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Index terms:
Kidney, MR, 81.121416
Kidney, US, 81.12989, 81.92
Magnetic resonance (MR), volume measurement, 81.121416
Ultrasound (US), comparative studies, 81.12989

Radiology 1999; 211:623–628

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Renal Volume Measurements: Accuracy and Repeatability of US Compared with That of MR Imaging[1]

PURPOSE: To determine the accuracy and repeatability of ultrasonography (US) with the ellipsoid formula in calculating the renal volume.

MATERIALS AND METHODS: The renal volumes in 20 volunteers aged 19–51 years were determined by using US with the ellipsoid formula and magnetic resonance (MR) imaging with the voxel-count method by two independent observers for each modality. The observers performed all measurements twice, with an interval between the first and second examinations. The voxel-count method was the reference standard. Repeatability was evaluated by calculating the SD of the difference (method of Bland and Altman).

RESULTS: Renal volume was underestimated with US by 45 mL (25%) on average. A comparable underestimation was found when the ellipsoid formula was applied to MR images. This indicates that the inaccuracy of US renal volume measurements (*a*) occured because the kidney does not resemble an ellipsoid and (*b*) was not primarily related to the imaging modality. Intra- and interobserver variations in US volume measurements were poor; the SD of the difference was 21–32 mL. For comparison, the SD of the difference in reference-standard measurements was 5–10 mL.

CONCLUSION: Use of US with the ellipsoid formula is not appropriate for accurate and reproducible calculation of renal volume.

Renal length and volume are important parameters in clinical settings such as the evaluation and follow-up of patients with kidney transplants, renal arterial stenosis, recurrent urinary tract infections, or vesicoureteral reflux (1–5). Furthermore, because small kidney size is an indication of irreversible chronic renal failure, it is less useful to perform interventional procedures such as percutaneous transluminal renal angioplasty or diagnostic biopsy (6). Because therapeutic decisions are frequently based on the size of the kidney, it is important that the method of measuring the organ is accurate and precise. Because these measurements are frequently repeated during the course of a patient's treatment or follow-up, a noninvasive method without ionizing radiation is preferred.

At present, ultrasonography (US) is the modality of choice for measuring renal size (7). With this modality, the volume of the kidney is usually calculated by measuring the three orthogonal axes of the kidney and applying these measurements to the ellipsoid formula (2,7). By using this formula, it is assumed that the kidney resembles an ellipsoid. However, the formula does not take into account the variability in the shape of kidneys, and as a result, errors in volume calculations may occur. There is very little information available about the accuracy of US for evaluating renal size (2,8), and the results of several studies (9–13) have shown that this modality is hampered by its poor repeatability (9–13).

More accurate calculation of the renal volume is possible with magnetic resonance (MR) imaging, because with this modality, multiple consecutive image sections through the entire kidney are obtained. After indicating the boundaries of the kidney, the total renal volume is obtained by using the voxel-count method—that is, taking the sum of all voxel

TABLE 1
Mean Renal Volumes and Lengths in 20 Healthy Volunteers

Measurement Method	Mean Value*
Renal volume	
US, ellipsoid formula	136 (92–205)
MR imaging, ellipsoid formula	145 (105–172)
MR imaging, voxel-count method	180 (137–204)
Renal length	
US	11.19 (10.26–12.22)
MR imaging	11.46 (10.55–13.02)

* Renal volume data are cited in milliliters; renal length data are cited in centimeters. Numbers in parentheses are the range.

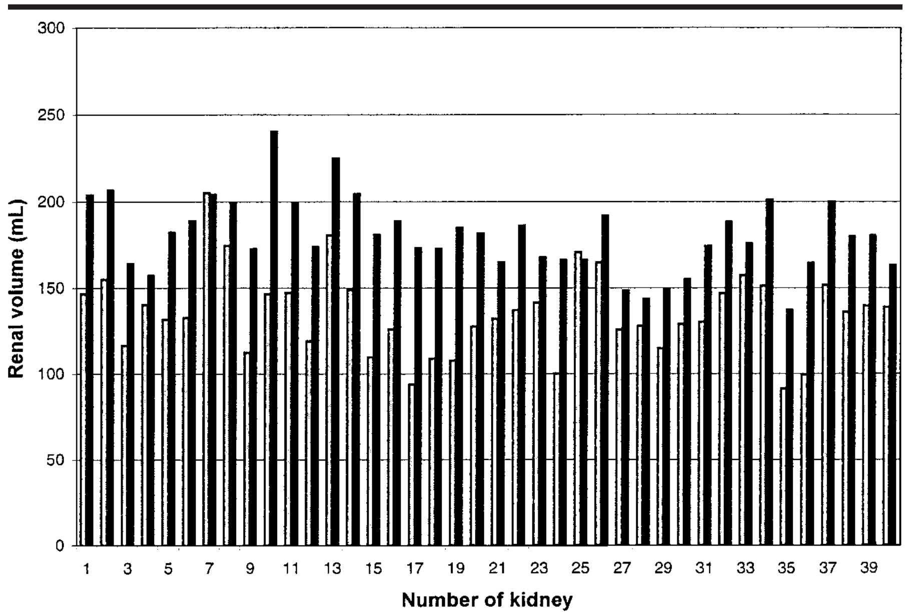

Figure 1. Renal volumes calculated with the ellipsoid formula at US (white bars) compared with those calculated with the standard of reference (ie, voxel-count method applied to MR images) (black bars). Renal volumes calculated with the ellipsoid formula at US were, on average, underestimated by 44.7 mL (25%) compared with those calculated with the standard of reference.

volumes lying within the boundaries. The advantage of using this method is that the shape of the kidney is irrelevant. The results of previous in vitro and in vivo studies (14–25) involving a variety of organs and structures have shown the high accuracy and repeatability of volume measurements obtained with the voxel-count method applied to MR images. Thus, the voxel-count method appears to be a suitable standard of reference to validate other modalities that are used for measuring the renal volume.

The purpose of this study was to determine the accuracy and repeatability of US with the ellipsoid formula in calculating the renal volume, by using the voxel-count method applied to MR images as the standard of reference.

MATERIALS AND METHODS

Study Population

Twenty healthy volunteers (10 men, 10 women; mean age, 36 years; age range, 19–51 years), who had no history of renal disease, hypertension, or other vascular disease, were included in the study. The volunteers were recruited from the hospital personnel. Volunteers with a contraindication for MR imaging were excluded from the study. Their mean body mass index (ie, body weight divided by the body height squared) was 23.2 kg/m^2 (range, 19.0–32.5 kg/m^2). After the study was approved by the local internal review board, written informed consent was obtained from all volunteers.

Modalities

Each volunteer underwent US and MR imaging of both kidneys. There were two independent observers for each modality. To prevent bias, the observers were blinded to the results of their first measurement and to the results of the measurements obtained with the other modality.

US was performed twice in each volunteer by each of the two US observers (R.K., F.J.A.B.), who both were radiologists experienced in this modality. The US studies were performed with an Ultramark 3000 HDI unit (Advanced Technology Laboratories, Bothell, Wash) by using a 2–4-MHz convex transducer. The examination was started with the volunteer in the supine position. If necessary, the volunteers were scanned from a lateral or posterolateral view—whichever approach enabled optimal visualization of the kidney. The renal volume was calculated by using the ellipsoid formula: volume = length × width × thickness × π/6. The maximum length of the kidney was measured in the longitudinal plane and was visually estimated to represent the largest longitudinal section. The width and thickness were measured in the transverse plane perpendicular to the longitudinal axis of the kidney. The level of this transverse section was placed at the level of the hilum. The width and thickness were measured in two orthogonal directions. The first and second US studies performed by each observer were separated by an interval of several days to weeks. For each kidney, the mean of the four US measurements (two obtained by each observer) was used to calculate the accuracy.

MR imaging was performed with a standard 1.5-T unit (Gyroscan ACS-NT; Philips Medical Systems, Best, the Netherlands). After obtaining scout images in two views, respiratory-triggered T2-weighted fast spin-echo imaging was performed in the sagittal, coronal, and transverse planes. The MR imaging parameters included 2,156/120 (repetition time msec/echo time msec), a 90° flip angle, a turbo factor of 17, six signals acquired, a 178 × 256 matrix, a 30-cm field of view, and a 5-mm section thickness without an intersection gap. The image acquisition time was 6–7 minutes. The body coil was used for signal transmission and reception. One MR image was obtained in each volunteer and subsequently read twice by each of the two MR observers (J.B., M.O.). The second measurements were obtained more than 3 weeks after the first measurements. The MR images were evaluated at an EasyVision workstation (Release 2.1; Philips Medical Systems).

Renal volumes were calculated with the voxel-count method applied to the coronal MR images. For this method, the kidneys were segmented by manually tracing the boundaries of the kidney on each section. Partial voluming, which occurs when voxels contain both kidney and surrounding tissue, could lead to an overestimation of the renal volume when all such voxels are included within the

TABLE 2
Intra- and Interobserver Variation in Renal Volume Measurements with US and MR Imaging

Measurement Method	Mean Difference (mL)	SDD* (mL)	95% Limits of Agreement (mL)	Relative SDD (%)†	95% Limits of Agreement (%)‡
US, ellipsoid formula					
Intraobserver, observer 1	−4.8	28.7	−61.0, 51.5	21.9	−46.9, 38.9
Intraobserver, observer 2	−1.0	20.7	−41.6, 39.6	15.5	−31.5, 29.2
Interobserver	−18.7	32.2	−81.9, 44.6	31.0	−75.7, 46.0
MR imaging, voxel-count method					
Intraobserver, observer 1	1.7	4.8	−7.7, 11.1	2.3	−3.5, 5.3
Intraobserver, observer 2	2.1	7.3	−12.2, 16.3	4.0	−6.6, 9.3
Interobserver	3.9	9.9	−15.5, 23.4	5.0	−7.8, 11.8

* SDD = SD of the difference between the first and second measurements obtained by each observer (intraobserver) and between the first measurements obtained by both observers (interobserver).
† SDD expressed as the percentage of the total renal volume.
‡ 95% limits of agreement expressed as the percentage of the total renal volume.

boundaries of the kidney. To avoid this overestimation, the segmentation line was drawn at the halfway point of the change in signal intensity, between the kidney and the surrounding tissue. The total renal volume was then calculated automatically by adding all voxel volumes lying within the boundaries of the kidney. The voxel-count method is also known as the "slice summation method", in which the sum of all areas of the segmented sections is multiplied by the section thickness, including a possible intersection gap. The mean of the four voxel-count measurements (two measurements obtained by each observer) was used as the reference-standard renal volume.

To assess whether the type of imaging modality had an effect on the accuracy of ellipsoid formula–based renal volume calculations, the two MR observers also determined the renal volumes in all volunteers by applying the ellipsoid formula to MR images. For this calculation, the length on multiplanar reformatted MR images of the coronal sections was determined. The width and thickness were measured at the hilum on multiplanar reformatted images of the transverse sections. Multiplanar reformatted images were used to obtain accurate measurements in the three orthogonal directions in both kidneys.

Statistical Analyses

The accuracy of the renal volume measurements, as determined with the ellipsoid formula applied to US and MR imaging, was investigated by calculating, in each kidney, the difference between the volume determined by using the ellipsoid formula and that determined by using the standard of reference (ie, MR imaging with voxel-count method), mean difference, and 95% CI of the mean difference. If this 95% CI did not include zero, the difference in volume calculated by using the two methods was considered to be statistically significant ($P < .05$). For these accuracy calculations, the mean of the four US measurements (two by each observer) and the mean of the four MR measurements, obtained in each kidney, were used.

To describe the intraobserver variation in US renal volume measurements, the method of Bland and Altman (26) was used. For each observer, the differences between the first and second measurements, mean difference, and SD of the differences were calculated. The SD of the difference is a measurement of intraobserver variation; the larger the SD of the difference, the poorer the repeatability of the method (18). Subsequently, the 95% limits of agreement (ie, mean difference ± 1.96 × SD of the difference) were calculated. If a measurement is repeated, there is a 95% probability that the difference between the first and subsequent measurements will lie between the limits of agreement. Similarly, the interobserver variation was evaluated by calculating the SD of the difference and 95% limits of agreement of the first measurements obtained by both examiners. To put the results of analyses of intra- and interobserver variations in US measurements in perspective, the intra- and interobserver variations in measurements obtained by using the standard of reference also were determined. In addition, the intra- and interobserver variations in renal length measurements obtained by using US and MR imaging were calculated.

RESULTS

The mean volumes and lengths of the kidneys in the 20 volunteers are shown in Table 1. In Figure 1, the accuracy of volumes obtained by using the ellipsoid formula with US is shown, and these volumes are compared with those obtained by using the voxel-count with MR imaging method (standard of reference). The volumes obtained with the US-ellipsoid formula method were, on average, 44.7 mL smaller (95% CI: −51 mL, −38 mL) than were those obtained with the standard of reference. This mean underestimation represented 25% (range, 3% to −44%) of the total renal volume and indicated a substantial underestimation of the renal volume with US. Calculating the renal volumes by applying the ellipsoid formula to MR images also resulted in an average underestimation of the volume of 35.3 mL (95% CI: −44 mL, −27 mL), or 19% of the total renal volume.

The intra- and interobserver variations in volume calculations, expressed as the SD of the difference and relative SD of the difference (ie, SD of the difference expressed as a percentage of the total renal volume), are shown in Table 2. The SDs of the difference of intraobserver variation in US renal volume measurements ranged from 20.7 to 28.7 mL. For illustration, US observer 1 had a mean difference between the first and second measurements of −4.8 mL, and an SD of the difference of 28.7 mL. The 95% limits of agreement were −61.0 mL and 51.5 mL, which means that there was a 95% probability that the repeated measurement differed no more than −61.0 to 51.5 mL from the first measurement. The SD of the difference of interobserver variation in US measurements was 32.2 mL. The SDs of the difference of intraobserver variation in reference-standard renal volume calculations ranged from 4.8 to 7.3 mL, and that of interobserver variation was 9.9 mL. The difference in observer variation between US and MR imaging was most obvious when the relative SDs of the difference were compared. The relative SD of the difference took into account that the renal volume was, on average, greater when it was calculated with the voxel-count method than when it was calculated with the ellipsoid formula.

The intra- and interobserver variations in renal length measurements are shown in Table 3. The lowest intra- and interobserver variations in renal length were found with MR imaging.

TABLE 3
Intra- and Interobserver Variation in Renal Length Measurements with US and MR Imaging

Measurement Method	Mean Difference (cm)	SDD* (cm)	95% Limits of Agreement (cm)	Relative SDD (%)†	95% Limits of Agreement (%)‡
US					
Intraobserver, observer 1	−0.13	−0.58	−1.26, 0.99	5.1	−11.2, 8.7
Intraobserver, observer 2	−0.01	0.69	−1.36, 1.33	6.1	−12.0, 11.8
Interobserver	−0.07	0.61	−1.27, 1.13	5.4	−11.2, 9.8
MR imaging					
Intraobserver, observer 1	0.01	0.37	−0.71, 0.72	3.0	−5.8, 5.9
Intraobserver, observer 2	0.06	0.24	−0.54, 0.42	2.1	−4.7, 3.7
Interobserver	0.06	0.17	−0.27, 0.39	1.5	−2.4, 3.4

* SDD = SD of the difference between the first and second measurements obtained by each observer (intraobserver) and between the first measurements obtained by both observers (interobserver).
† SDD expressed as the percentage of the total renal length.
‡ 95% limits of agreement expressed as the percentage of the total renal length.

DISCUSSION

The results of this study show that renal volume calculations obtained by using US with the ellipsoid formula resulted in a substantial systematic underestimation (25%) of the renal volume compared with those obtained by using MR imaging with the voxel-count method (standard of reference). Use of the ellipsoid formula with MR imaging also resulted in a systematic underestimation of the renal volume. That this underestimation of the renal volume occurred with both imaging modalities shows that the inaccuracy is not dependent on the imaging modality but rather related to the use of the ellipsoid formula. The inaccuracy occurs because the kidney is not a true ellipsoid. Because the range of the underestimation was large (3% to −44% of the total renal volume), correction of the inaccuracy is not possible. We found that the mean renal volume calculated with the ellipsoid formula applied to US was comparable to the renal volumes described in other US studies (10,27); thus, our use of the ellipsoid formula seems to be correct.

The inaccuracy of the US renal volume calculations that we found in our study was demonstrated by using the voxel-count method applied to MR images as the standard of reference. Although, to our knowledge, the accuracy of the voxel-count method in measuring renal volumes has never been confirmed in an in vivo study in humans, its reliability in assessing volumes of phantoms and several organs and structures, both in vitro and in vivo, has been shown in several studies (14–25). In a recent in vitro study (14), the accuracy of MR imaging and US in measuring the volumes of porcine kidneys was evaluated. The fluid displacement method was used as the standard of reference. Volumes calculated with the voxel-count method applied to MR images resulted in no substantial deviation from the true renal volume. Volumes calculated with the ellipsoid formula applied to either US or MR imaging resulted, on average, in a 24% underestimation of the renal volume. The results of that in vitro study are additional proof of the high accuracy of the voxel-count method in assessing volumes and confirm the substantial systematic underestimation of renal volumes determined with the ellipsoid formula.

Besides the limited accuracy of US renal volume measurements, the results of this study also showed that the repeatability of this method is not very good. For intraobserver variation in US renal volumetry, the relative SD of the difference varied between 16% and 23% of the total renal volume. The repeatability of renal volumetry with the voxel-count method applied to MR imaging was found to be excellent, with SDs of the difference of intraobserver variation ranging from 2% to 4%. The repeatability of length measurements also was better with MR imaging than with US, with relative SDs of the difference of intraobserver variation of 2%–3% and 5%–6%, respectively. Other investigators studying intra- and interobserver variations in renal length and volume measurements with US have found comparable or slightly better repeatability. For example, Emamian et al (10) found a relative SD of the difference of 4%–5% for renal length and of 14%–17% for renal volume in adults. Ablett et al (9) investigated the repeatability of measuring renal length in adults by using US and found SDs that varied between 0.48 and 0.72 cm. Sargent and Wilson (11) and Schlesinger et al (12), in their studies involving children, found observer variations that were equal to the normal increase in renal length that occurs in 1–2 years, which suggests that two-dimensional US is not very suitable for evaluating renal growth.

Besides the inherent limitation of the ellipsoid formula, the reasons for the poor accuracy and repeatability of renal size measurements with US may be inadequate depiction of the kidney because of obesity or overlying bowel gas or ribs, and inadequate demarcation of the renal borders due to surrounding tissue, renal scarring, or a lack of perirenal fat (7). Furthermore, accuracy and precision can be impaired when length measurements are not obtained along the longest axis of the kidney, which leads to underestimation of renal length (28), and by the measuring width and thickness in a section that is not truly transverse.

The results of this study indicate that when accurate and precise determination of the renal volume is demanded, US with use of the ellipsoid formula is inappropriate. If use of US for measurement of renal size is still preferable, then renal length may be more suitable to determine than renal volume, because the repeatability of renal length measurements with US is reasonably good. Nevertheless, by studying the correlation between renal length and renal volume by plotting both parameters in each kidney against each other (Figure 2), and by calculating the correlation coefficient ($r = 0.36$), one can appreciate that the correlation between these two parameters is weak: Kidneys of a certain length can have a wide range of volumes. This indicates, as suggested in previous studies (27), that renal length is a poorer indicator of the amount of renal parenchyma than is renal volume, and, therefore, it is a poorer parameter for the diagnosis of renal disease. Thus, two-dimensional US is unsuitable for accurate and precise determination of renal size.

In view of the higher costs and increased processing time of MR imaging–based volumetry, US will probably remain the modality of choice in cases

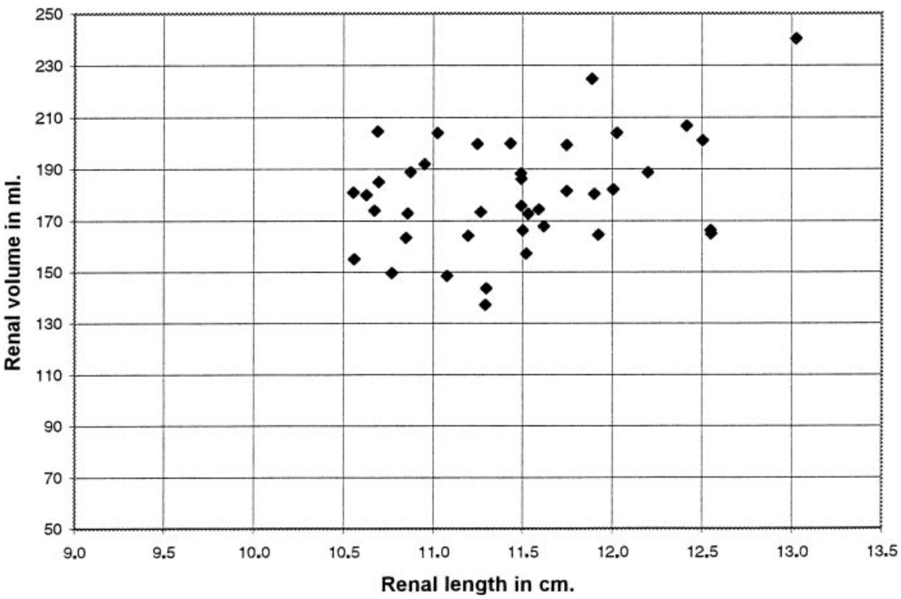

Figure 2. Length and volume of each kidney. Renal lengths were measured on coronal MR images (mean of the two measurements obtained by the two observers). Renal volumes were obtained by applying the voxel-count method to MR images (mean of the two measurements obtained by the two observers). The plot shows that kidneys of a certain length can have a wide range of volumes.

where a ''rough'' impression of the kidney size is sufficient. MR imaging will probably be reserved for cases in which a more accurate and precise determination of renal volume is necessary. For instance, MR imaging could be used in scientific projects for evaluating vascular interventional procedures to assess renal size changes over time. Another research application of MR imaging–based volumetry is the investigation of the normal dimensions of the kidneys in adults in correlation with age, sex, and habitus, because this has been evaluated to a limited extent (27). Examples of clinical indications are important therapeutic decisions such as to start immunosuppressive therapy for progressive glomerulonephritis or to perform a revascularization procedure. One could start with a US measurement of renal length and reserve MR imaging as a second-level method in case of uncertainty. When the renal length was 10 cm or longer, one would be ''safe'' to start a certain treatment or perform a certain procedure. When the renal length was 8–9 cm at US, MR imaging could be used to obtain a more accurate measurement, which could help in the decision making.

In this study, two-dimensional US was used. Volumetry with use of three-dimensional US, like that with the voxel-count method applied to MR images, has the advantage theoretically of not being influenced by the shape of the kidney. In several studies (29–31), it has been shown that three-dimensional US results in accurate volume measurements of phantoms and abdominal organs in vitro. However, the availability of the special equipment required for three-dimensional US is limited, and reports of the accuracy of this method in the kidneys in vivo are scarce (32). Further studies on the accuracy and precision of renal size measurements are warranted to investigate whether three-dimensional US is a useful technique and could be an alternative to two-dimensional US.

A limitation of this study is that the US measurements were obtained at different times, and only one MR image per volunteer was obtained, which was subsequently evaluated two times by each observer. This study design was chosen because we assumed that variation in MR volume measurements would be caused by manually indicating the boundaries of the kidneys and not so much by obtaining a new MR image and the repeated positioning of the imaging volume. Evidence that the repeatability of MR imaging–based renal volumetry is hardly influenced by the positioning of the imaging volume can be derived from the results of our study. We found that renal volumes obtained with the voxel-count method applied to coronal and sagittal MR images were closely related (mean difference and SD of the difference, −2.2 mL and 6.1 mL, respectively). Another source of bias could have resulted from our study design if actual physiologic changes in renal size had occurred over time. This could have led to an even poorer repeatability of US compared with that of MR imaging. To assess the magnitude of these potentially existing physiologic changes in renal size, we obtained a second MR image in four volunteers a few weeks after the first imaging examination and calculated the renal volume with the voxel-count method. The differences in renal volume between the first and second image were small (mean difference, 3.8 mL; SD of the difference, 6.9 mL) and within the range of observer variation. Therefore, it is unlikely that our study design substantially biased the repeatability results. Although changes in renal size under changing physiologic circumstances have been described, the marked changes were found only under experimental circumstances such as with the administration of epinephrine, injection of osmotic and diuretic substances, or artificial inducement of hypotension (33,34). Because the volunteers were examined under normal physiologic circumstances, it is unlikely that possibly minor changes in renal volume influenced the results substantially.

In summary, the results of this in vivo study in humans indicate that volumes calculated with the ellipsoid formula applied to US images can result in a considerable systematic underestimation of the renal volume and have large intra- and interobserver variations. The repeatability of volume measurements with the voxel-count method applied to MR images was good. The correlation between renal length and renal volume was weak, which means that renal length is a poor indicator of renal volume. For accurate and precise calculation of renal volume, US with use of the ellipsoid formula seems to be inappropriate, and MR imaging with use of the voxel-count method is preferred.

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