Normal Values for Renal Length and Volume as Measured by Magnetic Resonance Imaging

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The objective of this magnetic resonance imaging (MRI) study was to (1) test the validity of the ellipsoid formula for estimating kidney volume using ex vivo and in vivo models and (2) establish a normal range of values for kidney length and volume in patients with no known history of renal disease. The volumes of five excised porcine kidneys were measured by (1) disc-summation method, (2) ellipsoid formula, and (3) water displacement method. In a retrospective, consecutive group of clinically referred patients (n = 150; 300 kidneys), individual kidney volume and length were calculated by the disc-summation method and by multiplanar reformation of MRI data, respectively. For comparison, kidney volumes also were calculated using the ellipsoid formula in all patients. Renal volume that was obtained by MRI using the disc-summation method was within 5% of the volume that was determined by the water displacement method, independent of the spatial resolution of the MRI technique used. Data from both the in vivo and the ex vivo models revealed that the ellipsoid formula that commonly is used in ultrasonography underestimates renal volume by 17 to 29% compared with the disc-summation method (P < 0.05). As measured by MRI (mean ± SD), kidney lengths were 12.4 ± 0.9 cm for men and 11.6 ± 1.1 cm for women, and kidney volumes were 202 ± 36 ml for men and 154 ± 33 ml for women. The results from the ex vivo MRI study show that the kidney volume that was obtained using the disc-summation method is within 5% of the true kidney volume as measured by the water displacement method. The ellipsoid formula consistently and significantly underestimates the true kidney volume. The length and the volume of kidneys that are obtained by MRI in patients with no known history of intrinsic renal disease are greater than the commonly quoted reference values that are obtained by ultrasonography.


The prevalence of ESRD increases each year. In 2002, 1435 patients per million had ESRD in the United States (1), with a total treatment cost in US dollars of $17 billion (6.7% of the 2002 Medicare budget) (2). Patients with renal insufficiency routinely undergo ultrasonography of the kidneys, and measurements typically consist of renal length and, less commonly, renal volume. A change in kidney dimensions from one examination to the next may be an important indicator of the presence or progression of disease. Renal length and volume also are important clinical parameters in the evaluation and follow-up of kidney transplant recipients (3,4), patients with hypertension and renal insufficiency related to renal artery stenosis (5,6), patients with recurrent urinary infections, and younger patients with vescicoureteric reflux. Because therapeutic decisions frequently are based on the results of these measurements, accurate and reproducible methods for assessing renal length and volume are of increasing importance. In addition, an understanding of reference values of normal renal metrics is critical to assess alterations from these values.

A number of investigators have reported reference values for renal length (7–12) and, to a lesser extent, renal volume in healthy adults (7,8), as measured by ultrasonography. The ultrasonography method used to measure kidney volumes is two-dimensional in nature, is subject to operator dependence, and uses geometric assumptions about the shape of the kidney to estimate kidney volumes. In contrast, tomographic imaging methods such as x-ray computed tomography (CT) and magnetic resonance imaging (MRI) can acquire three-dimensional data and, therefore, do not rely on geometric assumptions to estimate organ volumes. In the case of CT, the need for ionizing radiation and potentially nephrotoxic contrast media limits its place as a routine non-invasive imaging method for measuring kidney volumes. Conversely, MRI has the benefit of acquiring true tomographic data along any orientation, without the constraints of ionizing radiation and nephrotoxic contrast burden. Nevertheless, the literature contains few reports of renal dimensions as determined by MRI (8). The purpose of this work was to establish reference values for renal length and volume using MRI in patients with no clinical history of renal disease.
Materials and Methods

Patients

The study was approved by the hospital’s ethics committee. All patients provided informed consent that the data from their MRI examination could be used for research purposes before undergoing the clinically requested MRI examination. We retrospectively identified 150 consecutive patients (89 women; 61 men) who had undergone abdominal MRI and magnetic resonance angiography (MRA) between September 2003 and April 2005 for indications other than renal parenchymal disease. Patients were excluded from the analysis when they had any degree of renal artery stenosis or insufficiency or a history of percutaneous or surgical renal intervention (including angioplasty, renal artery stenting, or transplantation). Other disqualifying factors included multiple renal cysts, polycystic kidney disease, hydronephrosis, a unilateral kidney, inadequate MRI quality as a result of extensive respiratory motion, and incomplete clinical or demographic data. Detailed demographic information of the population is provided in Table 1. All clinical data were extracted from hospital records.

MRI

A three-dimensional, contrast-enhanced MRA of the abdominal aorta is performed routinely as part of the abdominal MRI/MRA study. MRI was performed with a commercially available 1.5-tesla MR scanner (Philips Intera MR scanner; Philips Medical System, Best, The Netherlands). A four-channel phased-array coil was used for signal reception. The water displacement method was used to obtain an independent determination of the kidney volume. The kidneys were immersed in 0.9% saline, and the displaced solution was measured using a graduated cylinder to determine the kidney volume. The measurements were used to suppress the signal from surrounding perirenal adipose tissue and improve delineation of the renal border.

Phantom Study

To evaluate the accuracy of MR for assessing renal volumes in vivo, we performed the following phantom study. Five freshly excised porcine kidneys were obtained from a local market. All surrounding tissues were removed to the extent possible without damaging the integrity of the kidney.

MRI Acquisition

All imaging was performed on the same 1.5-tesla MR scanner that was used for patient studies. A quadrature head coil was used for signal reception. The excised kidneys were placed in the MR scanner and were imaged with four different imaging techniques of progressively increasing acquired spatial resolution (A: 1.9 × 2.1 × 7 mm³; B: 2 × 2 × 4 mm³; C: 2 × 2 × 2 mm³; and D: 1 × 1 × 1 mm³). Techniques A had acquisition parameters and spatial resolution identical to that used in the clinical studies described above. Techniques B, C, and D had progressively higher spatial resolutions and required scan times of 21, 47, and 189 s, respectively.

To assess the effect of the orientation of the kidneys with respect to the imaging plane on volumetric measurements, we performed the following experiment. The transverse imaging volume was angulated with respect to the kidney by adjusting the orientation of spatial encoding gradients. The imaging plane of the ex vivo kidneys was rotated about the right-to-left axis and the anterior-posterior axis, at various angulations from 0 to 40 degrees. This resulted in a total of 84 imaging volumes of the kidneys (four resolutions with nine angulations for each kidney, and four resolutions and three angulations for four kidneys).

Water Displacement Method

The water displacement method was used to obtain an independent determination of the kidney volume. The kidneys were immersed in 0.9% saline, and the displaced solution was measured using a graduated cylinder to determine the kidney volume. The measurements were

Table 1. Demographic data

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Men</th>
<th>Women</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patients</td>
<td>61</td>
<td>89</td>
<td></td>
</tr>
<tr>
<td>Age (yr)</td>
<td>57 ± 15</td>
<td>54 ± 17</td>
<td>NS</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>176 ± 7</td>
<td>162 ± 6</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>90 ± 16</td>
<td>73 ± 18</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>29.3 ± 5.1</td>
<td>28.0 ± 7.0</td>
<td>NS</td>
</tr>
<tr>
<td>BSA (m²)</td>
<td>2.09 ± 0.20</td>
<td>1.81 ± 0.23</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Serum creatinine level (mg/dl)</td>
<td>1.0 ± 0.1</td>
<td>0.8 ± 0.1</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>GFRb (ml/min per 1.73 m²)</td>
<td>85 ± 16</td>
<td>86 ± 23</td>
<td>NS</td>
</tr>
<tr>
<td>Hyperlipidemia (n [%])</td>
<td>30 (49)</td>
<td>12 (13)</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Diabetes (n [%])</td>
<td>15 (25)</td>
<td>14 (20)</td>
<td>NS</td>
</tr>
<tr>
<td>Hypertension (n [%])</td>
<td>43 (70)</td>
<td>48 (54)</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Ischemic heart disease (n [%])</td>
<td>14 (23)</td>
<td>6 (7)</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Cerebrovascular disease (n [%])</td>
<td>5 (8)</td>
<td>6 (7)</td>
<td>NS</td>
</tr>
<tr>
<td>Peripheral vascular disease (n [%])</td>
<td>4 (7)</td>
<td>10 (11)</td>
<td>NS</td>
</tr>
</tbody>
</table>

aData are mean ± SD unless otherwise indicated. BMI, body mass index; BSA, body surface area.

bCalculated by the Modification of Diet in Renal Disease equation: GFR = 186 × (serum creatinine)⁻¹·¹⁵⁴ × (age)⁻⁰·₂⁰₃ × (0.742 if female) × (1.210 if black).
repeated six times, and the mean and SD of the six repeated measurements were calculated (total of 30 measurements). MRI and determination of porcine kidney volume using the water displacement method were completed within 2 h of each other.

**Data Analysis**

Both the patient data and the phantom data were transferred to a commercially available postprocessing workstation (EasyVision, release 5.0; Philips Medical Systems) for analysis. On the transverse T1-weighted gradient echo images, an experienced cardiovascular imager (B.C.) traced the contour of the kidneys. The renal pelvis and vasculature were excluded from the area measurements (Figure 1). The areas that were circumscribed by the manual contour on each slice were summed for each kidney by multiplying the number of pixels within the contour and the area per pixel. Then, multiplying the total area by the slice thickness (0.8 cm), the kidney volume was computed (i.e., the disc-summation or the voxel-count method) for all 150 patients. To determine the length of each kidney, we found the true long axis by reorienting the transverse slices using multiplanar reformations that were angled obliquely along the coronal and sagittal axes of each kidney. In general, the length of the long axis was measured along the craniocaudal direction of each kidney, but occasionally it was measured in the oblique anteroposterior axis for more horizontally oriented kidneys.

To investigate whether there was any difference in renal volume as obtained by the disc-summation method versus renal volume as obtained by the ellipsoid formula that was used in ultrasonography, we performed the following analysis. The length, width, and depth (craniocaudal, left-right, and anteroposterior dimensions, respectively) of each kidney of all 150 patients were measured by multiplanar reformations of the MRI data, and the renal volume was computed using the ellipsoid formula: Volume = \( \pi/6 \times (\text{length} \times \text{width} \times \text{depth}) \), with the width and depth measured at the renal hilum (8,13,14).

**Statistical Analyses**

All data are presented as mean ± SD. Statistical differences were assessed with the two-sample t test when variables were continuous or with the \( \chi^2 \) test for nominal data, using a cutoff value of \( P < 0.05 \) to indicate significance. Correlations between variables were calculated with the Pearson correlation coefficient. All statistical analyses were performed using a commercially available analysis package.

**Results**

**Phantom Study**

Compared with the kidney volume that was determined using the water displacement method (112.7 ± 1.0 ml), the MRI methods (independent of the acquired spatial resolution) consistently underestimated the kidney volumes by no more than 4 to 5%. The mean kidney volumes that were calculated from different angulations between the imaging volume and five kidney specimens showed little difference (between 2 and 3%) when imaged with MR techniques with increasing spatial resolution. The SD of the kidney volume for the MRI method with the highest spatial resolution was the smallest (Table 2), indicating the robustness of high spatial resolution acquisitions in determining the volumes independent of the orientation of the imaging volume with respect to the kidney. In contrast, when the ellipsoid formula was used to calculate ex vivo kidney volumes, it underestimated the true kidney volume by 21 to 29% (Table 3).

**Patient Results**

Compared with women, the men in the study were taller (\( P < 0.0001 \)), were heavier (\( P < 0.0001 \)), and had a higher prevalence of hypertension (\( P < 0.05 \)) and ischemic heart disease (\( P < 0.01 \); Table 1). The serum creatinine in men and women was 1.0 ± 0.1 and 0.8 ± 0.1 mg/dl, respectively. The GFR, calculated by the simplified Modification of Diet in Renal Disease (MDRD) equation (15), in men and women was 86 ± 16 and 86 ± 23 ml/min per 1.73 cm\(^2\), respectively. The MDRD GFR values all were above −2 SD of normal age-adjusted

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**Figure 1.** Representative images depicting the manual tracing of kidney contour for volume calculation using the disc-summation method.
values in both genders, as proposed by Manjunath et al. (15), and are illustrated in Figure 2. No patients were excluded because of inadequate MRI quality as a result of respiratory or other motion. All MRI data sets were of adequate diagnostic quality for kidney length and volume determinations. The length and the volume of the left and right kidneys for men and women are listed in Table 4. Absolute kidney lengths in men were greater than in women ($P < 0.0001$); the difference remained statistically significant when indexed to body surface area (BSA) or weight (although indexed lengths were greater in women than in men) but not to body mass index (BMI) or height (data not shown). With or without indexing to BSA, BMI, or height, male kidney volumes were larger, and this difference was statistically significant ($P < 0.0001$; data not shown).

There was a modest correlation between kidney length and volume in both men and women ($r = 0.5$ in men; $r = 0.6$ in women). There was no correlation between the kidney volumes and BSA in women. However, there was a modest correlation between kidney volume and BSA in men ($r = 0.5$).

The kidney volumes that were calculated by the ellipsoid method were significantly smaller in both genders ($P < 0.0001$; Table 4) when they were compared with the MRI disc-summation method. The mean kidney volume was approximately 18% less by the ellipsoid method in men and 15% less in women.

For clarification of a potential decline in kidney volume with age, the patients were divided empirically into three age groups: ≤40 yr, 41 to 60 yr, and >60 yr. Finer gradations (e.g., by decade) were not made because of the relatively small number of patients within each gender. For men, the right and left renal volumes for the three groups were as follows: 219 ± 38 and 213 ± 41, 212 ± 37 and 217 ± 37, and 190 ± 29 and 192 ± 26 ml, respectively. For women, the right and left renal volumes for the three groups were as follows: 167 ± 41 and 166 ± 39, 152 ± 27 and 160 ± 37, and 147 ± 30 and 148 ± 28 ml, respectively (Figure 3). In both men and women, renal volumes tended to decline with age; however, this trend did not reach statistical significance except between the groups of 41 to 60 yr and >60 yr in men ($P = 0.02$). The findings were similar when the kidney volumes were indexed to BSA.

### Table 2. SD of kidney volumes measured by water displacement and by disc-summation methods in various imaging resolutions

<table>
<thead>
<tr>
<th>Kidney</th>
<th>Mean ± 1 SD</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Water Displacement Volume (ml)</td>
<td>Volume by Disc-summation Method at 28 mm$^3$ Resolution (ml)</td>
</tr>
<tr>
<td>A</td>
<td>101 ± 1.7</td>
<td>99</td>
</tr>
<tr>
<td>B</td>
<td>113 ± 1.0</td>
<td>107</td>
</tr>
<tr>
<td>C</td>
<td>126 ± 2.4</td>
<td>125</td>
</tr>
<tr>
<td>D</td>
<td>158 ± 2.1</td>
<td>151</td>
</tr>
<tr>
<td>E</td>
<td>197 ± 2.1</td>
<td>197</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>MRI ml at 28 mm$^3$</th>
<th>MRI ml at 16 mm$^3$</th>
<th>MRI ml at 8 mm$^3$</th>
<th>MRI ml at 1 mm$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>3.5</td>
<td>2.5</td>
<td>1.7</td>
<td>0.6</td>
</tr>
<tr>
<td>B</td>
<td>5.4</td>
<td>5.8</td>
<td>3.7</td>
<td>1.4</td>
</tr>
<tr>
<td>C</td>
<td>4.2</td>
<td>3.0</td>
<td>1.7</td>
<td>1.0</td>
</tr>
<tr>
<td>D</td>
<td>4.9</td>
<td>3.1</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>E</td>
<td>4.2</td>
<td>3.5</td>
<td>2.9</td>
<td>1.7</td>
</tr>
</tbody>
</table>

aMRI, magnetic resonance imaging.

### Table 3. Ex vivo kidney volumes measured by water displacement and ellipsoid formula: Percentage volume underestimation by the ellipsoid formula compared with the disc-summation and water displacement methods

<table>
<thead>
<tr>
<th>Kidney</th>
<th>Mean Water Displacement (ml)</th>
<th>Volume by Disc-summation Method at 28 mm$^3$ Resolution (ml)</th>
<th>Volume by Ellipsoid Formula (ml)</th>
<th>Volume Underestimation by Ellipsoid Formula versus Disc-Summation Method (%)</th>
<th>Volume Underestimation by Ellipsoid Formula versus Water Displacement (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>101</td>
<td>99</td>
<td>75</td>
<td>24</td>
<td>26</td>
</tr>
<tr>
<td>B</td>
<td>113</td>
<td>107</td>
<td>89</td>
<td>17</td>
<td>21</td>
</tr>
<tr>
<td>C</td>
<td>126</td>
<td>125</td>
<td>93</td>
<td>26</td>
<td>26</td>
</tr>
<tr>
<td>D</td>
<td>158</td>
<td>151</td>
<td>113</td>
<td>25</td>
<td>28</td>
</tr>
<tr>
<td>E</td>
<td>197</td>
<td>197</td>
<td>140</td>
<td>29</td>
<td>29</td>
</tr>
</tbody>
</table>

Discussion

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. A number of reports have described ultrasonography measurement of renal length and volume in the healthy Western population, (7–12), but there are scant data regarding MR measurement of renal dimensions in adults. Bakker et al. (8) examined the kidney sizes of 20 healthy volunteers, and Binkert et al. (5) measured the kidney volumes and blood flow in 65 patients. Approximately 50% of the patients in the study by Binkert et al. had significant renal artery stenoses,
and neither study was designed to estimate reference values for
the length and volumes of kidneys in patients without intrinsic
renal disease. To the best of our knowledge, this is the largest
MRI study to report the length and the volume of kidneys in
patients with no known intrinsic renal disease.

The results from our phantom study highlight several impor-
tant factors. First, the MRI estimates of kidney volumes were
within 5% of the volume as determined using the water dis-
placement method, corroborating that tomographic images of
the kidneys that were acquired using MRI indeed can provide
reliable and consistent determinations of kidney volume with-
out the geometric assumption limitations that are inherent in
the ellipsoid method. Use of the ellipsoid formula for volume
calculation underestimated the true volume of the \textit{ex vivo}
kidneys by 21 to 29%. There is consistent, although only slight,
underestimation of kidney volume as determined by the MRI
disc-summation method compared with the water displace-
ment method. This underestimation may be attributed partly to
the presence of extraparenchymal tissues that were not com-
pletely removed to avoid damaging the renal integrity.

Second, the changes in the acquired spatial resolution of the
imaging techniques from a coarse spatial resolution (a voxel
volume of 28 mm$^3$) to a fine spatial resolution (a voxel volume
of 1.0 mm$^3$) did not have an appreciable effect on the mean
kidney volume measured. This suggests that the spatial reso-
lation that was used in routine patient studies (28 mm$^3$ voxel
volume) is sufficient to measure the kidney volumes accurately,
and the partial volume effect at this level of spatial resolution
does not introduce significant errors in volume calculations.

Third, the relative orientation of the kidney with respect to
the imaging volume also did not have an adverse effect in the
measurement of kidney volumes. Independent of the spatial
resolution of the MRI method (1, 8, 16, or 28 mm$^3$) or the
orientations of the imaging volume with respect to the \textit{ex vivo}
kidney specimen, the volume estimates were within 5% of the
true kidney volume. Therefore, the variations in anatomic ori-
entation of the kidney \textit{in vivo} seem to have little effect on the
volumetric measurements. Predictably, the SD of the high spa-
tial resolution imaging technique (1 mm$^3$) was the smallest
among the four techniques used (Table 2), reflecting the immu-
nity of high spatial resolution acquisition to the relative orien-
tation between the object and the imaging volume. Even at the
coarsest spatial resolution acquisition (28 mm$^3$ voxels), the SD
(5.4 ml) of volume in kidney B remained <5% of the mean.

The results from our patient study suggest the following.
First, our work demonstrates that kidney lengths and volumes
by MRI disc summation (men 12.4 $\pm$ 0.9 cm for length and
202 $\pm$ 36 ml for volume; women 11.6 $\pm$ 1.1 cm for length and
154 $\pm$ 33 ml for volume) are consistently larger than reported.
Specifically, the current literature reference values, principally
from ultrasonography measurements, suggest that a normal
adult kidney is approximately 11 $\pm$ 1.0 cm long (7–12), with a
normal volume of 110 to 190 ml in men and 90 to 150 ml in
women (16). An important caution is that these reference values
are based on ultrasonography data where calculations are de-
rived from the ellipsoid formula, which has the previously
noted inherent geometric assumption limitations. Furthermore,
accurate measurement of the length, width, and depth of the
kidney using ultrasonography may be hampered by limited
acoustic windows from overlying bowel gas, other soft tissue
structures, or patient body habitus. In addition, the double
oblique orientation of the kidney requires the ultrasonography
operator to make subjective decisions to measure the true
length of the kidneys, values that then are incorporated into
volumetric calculations. Indeed, Bakker et al. (14), using a pig
model, noted the ellipsoid method underestimated kidney vol-
ume by 9 to 24%, and in their group of 20 healthy volunteers
noted a 24% underestimation of ultrasonography ellipsoid for-
mula–derived kidney volumes compared with the MRI disc
summation–determined volumes (Table 5). In contrast, Coulam
et al. (17), also using a pig model, noted that kidney volume as
measured by MRI correlated well with that obtained by water

Figure 2. Modification of Diet in Renal Disease (MDRD) GFR
versus age in men (A) and women (B). The $\pm$2 SD limits of GFR
according to age also are included (15).
displacement ($R^2 = 0.86$), with MRI-based kidney volume underestimating true kidney volume by only 5 to 8%. The ex vivo kidney volume calculations from this MR study also are in agreement with previous reports regarding renal volume measurements (18).

Second, in both our ex vivo and in vivo studies, the kidney volumes that were estimated using the ellipsoid formula consistently were smaller than the volumes that were obtained from the disc-summation method. This underestimation is particularly striking because the ellipsoid formula computed the kidney volume from dimensions that were measured from the reformation of MRI data and did not suffer from intrinsic limitations that are associated with using ultrasonography to make these measurements, as previously discussed.

Third, in contrast to previous reports, the results from our study do not suggest any significant difference between the left and right kidney volumes of either gender (7,10). A study by Emamian et al. (7) of 665 adult volunteers who were examined by ultrasonography found that kidney volume correlated with BSA in both genders. Furthermore, by indexing the volume to BSA, the gender differences between renal volume were eliminated. In contrast, our study reveals only a modest correlation ($r = 0.5$) between kidney volume and BSA in men and no correlation with BMI, height, or weight. Our data suggest that the range of normal reference values (mean ± 2 SD) for male and female kidney lengths when using MRI is 10.7 to 14.3 and 9.5 to 13.9 cm, respectively; the range of normal reference values (mean ± 2 SD) for male and female kidney volumes is 132 to 276 and 87 to 223 ml, respectively (Table 5).

In addition, it seems that there is a trend for modest decline in renal volume with age (Figure 3), although the trend did not reach statistical significance except between men in the 41- to 60-yr and the >60-yr groups. Greater numbers of patients may be necessary to determine whether a true decline in kidney volume occurs with age.

MRI may be uniquely suited for noninvasive evaluation of renal pathology. Although CT also can provide noninvasive determination of kidney size and volume, the technique entails substantial ionizing radiation and potentially nephrotoxic contrast agent administration that limits its use as a method of choice for routine noninvasive evaluation, particularly in patients with potential renal pathology. Moreover, MRI provides a breadth of information in a single examination that can benefit patient management. For example, in addition to renal morphology and tissue characterization, MRI delineates renal vascular morphology from three-dimensional contrast-enhanced MRA (19), further defines the hemodynamic signifi-

### Table 4. Renal volumes by disc-summation and ellipsoid methods in men and women (mean ± 1 SD)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Disc-Summation Method (ml)</th>
<th>Ellipsoid Method (ml)</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Men</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>right</td>
<td>202 ± 36</td>
<td>166 ± 29</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>left</td>
<td>205 ± 35</td>
<td>168 ± 28</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td><strong>Women</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>right</td>
<td>154 ± 33</td>
<td>130 ± 30</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>left</td>
<td>156 ± 34</td>
<td>131 ± 33</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

![Figure 3. Renal volumes in men (A) and women (B) by different age groups.](image)
cance of renal artery stenoses from signal dephasing in phase-contrast MRA (6,20), and can reveal quantitative information regarding the amount and the pattern of blood flow through renal arteries (21). Accurate kidney volumes and lengths provide additional valuable information to the clinician in determining renal status, as well as in monitoring response to treatment. Our ex vivo phantom study confirms that MRI estimation of renal volumes is not hampered either by the relatively modest spatial resolution of the MRI techniques used in routine clinical practice or by the natural variation in orientation of the kidneys with respect to the orthogonal planes of the body.

Study Limitations

The patients in this study were identified retrospectively from our MRI database. Hospital records were reviewed carefully to ensure that the participants had no intrinsic renal disease. Specifically, the GFR of each patient was calculated using the MDRD formula, and the results were within the mean ± 2 SD of the reference ranges for GFR by age and gender as proposed by Manjunath et al. (15). It is possible that our patients had subclinical renal disease, because more than half were hypertensive; approximately 25% of patients had diabetes; and the mean BMI (29 and 28 kg/m² in men and women, respectively) indicates that our patient group is overweight bordering on obesity. Nonetheless, despite these potentially adverse influences, our measured kidney lengths and volumes still were considerably larger than current reference standards as obtained by ultrasonography.

Our sample size is modest because we included in our database only patients who had normal renal function and did not meet any exclusion criteria. We are currently collecting data prospectively and anticipate having results from a larger population over varying age ranges.

Recent reports have suggested that gadolinium-based contrast agents may lead to acute renal failure in patients with advanced renal disease (22,23). We also routinely obtain images through the abdomen with steady-state free-precession gradient echo and fat-saturated T2-weighted spin echo sequences before gadolinium administration. High contrast between the renal parenchyma and the surrounding tissues is obtained similar to that for postgadolinium imaging sequences. Renal volume as calculated from the aforementioned sequences and the postgadolinium sequences should be comparable; however, direct comparison was not made in this study.

Conclusion

MRI-derived kidney volumes using the disc-summation method are within 5% of true kidney volume as determined by the reference standard water displacement method. In contrast, the ellipsoid formula that is used in ultrasonography for kidney volume calculations in our patient series consistently underestimates kidney volumes by 15 to 18% when compared with the disc-summation method that is used by MRI and, thus, underestimates true kidney volumes by ≥20%. The length and the volume of kidneys as obtained by MRI in patients with no known history of intrinsic renal disease are greater than the commonly quoted reference values that are based on ultrasonography measurements: By MRI, the range of normal reference values (mean ± 2 SD) for male and female kidney lengths is 10.7 to 14.3 and 9.5 to 13.9 cm, respectively; for male and female kidney volumes, the normal reference values (mean ± 2 SD) are 132 to 276 and 87 to 223 ml, respectively. Larger,
prospective studies may provide further incremental refinements in these reference values. The current clinical practice of using traditional ultrasonography-based kidney dimensions can be improved on by the disc-summation technique via MRI, providing more accurate data for clinical decision-making.

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Disclosures
None.

References