Objective. The purpose of this study was to evaluate split renal function, estimate single-kidney renal function, and identify cause of obstruction in patients with ureteropelvic junction (UPJ) obstruction by using contrast-enhanced dynamic MR renography (MRR).

Materials and Methods. Seventeen patients with UPJ obstruction underwent MRR and diuresis nuclear renography. Nuclear renography assessment of split renal function and mechanical versus functional obstruction served as the reference standard. The Baumann-Rudin model for determining glomerular filtration rate (GFR) was applied to generate single-kidney renal function (SK-GFRMRR) from MRR cortical and medullary enhancement curves. MRR split renal function of the right kidney (SK-GFRMRR of the right kidney normalized to the sum of SK-GFRMRR of both kidneys) was compared with nuclear renography. The MRR estimate of total GFR (eGFRMRR) was compared with that derived from Modification of Diet in Renal Disease (MDRD) formula (eGFRMDRD). Renal pelvic rate of signal intensity change (PUR) was compared between functionally and mechanically obstructed kidneys.

Results. There was excellent correlation between MRR and nuclear renography measure of split renal function ratio \( r = 0.87, p < 0.01 \), with mean difference of less than 10%. There was moderate correlation \( r = 0.60, p = 0.01 \) between eGFRMRR and eGFRMDRD; eGFRMRR underestimated eGFRMDRD, with mean difference of 13.3 mL/min/1.73 m\(^2\). PUR in mechanically obstructed units was significantly lower \( (0.39 \pm 0.26 \text{ vs } 2.0 \pm 1.38 \text{ min}^{-1}; p < 0.01 \) compared with functionally obstructed units. PUR discriminated mechanical from functional obstruction with accuracy of 89%.

Conclusion. In patients with UPJ obstruction, MRR can measure split renal function, estimate eGFRMDRD with moderate correlation, and accurately discriminate mechanical from functional obstruction, thus potentially providing a “one-stop shop” examination.

Keywords: glomerular filtration rate, MR renography (MRR), renal function, single-kidney renal function, ureteropelvic junction (UPJ) obstruction
MR Renography in UPJ Obstruction

We have implemented a method of measuring the split renal function and GFR from MRR data that appears particularly appealing for diagnosis of UPJ obstruction. The method uses the simple but not well-studied Baumann-Rudin (BR) model [10], an inflow-only model that can be used with low-dose gadolinium contrast agent; does not require an arterial input function [8]; is more robust than other renal models; and provides accurate GFR estimates that compare very favorably to the reference standard values [8].

To provide a “one-stop shop” in the evaluation of UPJ obstruction, our study aimed to evaluate split renal function and estimated single-kidney and total GFR utilizing the Baumann-Rudin model. We also sought to establish a simple MRR metric for the discrimination of functional versus mechanical obstruction using diuresis nuclear renography as a reference standard.

Materials and Methods

Patient Population

This retrospective HIPAA-compliant study received approval from our hospital’s institutional review board and a waiver of consent. We reviewed all cases with UPJ obstruction in our institution between January 2009 and October 2012 that had MRR and diuresis nuclear renography performed within 3 months of each other, with no intervention between the two studies and no change in renal function. A total of 17 such cases were identified with average delay between MRR and nuclear renography of 26 (range, 0–90) days.

These cases were inspected for the presence of identifiable medulla in the kidney with UPJ obstruction, a requirement for the calculation of single-kidney GFR (SK-GFRMDRD). In four patients (one woman, three men; mean age, 50 [range, 38–70] years), owing to long-standing renal atrophy, the renal medulla was not discretely identified, and this group was separately analyzed. For these patients, the mean (SD) serum creatinine was 1.4 ± 0.3 (range, 1.0–1.6) mg/dL, and mean estimated GFR derived from the Modification of Diet in Renal Disease (MDRD) formula (eGFRMDRD) was 52.3 ± 5.7 (range, 46–58) mL/min/1.73 m². The remaining 13 cases were in 8 female and 5 male patients. The mean patient age was 42 (range, 13–83) years; 12 of these 13 patients were 21 years old or older. The mean serum creatinine for these patients was 0.9 ± 0.2 (range, 0.6–1.4) mg/dL, and their mean eGFRMDRD was 84.4 ± 20.7 (range, 52–130) mL/min/1.73 m².

MR Renography Protocol

MRI was performed at 1.5 T (Avanto, Siemens Healthcare). The routine renal protocol included the following sequences: transverse breath-hold T1-weighted in and opposed phases, transverse and coronal breath-hold T2-weighted HASTE sequence, and transverse 3D fat-suppressed T1-weighted interleaved spoiled gradient-echo (VIBE [volumetric interpolated breath-hold examination]) sequence (before contrast agent administration). The parameters of the VIBE sequence were as follows: TR/TE, 3.3–4.5/1.4–1.9; flip angle, 12°; acquisition matrix interpolated to 192 × 256; FOV, 300–400 mm; interpolated slice thickness, 2–3 mm.

Ultralow-dose MRR [11] was performed using a 3D T1-weighted gradient-echo FLASH sequence. Imaging was initiated 5 seconds after administration of 4 mL of gadolinium-DTPA contrast medium (Magnevist, Berlex Laboratories) at a rate of 2 mL/s followed by 20 mL saline flush at the same rate. Imaging was performed coronally covering the abdominal aorta and both kidneys. The parameters of the FLASH sequence were as follows: TR/TE, 2.8–2.9/0.8–1.05; flip angle, 12°; slice thickness, 2.5 mm; bandwidth, 650 Hz/voxel; matrix, 256 × 161; voxel size, 2.2 × 1.4 × 2.5 mm; parallel imaging factor (generalized autocalibrating partial parallel acquisition), 3; slices acquired per sequence, 40; Dynamic acquisitions consisted of 10 initial images at 3 seconds temporal resolution in a long breath-hold (30 seconds), followed by 18 images (each measure with acquisition time of 3 seconds) every 15 seconds, 7 measures every 30 seconds, and 7 measures every 60 seconds, for a total acquisition time of approximately 15 minutes.

Subsequently, high-resolution anatomic imaging was performed utilizing breath-hold coronal FLASH acquisition before contrast agent administration and three times after injection of the remainder of the standard weight-based dose of gadolinium-DTPA contrast material at a rate of 2 mL/s followed by 20 mL saline flush. A first coronal FLASH acquisition was initiated with scan delay equal to time to peak (TTP); TTP was calculated from the initial low-dose gadolinium injection for MRR. This was followed by a second acquisition initiated 7 seconds after the completion of the first acquisition, and a urographic phase coronal FLASH acquisition was performed with scan delay of 7 minutes.

Diuresis Nuclear Renography Protocol

Diuresis nuclear renography was performed using 99mTc-MAG3 radiotracer. Briefly, dynamic images of the kidneys were acquired after IV administration of 10 mCi of 99mTc-MAG3. An initial 30 images were acquired every 2 seconds, followed by 29 images every 1 minute. A postvoiding image was then acquired for 1 minute. IV furosemide (Hospira, USA) was administered at a dose of 40 mg for adults and 2 mg/kg for children (if weighing > 20 kg). Right and left kidney regions...
of interest (ROIs) were outlined on the coronal projection images. The relative right and left radionuclide counts at 2 minutes after tracer injection \((C_{r2min} \text{ and } C_{l2min})\) and before Lasix administration were used to determine the single-kidney renal function ratio \((SK-NUC_{r})\) as follows: \(SK-NUC_{r} = C_{r2min}/(C_{r2min} + C_{l2min})\). Tracer washout kinetic curves were generated before and after furosemide injection with an ROI placed around each kidney and utilizing appropriate background subtraction. The tracer washout half-life was used to assess for the presence of obstruction and to classify the type of obstruction. Half-life of less than 20 minutes before furosemide injection was considered to exclude obstruction; half-lives of more than 20 minutes before and less than 20 minutes after furosemide injection were consistent with functional obstruction; and half-lives of more than 20 minutes both before and after furosemide injection were consistent with mechanical obstruction. All studies were interpreted by a nuclear medicine specialist.

**Baumann-Rudin Model**

MRK concentration curves were used to calculate the single-kidney GFR \((SK-GFR_{MRR})\) according to the Baumann-Rudin model [10] (Fig. 1). This two-compartment model considers the flow of contrast material from cortex to medulla, with no requirement for arterial input function. To avoid outflow effects and contamination of medullary signal by collecting system and renal pelvis, the computation is based on the upslope period, defined as the portion of the medullary time concentration curve up to the maximum value. \(SK-GFR_{MRR}\) was calculated as the product of the renal medullary volume and the average slope of the upslope segment, divided by the mean renal cortex concentration during the upslope period.

**MR Renography Image Analysis**

Dynamic contrast-enhanced images were transferred to a separate workstation and analyzed using in-house software (FireVoxel, New York University School of Medicine). Coregistration of dynamic images across different time points was performed using a mutual information algorithm to allow accurate segmentation of the dynamic sequences (Mikheev A, Lee VS, Rusinek H, presented at the 19th scientific meeting of ISMRM). ROIs were drawn around the cortex, medulla, and pelvis of each kidney (Fig. 1A). MR signal intensity was converted to gadolinium concentration by subtracting the baseline unenhanced signal from the signal at a given time point and dividing the difference by the baseline unenhanced signal [7].

The estimate of total GFR based on MRR \((eGFR_{MRR})\) was calculated as the sum of \(SK-GFR_{MRR}\) for both kidneys. All \(GFR_{MRR}\) values were normalized to body surface area of 1.73 m². \(eGFR_{MRR}\) was compared with \(eGFR_{MDRD}\) [12]. The split renal function ratio was defined as the \(SK-GFR_{MRR}\) divided by the sum of the \(SK-GFR_{MRR}\) of both kidneys, similar to nuclear renography, as described earlier in this article. The four cases without identifiable medulla in the kidney with UPJ obstruction were excluded from calculations of split renal function because \(SK-GFR_{MRR}\) could not be calculated using the Baumann-Rudin model for the kidney with UPJ obstruction. These cases were used in estimations of GFR, however, by assuming that the kidney with UPJ obstruction did not contribute to the total renal function and that \(eGFR_{MRR}\) was equal to \(SK-GFR_{MRR}\) of the normal kidney.

Renal pelvis uptake rate \((PUR)\) was computed as the pelvic signal intensity change over time divided by the baseline signal intensity. The time interval for the calculation was taken as the interval from the time point immediately before contrast material arrival in the renal pelvis to the time of maximum signal intensity in the pelvis. Renal transit time \((RTT)\) was assessed visually as the time interval between appearance of contrast material in the renal cortex and in the proximal ureter at or below the level of the lower pole of the kidney [13].

Each case was processed independently by two readers—a 3rd-year radiology resident and a 4th-year medical student, who underwent supervised training before image analysis—beginning with the image coregistration step. Each observer independently calculated \(SK-GFR_{MRR}\) for each kidney, split renal function, \(eGFR_{MRR}\), and \(PUR\).

**Statistical Analysis**

Bland-Altman analysis and intraclass correlation coefficient (ICC) (absolute agreement) were used to assess the agreement between the split renal function based on MRR and nuclear renography data. Similar analysis was performed to assess the agreement between MRR and MDRD estimates of GFR \((eGFR_{MRR}\) and \(eGFR_{MDRD}\)). Corresponding mean difference and 95% limits of agreement were calculated. Pearson correlation coefficients \((r)\) were also calculated to analyze the association between split renal function ratios obtained by MRR and nuclear renography, as well as between \(eGFR_{MRR}\) and \(eGFR_{MDRD}\). For consistency, the right kidney split function ratio was used for all split renal function calculations. An unpaired Student \(t\) test was used to assess the difference in \(PUR\), as well as \(RTT\), between functionally and mechanically obstructed kidneys. Diagnostically performance of \(PUR\) and \(RTT\) in differentiating mechanical from functional obstruction was calculated. Multivariate logistic regression was used to determine if the combination of \(PUR\) and \(RTT\) would be a better predictor of mechanical or functional obstruction versus \(PUR\) or \(RTT\).
MR Renography in UPJ Obstruction

Results

Of the 17 cases, seven patients had UPJ obstruction (Fig. 2) in the right kidney, nine in the left kidney, and one case had bilateral UPJ obstruction in the setting of horseshoe kidney. There was excellent correlation between MRR and nuclear renography measure of split function ratio \(r = 0.87, p < 0.01; \text{ICC} = 0.84, p < 0.01\), with absolute mean difference in split function of 6.3% (95% CI, 3.6–8.9). Bland-Altman and linear regression analyses show that no significant bias existed in the MRR measurement of split renal function (Fig. 3). The four patients without identifiable medulla in the kidney with UPJ obstruction who were excluded from split renal function calculations had mean nuclear renography split renal function of 14.1% (range, 5–29.5%) in the kidney with UPJ obstruction, with less than 15% in 3 of the four cases.

Comparing \(eGFR_{MRR}\) to \(eGFR_{MDRD}\) yielded a Pearson correlation coefficient of \(r = 0.60(\ p = 0.01)\) and an ICC of \(0.49(\ p = 0.02)\). Bland-Altman and linear regression analyses show that \(eGFR_{MRR}\) tended to underestimate \(eGFR_{MDRD}\) with mean difference of \(-13.3\) (95% limits of agreement, \(-53.6, 27.0\) mL/min/1.73 m² (Fig. 4).

Nuclear renography evaluation of the 18 renal units (including both kidneys in one patient) with UPJ obstruction revealed six kidneys with functional obstruction and 12 kidneys with mechanical obstruction. \(PUR\) was significantly lower in mechanically obstructed compared with functionally obstructed kidneys (0.39 ± 0.26 vs 2.00 ± 1.38 min⁻¹, \(p < 0.01\)). Figure 5 shows sample signal intensity time curves for calculating \(PUR\). Optimal \(PUR\) cutoff of 0.85 min⁻¹, which yields the highest accuracy, could discriminate mechanical and functional obstruction with an accuracy of 89% (95% CI, 75–100%). The proposed cutoff had a sensitivity of 100% and a specificity of 67% for identifying mechanical obstruction. There was also a statistically significant difference in \(RTT\) between mechanically and functionally obstructed kidneys (742.5 ± 151.7 vs 376.7 ± 230.2 seconds, \(p < 0.01\)). By use of a maximum-accuracy \(RTT\) cutoff of 245 seconds, the overall accuracy for discriminating mechanical and functional obstruction was 83% (95% CI, 66–100%). The \(RTT\) cutoff had a sensitivity of 100% and a specificity of 50% for identifying mechanical obstruction. The combination of \(PUR\) and \(RTT\) did not improve accuracy in discriminating between mechanical and functional obstruction compared with \(PUR\) alone (both 89% accuracy).

Interobserver Agreement

There was strong statistically significant interobserver agreement for all MRR-measured parameters, with ICC ranging from 0.84 to 0.92 (Table 1).

Discussion

UPJ obstruction is a common cause of hydronephrosis in both the pediatric and adult
TABLE 1: Interobserver Agreement Between Two Readers for MR Renography—Measured Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ICC</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right kidney SK-GFR&lt;sub&gt;MRR&lt;/sub&gt;</td>
<td>0.88</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Left kidney SK-GFR&lt;sub&gt;MRR&lt;/sub&gt;</td>
<td>0.88</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Right kidney split function ratio</td>
<td>0.92</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>eGFR&lt;sub&gt;MRR&lt;/sub&gt;</td>
<td>0.94</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>PUR</td>
<td>0.84</td>
<td>&lt;0.01</td>
</tr>
</tbody>
</table>

Note—ICC = intraclass correlation coefficient, SK-GFR<sub>MRR</sub> = single-kidney glomerular filtration rate (GFR) on MR renography, eGFR<sub>MRR</sub> = estimated GFR on MR renography, PUR = renal pelvic uptake rate.

populations. The incidence of UPJ obstruction is 1 in 500 live births when screened by antenatal ultrasound [14], with functionally significant obstruction occurring in 1 in 1500 fetuses [15]. The potential complications of UPJ obstruction include renal insufficiency, urinary tract infections, and development of urinary calculi. However, not all patients develop significant complications, with up to 83% following a benign course, with stabilization or even improvement in renal function [16]. Imaging plays a particularly important role in determining which patients require corrective surgery and which can be managed conservatively. However, the current combined imaging approach has several disadvantages, including the increased cost because of use of multiple imaging modalities; the risk of ionizing radiation, especially given the multiple follow-up examinations required for many patients; and the inconvenience to patients of having to schedule and endure multiple tests.

We have shown that a single dynamic contrast-enhanced MRI examination (i.e., MRR), in addition to providing anatomic information, can yield functional characterization of UPJ obstruction. MRI provides exquisite anatomic detail of the urinary tract; it can assess the position of the kidneys, as well as the shape and configuration of the collecting system. The post-contrast T1-weighted MR sequence is highly sensitive for the detection of crossing vessels at the UPJ, a finding that is crucial for surgical planning [17]. MRR can also determine the functional parameters: the estimated GFR for each kidney; the split renal function; and measures of the severity of obstruction PUR and RTT. These latter parameters have high accuracy when compared with the reference standard determined by nuclear renography. Our results are also in close agreement with prior work showing that eGFR<sub>MRR</sub> overestimates the MRR GFR as well as the reference standard GFR measurement obtained by 99mTc-DTPA urinary clearance in cirrhotic subjects [18].

It is of great interest that a relatively simple tracer kinetic model initially proposed by Baumann and Rudin in an animal model can estimate the single-kidney and total GFRs. Most previous studies required an arterial input function [8]. Obtaining robust arterial input function is difficult because it requires high-temporal-resolution imaging and is inaccurate owing to inflow MRI artifacts. The Baumann-Rudin model provides a simple and straightforward method to calculate the total GFR, single-kidney GFR, and split renal function, making it appealing for potential clinical use. Furthermore, the Baumann-Rudin model can be used with low-dose gadolinium contrast agent and hence can be integrated in a routine renal protocol for morphologic evaluation for crossing vessels or other anatomic abnormalities using the remainder of the contrast agent.

The Patlak-Rutland model is often used to calculate the split renal function [19–21] but is incapable of accurately calculating the total GFR owing to high discrepancy compared with reference standard GFR measurements [8, 22, 23]. Thus, the Baumann-
MR Renography in UPJ Obstruction


References


2. Chan


