Measurement of renal dimensions in vivo: A critical appraisal

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ABSTRACT

Kidney volume is regarded as the most precise indicator of kidney size. However, volume assessment is not widely used clinically because its measurement is difficult due to the complex kidney shape. Apart from the conventional methods of measurement of renal dimensions from X-rays, ultrasound scan, computed tomography scan and magnetic resonance imaging have evolved as the three best modalities for this purpose currently. Assessment of kidney size should also be made individually since many factors like body mass index, height, gender, age, position of kidneys, sex, stenoses and number of renal arteries influence the measurements. In this paper, we have critically analysed the advantages and disadvantages of the various methods of renal morphometry, by reviewing the literature spanning over the period of 1976 – 2009.

Key words: BOLD MRI, computerized tomography, ellipsoid formula, kidney volume, magnetic resonance imaging, ultrasound scan.

INTRODUCTION

The length and volume of kidneys are considered very important parameters for clinical assessment of patients with diabetes, renal artery stenosis and for assessment of renal transplant candidates. A change in kidney dimensions from one examination to the next may be an important indicator for the presence or progression of disease. Renal volume assessment is an important parameter in evaluation and follow up of kidney transplant recipients, CRF and hypertension secondary to renal artery stenosis. It is also useful in younger patients with vesico ureteric reflux (VUR) which alters the morphometrical profile of the kidney. Since therapeutic decisions frequently are based on the results of these measurements, accurate and reproducible methods for assessing renal length and volume are of utmost importance.

Renal size was conventionally determined on X-rays or urography by measuring the renal length, distance of the 1st lumbar vertebra (L1) to the 3rd (L3) or 4th lumbar vertebra (L4), area and parenchymal thickness. The measurements obtained by these methods were associated with various drawbacks. With the advent of newer modalities of investigations, ultrasound sonography (US), computed tomography (CT) and magnetic resonance imaging (MRI) have been effectively used for estimating kidney size and function. The US method that is used to measure kidney volumes is two-dimensional in nature, is subject to operator dependence and uses geometric assumptions about the shape of kidney to estimate kidney volumes. In contrast, CT and MRI can acquire three-dimensional (3D) data and therefore, do not rely on geometric assumptions to estimate organs volumes. In the case of CT, the need for ionizing radiation and potentially nephrotoxic contrast media limits its place as a routine noninvasive imaging method for measuring kidney volumes. Similarly, MRI also has its own limitations in clinical use.

This paper critically evaluates the current methods for assessment of renal dimensions in vivo.

ULTRASOUND SONOGRAPHY

The use of US measurements of renal length to monitor renal
size and growth is widely accepted. The advantages of US include the fact that it is noninvasive, involves no radiation exposure, is widely available and importantly standard nomograms exist for comparison. Sonographically the kidney is seen to consist of a central highly echogenic core called the renal sinus, surrounded by a comparatively less echogenic layer called the renal parenchyma. The central echo complex (or the renal sinus) includes the renal collecting systems, calyces, renal infundibula, arteries, veins, lymphatics, peripelvic fat and part of the renal pelvis. The renal parenchyma consists of the cortex and medulla. The total renal volume includes both the renal sinus and renal parenchyma. An accurate assessment of the renal parenchymal volume (RPV) can be made by excluding the volume of the renal sinus from the total renal volume. The method for US measurement of renal dimensions has been described by Dixit et al., Electronic calipers were used to measure the renal morphometric parameters. Maximum renal depth (D), length (L) and width (W) and the maximum length (l), depth (d) and width (w) of the echogenic central sinus were measured in cm. The volume of the entire kidney and that of the central sinus echoes were calculated using the prolate ellipsoid formula:

\[ V (\text{ml}) = L \times W \times \frac{D_1 + D_2 \times 0.523}{2} \]

where, \( D_1 = \) maximum depth in longitudinal section \\
\( D_2 = \) maximum depth in transverse section

The RPV was calculated by subtracting the renal sinus volume from the renal volume. RPV for children less than 1 year of age was not calculated to avoid error due to paucity of renal sinus fat in that age group. Dixit et al., in their paper reported specific norms for RPV in Indian children. They also observed a significant increase in renal parameters with rise in age, body length, body weight and body surface area (BSA) in children. In a sonographical study conducted by Safak et al., in 712 healthy school-aged children (7-15 years), it was observed that there were no significant differences in organ dimensions with respect to sex. The mean right kidney length was shorter than the left kidney length and the difference was significant (\( P = 0.009 \)).

Longitudinal dimensions of right and left kidneys showed a statistically significant correlation with the measured

| Weeks of gestation | Mean longitudinal length cm (± SD) | Mean transverse length cm (± SD) | Mean longitudinal area cm² (± SD) | Mean transverse area cm² (± SD) |
|--------------------|-----------------------------------|----------------------------------|---------------------------------|--------------------------------|
| 16                 | 1.7 (0.3)                         | 1.0 (0.0)                        | 1.4 (0.2)                       | 1.0 (0.0)                      |
| 17                 | 1.8 (0.1)                         | 1.0 (0.1)                        | 1.6 (0.1)                       | 1.0 (0.0)                      |
| 18                 | 2.0 (0.0)                         | 1.2 (0.0)                        | 2.1 (0.0)                       | 1.2 (0.0)                      |
| 19                 | 2.3 (0.3)                         | 1.2 (0.2)                        | 2.3 (0.3)                       | 1.3 (0.2)                      |
| 20                 | 2.1 (0.1)                         | 1.4 (0.1)                        | 2.0 (0.2)                       | 1.4 (0.1)                      |
| 21                 | 2.1 (0.1)                         | 1.5 (0.0)                        | 2.3 (0.1)                       | 1.5 (0.0)                      |
| 22                 | 2.4 (0.3)                         | 1.6 (0.1)                        | 2.5 (0.4)                       | 1.8 (0.4)                      |
| 23                 | 2.5 (0.3)                         | 1.6 (0.2)                        | 2.8 (0.7)                       | 1.9 (0.3)                      |
| 24                 | 2.8 (0.2)                         | 1.7 (0.2)                        | 3.9 (0.5)                       | 2.4 (0.4)                      |
| 25                 | 2.9 (0.2)                         | 1.6 (0.3)                        | 4.0 (0.4)                       | 1.9 (0.5)                      |
| 26                 | 2.8 (0.1)                         | 1.6 (0.1)                        | 4.5 (0.2)                       | 2.4 (0.3)                      |
| 27                 | 3.0 (0.1)                         | 1.7 (0.2)                        | 4.5 (0.2)                       | 2.4 (0.3)                      |
| 28                 | 3.3 (0.3)                         | 1.9 (0.1)                        | 5.3 (0.7)                       | 3.1 (0.5)                      |
| 29                 | 3.5 (0.2)                         | 2.0 (0.2)                        | 5.8 (0.8)                       | 3.1 (0.5)                      |
| 30                 | 3.4 (0.3)                         | 2.1 (0.3)                        | 6.1 (0.7)                       | 3.7 (0.5)                      |
| 31                 | 3.6 (0.1)                         | 2.1 (0.2)                        | 6.0 (1.0)                       | 3.6 (0.5)                      |
| 32                 | 3.7 (0.2)                         | 2.1 (0.2)                        | 6.4 (0.7)                       | 3.8 (0.3)                      |
| 33                 | 3.7 (0.2)                         | 2.2 (0.3)                        | 6.4 (1.1)                       | 3.9 (0.9)                      |
| 34                 | 3.8 (0.2)                         | 2.4 (0.2)                        | 6.7 (1.2)                       | 4.1 (0.7)                      |
| 35                 | 3.9 (0.3)                         | 2.5 (0.1)                        | 7.1 (1.2)                       | 4.6 (0.3)                      |
| 36                 | 4.1 (0.3)                         | 2.5 (0.1)                        | 7.2 (1.1)                       | 5.2 (0.5)                      |
| 37                 | 4.3 (0.3)                         | 2.6 (0.2)                        | 8.5 (1.1)                       | 5.0 (0.7)                      |
| 38                 | 4.2 (0.3)                         | 2.5 (0.2)                        | 8.3 (0.9)                       | 5.2 (0.8)                      |
| 39                 | 4.2 (0.2)                         | 2.4 (0.3)                        | 7.9 (1.0)                       | 4.7 (0.6)                      |
| 40                 | 4.3 (0.2)                         | 2.4 (0.1)                        | 8.1 (0.5)                       | 5.0 (0.4)                      |
| 41                 | 4.1 (0.2)                         | 2.4 (0.2)                        | 7.1 (1.1)                       | (0.8)                          |

*Shin JS et al., 2007
BSA. Body weight showed the best correlation with right kidney dimension whereas body mass index (BMI) and age showed the weakest correlation with organ dimensions. Chen et al.,[16] also showed that renal length is not only age dependent, but also significantly correlated with other important demographical variables.

Shin et al.,[17] has prepared a nomogram for fetal renal growth expressed in length and parenchymal areas from the longitudinal and transverse US in images from 216 normal fetuses, 16-41 weeks of gestation [Table 1].

Rottenberg et al.,[18] investigated the sonographical measurements of the functioning kidney of children who were born with a single functioning kidney. They observed that compensatory hypertrophy of single functioning kidneys occurs in utero and the size of the single functioning kidneys exceeded established standards for the size of bilateral functioning kidneys in the subjects they studied. Chevalier et al.,[19] also had made similar observations in his studies.

Studies by Emamian et al.,[20] on 665 adult volunteers using renal sonography reported that the median renal lengths were 11.2 cm on the left side and 10.9 cm on the right side. Median renal volumes were 146 cm³ in the left kidney and 134 cm³ in the right kidney. Renal size decreased with age, almost entirely because of parenchymal reduction. Kidneys become relatively wider and thicker with age. One possible explanation for this could be the relaxation of the abdominal wall with age, so that the kidneys are squeezed less in older persons. This would also explain the broadening that becomes most pronounced for the right kidney, which has been squeezed more because of the liver. In their study renal length correlated best with body height. Measurements of renal length obtained with the subjects supine were not significantly different from those obtained with the subjects prone. In all age groups, the parenchymal volume of right kidney was significantly smaller than that of the left. An explanation is that the left renal artery is shorter and straighter than the right one and hence increased blood flow in the left artery may result in relatively increased volume. Gavela et al.,[21] also reported a good correlation of renal parameters with body parameters, the height being the one having the best correlation. The height accounted for 83% of kidney length variability for the left kidney and 85% for the right kidney. However, Moel H[22] showed that renal dimensions measured by using sonography were smaller than those obtained by using radiography because no geometric magnification and no osmotic diuresis caused by intravenous contrast occurred in the former study. In another study conducted on donor kidneys,[23] the measurements made by using sonography were more accurate than measurements based on plain radiographs, excretory urograms or renal angiograms.

In an interesting study by Sargent and Gupta,[24] DMSA scintigraphy and renal sonography performed on the same day in 52 children between 2 months and 16 years were compared. Relative function of the right kidney as shown in the DMSA scintigrams in the direct posterior view was compared with relative volume as determined with US. Renal volumes were calculated by using the formula for a prolate ellipsoid. They observed that the relative renal function and relative renal volume correlated well. In children with normal kidneys, estimated relative renal volume derived from sonography could be expected to lie within 6.7% of the relative renal function determined by scintigraphically. Another modification to significantly reduce renal volume measurement errors was the use of 3D sonography with a matrix array transducer.[25]

The role of renal biometry in the evaluation of UTIs has been a subject of interest. Khan et al.,[26] observed that the renal size and serum C-reactive protein levels were the best predictors for upper UTI in children. The sonographical mean volume of larger kidney in patients with upper UTI (184.4 ± 55.8%) was more than those with lower UTI (95.2 ± 15.4%; P<0.001). Mean volume difference between the two kidneys in patients with upper UTI (45.2 ± 9.5%) was more than lower UTI (9.0 ± 4.7%; P<0.001). Follow-up estimation in 16 patients with upper UTI showed an average of 43.6% reduction in volume of the affected kidney within 7-14 days of starting antibiotics.

There are interesting studies on US measurements of hydronephrotic kidneys. Cost et al.,[27] in their study measured the renal length, bipolar parenchymal thickness and anteroposterior pelvic diameter from serial sonograms of patients with hydronephrosis. Renal longitudinal parenchymal area and renal longitudinal pelvi-caliceal area were also determined. They observed that normal parenchymal area correlated well with normal renal length (r²=0.2). Differential parenchymal area correlated with differential function (r²=0.75), while differential length and bipolar thickness correlated poorly with function (r²=0.01 and 0.42, respectively). The ratio of parenchymal to pelvicaliceal area differentiated patients with unilateral hydronephrosis requiring pyeloplasty from those treated conservatively. The ratio was less than 1.6 in all patients requiring pyeloplasty and greater than 1.6 in those followed conservatively. Therefore, renal parenchymal area was found out to be a more accurate estimate of renal size and function in the hydronephrotic kidney than traditional one-dimensional measurement.

Contrast-enhanced ultrasound (CEU) has been reported as a safe and noninvasive imaging technique suitable for assessment of tissue blood flow, which has been used clinically to assess myocardial blood flow. Kalantarinia et al.,[28] utilized CEU to monitor changes renal blood flow in healthy volunteers following a high protein meal. Renal cortical perfusion was assessed by CEU using low mechanical
index (MI) power modulation angio during continuous infusion of Definity. The ultrasound contrast agent was tolerated well with no serious adverse events. CEU was found out to be a fast, noninvasive and practical imaging technique that could be used for monitoring renal blood velocity, volume and flow.

Although US is a very popular tool for renal morphometry, several authors have questioned the accuracy of renal US measurements, since there could be significant inter observer and intraobserver variability in kidney US measurements. Ferrer et al.,[29] reported that serial length measurements in experimental animals were not more accurate than isolated measurements for predicting final length. Volume measurement was not more accurate then renal length. These could well be the limitations of US.

**COMPUTED TOMOGRAPHY**

Although US has been widely used to measure renal size, many studies have shown that renal length alone is not a good predictor of renal volume. Renal volume best correlates with BSA whereas renal length correlates with body height and the kidney becomes shorter and thicker with age [20]. This, along with inter and intraobserver variability and poor repeatability[30-32] inherent to US, has made this investigative modality questionable to assess renal volume. Contiguous CT slices to evaluate renal volume have been shown to be a reliable, objective and reproducible method of assessing renal volume.[33-35] One potential limitation for the use of CT is the radiation dose involved, particularly if these studies are repeated regularly. To overcome this, Widjaja et al.,[36] suggested that low-dose CT technique was reasonably reproducible and renal volume measurements correlated with single kidney GFR (SKGFR) than length.

Kang et al.,[37] in a comparative study of methods for estimating kidney length in renal transplant donors, suggested that abdominal coronal CT section predicted kidney length more accurately. These authors studied the sizes of donor kidneys obtained after nephrectomy for kidney transplantation in 125 donors. The kidney length was also estimated from the distance between the first and third lumbar vertebrae (L1 – 3), intravenous pyelogram (IVP), abdominal US and abdominal CT. The BSA and total body water (TBW) were calculated using the following formulae

\[ \text{BSA} (\text{m}^2) = \frac{\text{height (cm) \times weight (kg)^{1/2}}}{3600} \]

TBW of males (liters) = 2.447 ± 0.3362 × weight (kg) ± 0.1074 × height (cm) – 0.09516 × age (years)

TBW of females (liters) = -2.097 ± 0.2466 × weight (kg) ± 0.1069 × height (cm)

Glomerular filtration rate (ml/min) was measured by creatinine clearance (Ccr) and technetium–99m diethylene triamine pentaacetic acid (99mTc DTPA) renal scintigraphy. CCcr was measured by using the standard formula (urine creatinine concentration × urinary volume/plasma creatinine concentration).

The sizes of kidneys from the left side were measured after donor nephrectomy. After removal, the kidneys were clamped before anastamosis, and length, width, thickness and weight were measured using sterilized vernier calipers and excluding as much peri-renall fat as possible. To estimate the kidney volume, either the stepped-section method clinically tested on pregnant women[38] and infants[39] or the ellipsoid method[40,41] [kidney volume = length × width × thickness × (π/6)]. The various dimensions of kidneys measured in the actual setting are given in Table 2.

The radiological estimation of kidney size is given in Table 3.

It was observed that all radiological methods were associated with prediction errors, the least being with CT. The kidney length best correlated with body index. Geraghty et al.,[40] also reported the advantages of abdominal CT in measuring renal and other organ volume in vivo.

The usefulness of multidimensional CT to measure kidney volume has been highlighted by various authors.[42,43] Janoff et al.,[44] concluded that CT angiography with 3D reconstruction accurately predicted arterial vasculature in more than 90% of their patients and hence could be used to compare renal volumes. However, these authors warned that accuracy decreased with multiple renal arteries and volume comparisons might be inaccurate when the difference in kidney volumes was within 17.8%.

**Table 2: Actual kidney size according to gender***

| Method     | Length (cm) | Width (cm) | Thickness (cm) | Weight (g) | Volume (cm3) |
|------------|-------------|------------|----------------|------------|--------------|
| All        | 11.08 ± 0.96| 6.25 ± 0.67| 4.83 ± 0.65    | 196.3 ± 41.0| 158.7 ± 62.9 |
| Male       | 11.15 ± 1.02| 6.33 ± 0.66| 4.81 ± 0.77    | 208.2 ± 41.2| 167.0 ± 64.2 |
| Female     | 10.98 ± 0.85| 6.12 ± 0.67| 4.61 ± 0.37    | 177.7 ± 33.2| 146.0 ± 59.2 |

*Kang K-Y et al., 2007

**Table 3: Radiological estimation of kidney size†**

| Method     | Kidney length cm (right) | Kidney length cm (left) |
|------------|--------------------------|-------------------------|
| L1 – L3*   | 10.6 ± 0.8               | 10.6 ± 0.8              |
| IVP        | 11.7 ± 1.0               | 12.3 ± 1.0              |
| US         | 10.2 ± 1.2               | 10.5 ± 0.8              |
| CT1**      | 10.0 ± 0.8               | 10.4 ± 0.9              |
| CT2***     | 10.3 ± 0.7               | 10.7 ± 0.9              |

*Distance between the upper surface of the first lumbar vertebra to the lower surface of the third lumbar vertebra, **(number of CT cuts through the kidney) × 7 mm, ***Kidney length measured by CT coronal section, *Kang K-Y et al., 2007
There have been studies to examine the correlation between CT based and radionuclide renogram-based measures of split renal function of potential live kidney donors. The findings of the above studies suggested that split renal function based on 3D CT models could provide “one stop” evaluation of both the anatomic and functional characteristics of the kidneys of potential live kidney donors. The excretory phase data and the split renal volume data had the best correlation and the smallest difference scores. 3D volumetric analysis of CT angiographical and nephrographical data thus could be a promising alternative to nuclear renography in potential donor kidneys.

MAGNETIC RESONANCE IMAGING

With the availability of MRI techniques, more accurate calculations of renal volume has been possible because with this modality, multiple consecutive image sections through the entire kidney are obtained. Cheong et al., concluded from their study that MRI-derived kidney volumes using the disc summation methods were within 5% of true kidney volume as determined by the reference standard water displacement methods. The ellipsoid formula used in US for kidney volume calculation in their patient series consistently underestimated kidney volumes by 15-18%. By MRI, the range of normal reference values (mean±2 SD) for male and female kidney lengths was 10.7–14.3 and 9.5–13.9 cm, respectively; for male and female kidney volumes, the normal reference values (mean±2 SD) were 132–276 and 87–223 ml, respectively.

The feasibility of functional renal volume assessment using 3D gadolinium-enhanced MR angiography (MRA) in a limited number of subjects (19) has been reported by van den Dool et al., Similar studies in experimental animals by Coulam et al., confirmed that MRI could provide high-resolution images of kidneys and collecting system. With the intravenous administration of a T1 shortening agent such as Gd-DTPA, MRA could be performed to evaluate for renal artery stenosis. Use of a multiphasic 3D fast spoiled gradient recalled echo (3DSPGR) sequence after contrast administration allowed for a combined MRA and renal parenchyma evaluation.

The ideal radiographical modality for the assessment of reflux nephropathy in children with VUR is a matter of debate. While renal US and radionuclide renal scintigraphy are routinely used for upper urinary tract evaluation in patients with VUR, IVU and CT are also used in certain situations. In the last decade, MRI has emerged as a powerful diagnostic tool for imaging the genito-urinary tract in the pediatric population by providing anatomical and functional information without ionizing radiation. Chang SL et al., examined the use of MRI-derived renal volume in 114 children with a history of primary VUR and febrile UTI. They found out that higher grades of reflux were associated with smaller volume and smaller volume was noted in the refluxing and nonrefluxing kidneys of children with VUR. Kidneys of patients with unilateral or bilateral reflux had significantly decreased renal volume compared to controls (P<0.0001). Kidneys in which VUR spontaneously resolved had renal volumes similar to control kidneys (P=0.23). Heuer R et al., also found out that normal renal growth curves could be constructed from MRI-derived renal volumes. In reflux nephropathy, they observed that the cortical fraction was reduced and renal differential function on nuclear scan correlated well with MRI-derived differential volume.

Blood oxygen level dependent (BOLD) MRI has been shown to be a useful method in monitoring the effects of physiological or pharmacological maneuvers in organs. BOLD MRI is an endogenous contrast mechanism and allows for rapid, noninvasive means to assess intra renal oxygenation both in animal models and humans. The technique has been shown to be of value in characterizing diseases that can potentially influence patient management, e.g: identifying kidneys that may be amenable to functional recovery by restoring blood flow in cases with renal artery stenosis and distinguishing between acute rejection from acute tubular necrosis in renal transplants. However, factors like temperature, oxygen supply, pH, blood flow, blood volume, hematocrit, etc. can influence BOLD signals. Hydration status can also significantly influence the renal BOLD MRI measurements.

CONCLUSIONS

Renal length and volume measurements are clinically relevant, serving as surrogates for renal functional reserve and are used frequently as the basis for making clinical decisions. Serial measurements also can provide information regarding disease progression or stability. With the conventional methods of assessing renal dimensions using radiography becoming obsolete due to various drawbacks including geometric magnification and osmotic diuresis caused by contrast medium, US, CT and MRI remain the methods of choice in current clinical practice. The advantages of each method should be weighed against the cost, availability of equipment, personal expertise, patient demographics and the experience of the clinician who analyses the information.

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