- C_O = original kidney counts
- X = kidney depth
- d = patient thickness
- μ = attenuation coefficient of Tc99m in tissue = 0.153 cm^{-1}

Intra-operator variation was studied by inserting the kidney phantom at the depth of 11.0 and 12.5 cm. One operator performed the above 3 steps of image analysis repeatedly for 10 times for each phantom depth. Then, for the inter-operator variation study, we repeated the studies by inserting the sphere phantoms at the depth of 8.3, 9.4, 10.7, 11.0, 12.2, 12.5, 14.0, 15.4, 16.2 and 16.9 cm respectively and kidney phantoms at the depth of 7.3, 8.0, 10.0 and 12.0 cm respectively. 4 operators performed image analysis repeatedly 3 times for each sphere and kidney phantom images, a total of 14 data sets for each operator.

Patient study

Ninety-eight consecutive patients undergoing Tc99m-DTPA or Tc99m-MAG3 renal scintigraphy were evaluated retrospectively. The study was approved by IRB Faculty of Medicine, Chulalongkorn University. The patients study included 30 children (age 3.11 ± 3.10 years old, rang 2/12 to 9 years old) and 68 adults (age 45.43 ± 14.55 years old, rang 17 to 90 years old). Weight (kg) and height (cm) of each patient were recorded. Patients were hydrated by drinking 100 – 500 cc of pure water 30 minutes before renal scintigraphic acquisition in supine position using 37-111 MBq (1 – 3 mCi). of Tc99m-DTPA or Tc99m-MAG3.

Image acquisition: The following images were acquired using the same SPECT system as in phantom study with 256×256 (static image), 64×64 (dynamic image) matrices size.

1. Static pre-injection syringe image: 1 minute of syringe image before injection.
2. Dynamic kidney images: immediately after intravenous injection of the radiotracer, anterior

and posterior dynamic images were acquired, covering the kidney and bladder. The acquisition protocol covers 3 phases; 60 frames of 1 sec/frame, 30 frames of 10 sec/frame and 30 frames of 60 sec/frame respectively.

3. Static post-injection syringe image: 1 minute of syringe image after injection.

4. One-minute static images of post-void anterior renal, posterior renal, both lateral renal and the injection site.

Kidney depth calculation

Three techniques of kidney depth calculation were performed.

1. Attenuation-related technique (KD-atten): The kidney depth results from this technique reflect the center of radioactivity in the images. As radiotracer move dynamically from renal cortex, which is slightly more posterior, in the early phase to more anterior in renal pelvocalyceal system in the later phase, hence to calculate kidney depth using early- or later-phase images may result in different depth value, so we applied the technique in 2 different phases of the study. Firstly, using the 30-frame-summed images of the 2nd dynamic phase (1 - 6 min post-injection) (KD-dyn) and secondly, using one-minute post-void static images (36 min post-injection) (KD-static) for depth determination by the same method as in phantom study.

2. Lateral measurement technique (KD-lat): Kidney depth was directly measured from the lateral renal image by averaging the depths of kidney measured from midpoint of upper, middle and lower pole of the kidney to posterior surface of the patient body.

3. Gamma camera's commercially pre-installed 3 formula packages: Kidney depth was calculated by the Gamma camera's pre-installed 3 formula packages, using patient's weight, height and/or age, as the following formulae;

Tonnesen formula (KD-Tonnesen)⁽¹⁰⁾

Right Kidney depth (cm) = 13.3 (weight/height) + 0.7

Left Kidney depth (cm) = 13.2 (weight/height) + 0.7

Emory formula (KD-Emory)⁽¹¹⁾

Right Kidney depth (cm) = 15.31 (weight/height) + 0.022 (age) + 0.077

Left Kidney depth (cm) = 16.17 (weight/height) + 0.027 (age) - 0.94 Itoh formula (KD-Itoh)⁽¹²⁾

Right Kidney depth (cm) = 13.6361 (weight/height)^{0.6996}

Left Kidney depth (cm) = 14.0285 (weight/height)^{0.7554}

Statistical analysis

For intra-operator variation study, the percentage deviation of the phantom depth was calculated from the known depth and Chi-square test was used to analyze the distribution of the results. For inter-operator variation, one way ANOVA was used to evaluate the result. If the ANOVA result was significantly difference, a multiple pair comparison was performed using the Newman Keuls test.

For the patients' studies, the relationship between KD-atten and kidney depth measured by other techniques were determined using one way ANOVA test. If the ANOVA result was significantly difference, a pair *t*-test statistics was used to test the difference between each technique. First we tested the results in all patients. Then we divided patients into adults (age > 15 years) and children (age ≤ 15 years) and performed the same statistics test again.

Results

Phantom study

For intra-operator variation study, the percentage deviation of the 10 calculated sphere phantom depths from the known actual depth ranged from -0.64% to +3.99% with Chi Square value of 1.00 and 0.99 for the depth of 11.0 and 12.5 cm, respectively.

For inter-operator variation study, the one way ANOVA analysis showed no significant difference between each operator (*P* - value = 0.9995).

Patient study

Table 1 - 3 show the results of ANOVA or pair *t* - test for kidney depth determined by each technique in all patients, adults only and children only groups respectively.

Figure 3 shows graph of Pearson correlation for kidney depth determined by each technique in all patients.

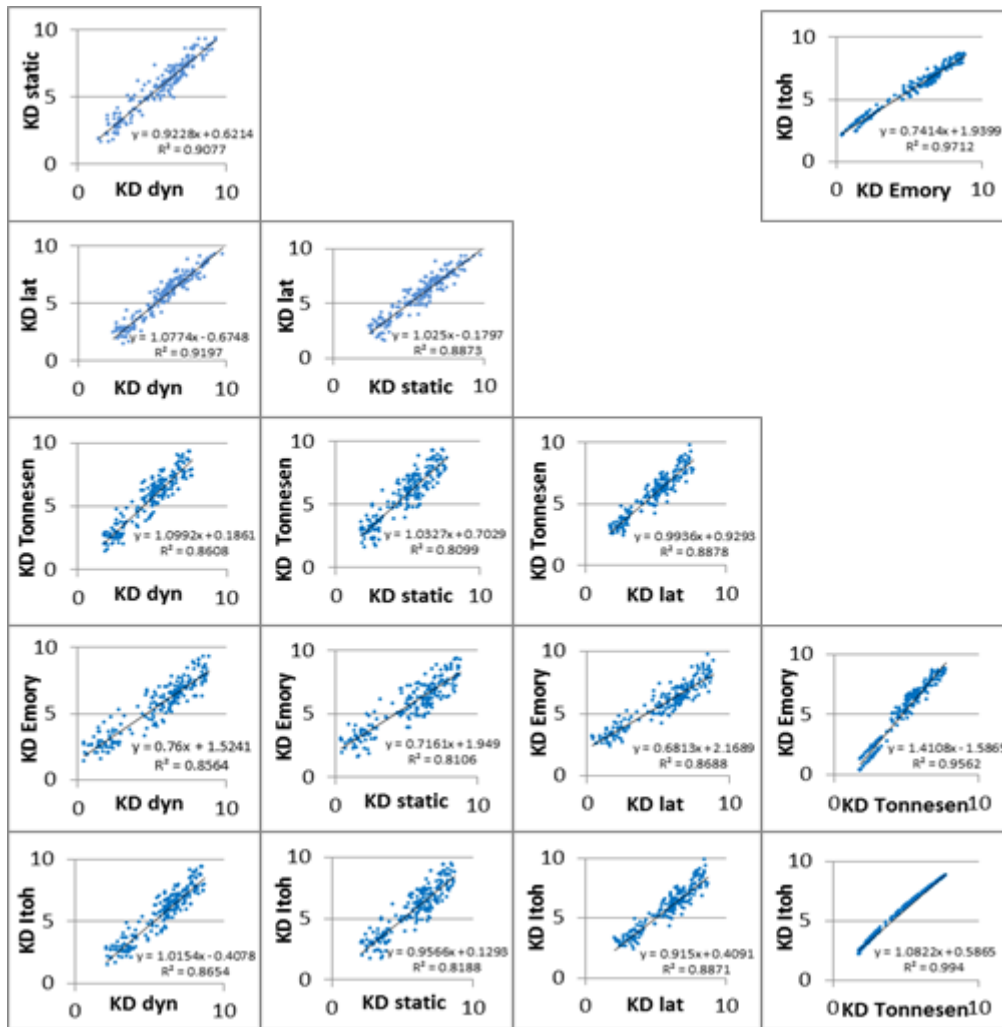


Figure 3. Relationship of kidney depths determined by various techniques.

Table 1. The means (cm), SD (cm) of kidney depths by each technique and the result of ANOVA or pair t-test for each technique comparison in all patients.

KD method	KD-dyn	KD-static	KD-lat	KD-Tonnesen	KD-Emory	KD-Itoh
Mean (cm)	5.5706	5.7675	5.7972	4.8991	5.3254	5.8888
SD (cm)	1.9659	1.9096	1.7505	1.6599	2.3948	1.8018
KD-static	0.9527**					
KD-lat	0.9590**	0.9419**				
KD-Tonnesen	0.9277*	0.8999*	0.9422*			
KD-Emory	0.9254**	0.9003*	0.9320*	0.9778*		
KD-Itoh	0.9302*	0.9049**	0.9418**	0.9969*	0.9854*	

*statistically significant different at 0.05 level ($P < 0.05$)

**statistically not significant different at 0.05 level ($P > 0.05$)

Table 2. The means (cm), SD (cm) of kidney depths by each technique and the result of NOVA or pair *t*-test for each technique comparison in adult patients.

KD method	KD-dyn	KD-static	KD-lat	KD-Tonnesen	KD-Emory	KD-Itoh
Mean(cm)	6.5532	6.6721	6.6486	5.7707	6.6712	6.8525
SD(cm)	1.2511	1.2475	1.1453	0.9773	1.1817	0.9663
KD-static	0.8942**					
KD-lat	0.8094**	0.8703**				
KD-Tonnesen	0.9108*	0.7476*	0.8417*			
KD-Emory	0.7932**	0.7593**	0.8393*	0.9413*		
KD-Itoh	0.8063*	0.7614**	0.8453**	0.9968*	0.9516**	

*statistically significant different at 0.05 level ($P < 0.05$)

**statistically not significant different at 0.05 level ($P > 0.05$)

Table 3. The means (cm), SD (cm) of kidney depths by each technique and the result of ANOVA or pair *t* - test for each technique comparison in pediatric patients.

KD method	KD-dyn	KD-static	KD-lat	KD-Tonnesen	KD-Emory	KD-Itoh
Mean(cm)	3.2774	3.8011	3.9364	2.8900	2.2235	3.6663
SD(cm)	1.5548	1.5449	1.3022	1.0513	1.3784	1.2179
KD-static	0.9108*					
KD-lat	0.9001*	0.8892**				
KD-Tonnesen	0.8732*	0.8336*	0.9187*			
KD-Emory	0.8641*	0.8411*	0.8935*	0.9539*		
KD-Itoh	0.8641*	0.8346**	0.9135**	0.9925*	0.9775*	

*statistically significant different at 0.05 level ($P < 0.05$)

**statistically not significant different at 0.05 level ($P > 0.05$)

Discussion

Attenuation correction for kidney depth is an important step for an accurate calculation of kidney function by renal scintigraphic study. Many methods of kidney depth estimation have been reported.^(7, 8, 11) Among these, the most popular one is to estimate kidney depth by the pre-defined formulae using

weight, height and/or age as variables. It had been shown that formula derived from adult group did not provide accurate results in children population.^(7, 8) Furthermore, the formula derived from Caucasian group may not provide accurate kidney depth in Asian patient due to the different body structure. CT scan and ultrasonogram also have been used for this

purposes, however, they are not convenient in routine practices. CT scan also exposes more radiation to the patient. In order to acquire kidney depth by ultrasonogram, the patient will be posed in different position from scintigraphic study, i.e. sitting or prone, result in different kidney depth results. One method used to acquire kidney depth from lateral renal scintigraphy requires an additional acquisition to measure kidney depths manually which may not provide a reproducible result.

We proposed an attenuation-related technique by using anterior and posterior renal scintigraphs. The calculation used simple mathematical equations and based on the assumption that attenuation coefficient of tissue anterior and posterior to the kidney is the same. Knowing patient's thickness (antero-posterior) kidney depth can be determined. To our best effort, there was no published study that used this same method before. Several published studies used geometric means from anterior and posterior images to estimate differential renal function but not for attenuation correction or kidney depth determination.

We first studied the feasibility, accuracy and operator variation of the technique in sphere and kidney phantoms and found that intra- and inter-operator results were very accurate with deviation from the known actual depth of not more than 5%. Moreover, a one way ANOVA test of the results from four operators confirmed that there was no significant inter-operator variation within 95% confidence.

In patient studies, there was no significant difference between KD-atten and KD-lat in all patients (Table 1). In subgroup analysis (adults and children), there was no significant difference between KD-atten and KD-lat only in the adults subgroups (Table 2).

But in children subgroup, there were significant difference between KD-dyn and KD-static and between KD-dyn and KD-lat (Table 3). The reason is that the methods of measured radioactivity at the center of the images had been used. In second phase, most radioactivity was still in renal cortex which located more posteriorly. Additionally, KD-static method used images from later stage of the examination, when most radioactivity located more anteriorly i.e. in pelvocalyceal system. Moreover, children subjects included in this study were suspected for urinary tract obstruction. Most of them had retention of radiotracer in dilated pelvocalyceal. As a result, most radioactivity would locate more anteriorly when KD-static was calculated, and consequently the KD-static values were different from KD-dyn. Furthermore, dilatation of pelvocalyceal system affected location at the midpoint of kidney used in calculating the KD-lat value. Therefore, there was no significant difference between KD-static and KD-lat in the children subgroups. Nevertheless, in the adult subgroups where most subjects had other renal diseases, there were no retention of radiotracer in pelvocalyceal system, hence there were no difference between KD-dyn and KD-static or KD-lat.

Comparing to other methods, we found that KD-Tonnesen has lower average value, which corresponded to the study done in adults by Taylor A, et al⁽¹¹⁾, and to the study in children by Maneval DC, et al.⁽⁷⁾ Therein, Tonnesen's formula was designed to underestimate renal depth probably because kidney depth measured from ultrasonogram in a sitting position had been used, unlike standard renal scintigraphy where the patient is supine. Comparing to KD-ltoh, our KD-dyn method tends to give lower

value (significant difference found in the adult group). Comparing to KD-Emory calculated by formula from a study in adults, we found similar trend despite no statistical significance. Both KD-Itoh⁽¹²⁾ and KD-Emory methods used kidney depth which the distance from skin to the middle of kidney was measured from CT scan. However, there are more cortical mass on posterior of kidney than the anterior side, results in that more radioactivity in the posterior of kidney in the second phase rather than in the middle.

Our proposed method is based directly on the mathematical formula for attenuation correction, which should be more accurate because it is the measurement of center of radioactivity not the measurement by assumption of attenuation distance from skin to the middle of the kidney. The radioactivity used to assess kidney function was between 2 - 3 minutes after administration, when radiotracer is still in the renal cortex and center of radioactivity is more to the posterior rather than the middle of the kidney. Even though there is no significant difference in general, we found that determining the midpoint of kidney is not straightforward if there is pelvocalyceal system dilatation. Moreover, our proposed method is applicable to all groups of patients.

Nevertheless, the method may not be performed well in obese patients where scatter radiation is substantial and in patients with high level of bowel gas or renal transplanted patients where soft tissue attenuation coefficient in the posterior and anterior is not the same.

Conclusion

A method to compute the kidney depth using attenuation correction in renal function assessment

by renal scintigraphy had been presented. The mathematical formula for attenuation correction, which calculates the center of radioactivity directly from the anterior and the posterior renal images is proposed. This should be more accurate than assuming that the attenuation distance is measured from the midpoint of the kidney, hence makes it applicable to all groups of patients. The proposed method is also practical because most SPECT systems are currently with dual detectors. However, the assumption that anterior and posterior attenuation coefficient are equal may introduce error in obese patients, patients with substantial amount of bowel gas or patients with renal transplantation.

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