Functional MR urography in children – update 2023

Funktionelle MR-Urografie im Kindesalter – Update 2023

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ABSTRACT

Background Functional MR urography (fMRU) has developed into an innovative, radiation-free option for assessing parameters of kidney function in pediatric radiology. The importance of fMRU in comparison to the standardized established nuclear medicine procedure (99mTc-Mercapto-acetyltriglycerine, MAG3 scintigraphy) is shown using SWOT analysis.

Methods To assess the current state of research, a selective literature search was carried out in PubMed. Taking into account the current scientific status, the examination technique, preparation, and evaluation of fMRU are presented.

Results As a result of the comparison with MAG3, fMRU is suitable for certain indications and represents an optimal combination of morphological and functional representation of the kidneys and urinary tract, especially in the case of surgical consequences.

Conclusion fMRU has been successfully established as a diagnostic method for assessing the morphology and function of the kidneys in competition with MAG3 scintigraphy.

Key Points

- Functional MRU allows reliable statements on the morphology and function of the kidneys and urinary tract.
- The results of the functional assessment of fMRU are comparable to the results of MAG3 scintigraphy.
- The complex implementation and demanding evaluation limits the spread of fMRU as a complete alternative to MAG3 scintigraphy. fMRU is reserved for special indications.
- Functional MRU has prevailed over MAG3 scintigraphy for complex renal and urinary tract anomalies (CAKUT) that require surgical correction. An example is the clarification of dribbling in girls, which is usually based on an ectopic opening of a ureter in a double system.

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ZUSAMMENFASSUNG

Hintergrund Die funktionelle MR-Urografie (fMRU) hat sich in der Kinder- und Jugendradiologie zu einer innovativen, strahlenfreien Möglichkeit zur Beurteilung von Parametern der Nierenfunktion entwickelt. Die Bedeutung der fMRU im Vergleich zum standardisierten etablierten nuklearmedizinischen Verfahren (99mTc-Mercapto-acetyltriglycerin, Tc99mMAG3-Diureseszintigrafie [MAG3]) wird mittels SWOT-Analyse aufgezeigt.

Methode Zur Beurteilung des derzeitigen Forschungsstandes erfolgte eine selektive Literaturrecherche in PubMed. Unter Berücksichtigung des aktuellen wissenschaftlichen Standes werden Untersuchungstechnik, Vorbereitung und Auswertung der fMRU dargestellt.

Ergebnisse Im Resultat des Vergleichs mit der MAG3 ist die fMRU bei bestimmten Indikationen geeignet und stellt insbesondere bei operativen Konsequenzen eine optimale Kombination von morphologischer und funktioneller Darstellung der Nieren und ableitenden Harnwege dar.

Schlussfolgerung Die fMRU hat sich bei speziellen Indikationen als diagnostische Methode zur Beurteilung von Morphologie und Funktion der Nieren in Konkurrenz zur MAG3-Szintigrafie etabliert.

Background

Congenital anomalies of the kidney and urinary tract (CAKUT) are one of the most common congenital diseases with a prevalence of approx. 3–6/1000 live births [1]. Some of these malformations can result in irreparable damage to the parenchyma and terminal renal insufficiency even in children, particularly if surgical correction is not performed. Therefore, a comprehensive anatomical-morphological workup must be performed, and renal function must be evaluated.

MRI (magnetic resonance imaging) is used as a supplementary method to ultrasound for visualizing the kidneys and the urinary tract in children due to the high soft tissue contrast and the lack of radiation exposure. Standard imaging in children and adolescents is based on the determination of the kidney volume and the parenchymal thickness. The echogenicity of the parenchyma, the width of the pelvicalyceal system and the urinary tract including the urethra, and the bladder are also evaluated on ultrasound. Innovative ultrasound techniques like shear wave elastography have not yet become established for renal parenchyma examination (at least in pediatrics). To date, the workup of renal function includes determination of the serum creatinine with the glomerular filtration rate (GFR; estimated in children based on age, sex, skin color, estimated eGFR and cystatin C in serum) and standardized nuclear medicine methods (primarily ^{99m}Tc-mercaptoacetyltriglycine scintigraphy, MAG3). The development of fast MRI sequences made MRI an interesting choice for the diagnostic workup of the urinary tract, evaluation of the renal parenchyma, and functional analysis in children. Static MR urography is based on T2-weighted imaging and requires that the collecting system be filled with fluid. Using modern applications like ASL (arterial spin labeling), BOLD-MRI (blood oxygen level-dependent), and DWI/DTI (diffusion-weighted imaging/ diffusion tension imaging), various functional parameters of the kidneys can be determined noninvasively and without the administration of contrast agent. In particular, contrast-enhanced functional MR urography (fMRU) replaces nuclear medicine methods in special cases [2].

Renal function

The kidneys are responsible for regulating water, electrolyte, and acid-base balance as well as the excretion of substances usually eliminated in the urine via glomerular filtration, tubular reabsorption, and tubular secretion. The endocrine functions include synthesizing erythropoietin to regulate erythropoiesis and producing and releasing renin for blood pressure regulation and 1.25 dihydroxycholecalciferol to control calcium homeostasis. The nephron is the smallest functional unit of the kidney and is comprised of the glomerulus with the Bowman's capsule and the associated tubule. The number and quality of nephrons determine renal function. All nephrons are present at birth (approx. 900 000, range: 210 000 to 2.7 million), while it takes the kidneys until the end of the third year of life to reach functional and structural maturity. The glomeruli comprise approx. 18 % of the renal cortex volume in newborns but only 8.5 % in adults. The length of the tubules increases from 2 mm to 12 mm [3, 4].

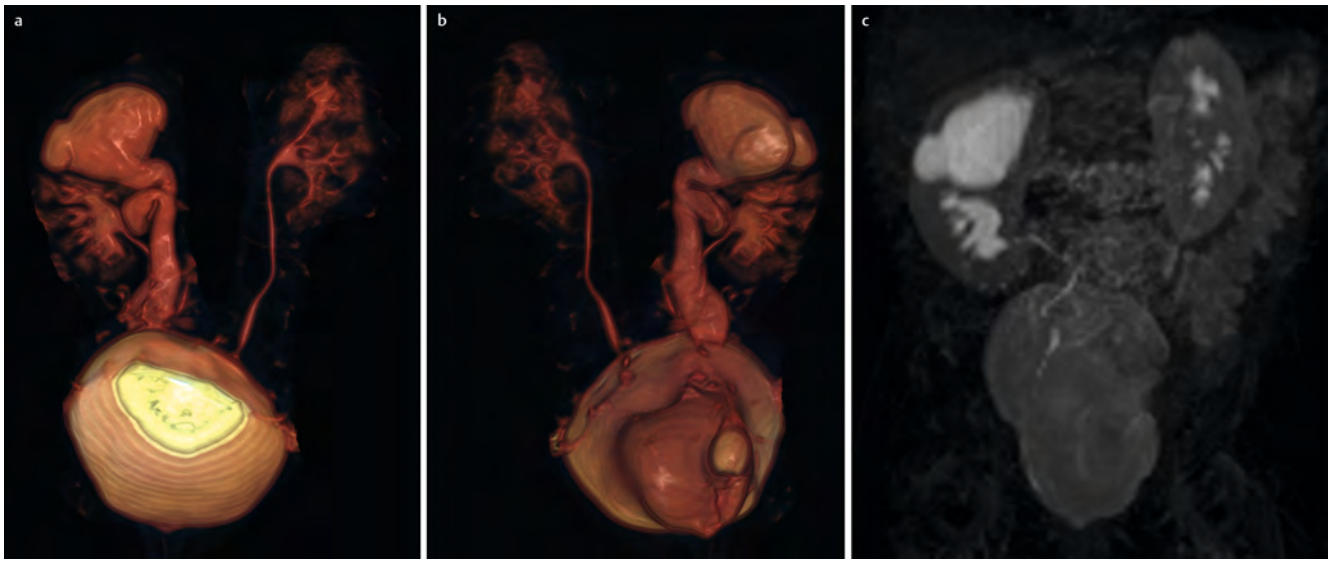
The glomerular filtration rate (GFR) as the volume filtered per time unit by the glomeruli of the kidneys is considered the best option for evaluating renal function. It is the product of the number of nephrons and the nephron-GFR and is represented by the serum creatinine and cystatin C. Only the global renal function and not unilateral function can be evaluated this way. The GFR normally fluctuates over the course of the day depending on physiological requirements. The loss of nephrons can be compensated by an increase in the performance of the individual nephrons (for example, after nephrectomy with compensatory hypertrophy and hyperfiltration of the remaining kidney). The goal of functional imaging is to identify and quantify the loss of nephrons in an irreversibly damaged parenchyma or to differentiate potentially reversible hemodynamic changes.

Functional MR urography

Functional MR urography (fMRU) was described for the first time in 1995 and has been continuously developed since then. It is usually performed as a dynamic contrast-enhanced MRI examination and combines the anatomical-morphological visualization of the kidneys and urinary tract with functional information acquired from the transit of an intravenously administered contrast bolus from the cortex and medullary pyramids into the calyces and renal pelvis (see ▶ **Fig. 1**). Other MRI techniques for functional evaluation like arterial spin labeling (ASL), blood oxygenation level dependent (BOLD), diffusion-weighted imaging (DWI), and diffusion tensor imaging (DTI) do not require the use of contrast agent [5]. The ASL technique is used for perfusion imaging of the kidneys, while the BOLD technique can be used to determine hemodynamic changes in the parenchyma based on oxygen content. The DWI diffusion coefficient correlates well with the GFR. The contrast agent used in fMRU is filtered in the glomerulus and is excreted without tubular secretion or reabsorption [6]. Thus, the GFR as well as additional functional parameters can be evaluated with contrast-enhanced fMRU. Combined with the high spatial resolution of MRI, fMRU has significant advantages compared to nuclear medicine with its largely standardized and established functional methods (^{99m}Tc-DTPA, MAG3) with limited spatial resolution, particularly in duplex kidneys and complex anatomy [7, 8].

Preparing the examination

Diagnostic fMRU examination requires a standardized approach that should be formulated in corresponding guidelines. After a detailed informed consent discussion, standard examination preparation includes hydration of the child via an intravenous infusion of a crystalloid solution (20 ml/kg body weight) for 30 minutes prior to the MRI examination to ensure an ideally linear relationship between contrast agent concentration and MRI signal intensity. Furthermore, as in MAG3, forced diuresis is induced by furosemide (1 mg/kg body weight, maximal 20 mg) administered just prior to the MRI examination to shorten the excretion time and thus reduce the MRI examination time. A macrocyclic gadolinium-based contrast agent in a dose of 0.1 mmol/kg body weight



▶ **Fig. 1** 10-month-old female infant with duplex kidney on the right side. Ureteral orifice stenosis of the upper moiety with urinary tract dilatation IV° of the upper moiety in the presence of inferior insertion of the ureter. 3D maximum intensity projection (MIP) reformatted from coronal T2-weighted FLASH sequence in anterior **a** and posterior **b** view. MIP reformatted from coronal post-contrast T1-weighted VIBE in the excretion phase **c**. The dilated ureter of the right upper moiety is not visible because of the delayed contrast excretion.

in a defined bolus of 0.5 mmol/ml at a rate of 0.2 ml/s is administered as the contrast agent [9]. A catheter is inserted into the bladder to avoid overfilling as this could delay contrast outflow into the ureter resulting in false-positive results. Since fMRU requires an examination time of approx. 30 minutes [10], a decision about the need for anesthesia must be made prior to the examination due to possible patient movement and motion artifacts even when the post-processing algorithms include motion correction. Although fMRU can be performed using the feed and wrap technique with immobilization aids like vacuum cushions [11, 12], the spatial resolution in particular is sometimes not satisfactory with this technique. Therefore, in complex duplex kidneys with unclear ureteral orifices, anesthesia is usually necessary to avoid the risk of performing a nondiagnostic examination. The risks associated with anesthesia and sedatives must be weighed against the benefits on an individual basis when determining the indication.

Performing the examination

fMRU on a 1.5 or 3.0 Tesla whole-body scanner is usually performed with the child in a supine position. The arms should be positioned over the head to avoid foldover artifacts. In the case of significant dilation of the pelvicalyceal system, a prone position is recommended since the ureteropelvic junction usually has a ventromedial orientation so that the contrast agent can flow with gravity more easily into the ureter. Body matrix and spine matrix coils are used in combination. In young infants, knee and head coils can be used as needed. There are various protocol recommendations for the sequence (▶ **Table 1**). Fast T2-weighted 2D sequences are used to obtain a quick overview and help with further planning. After an axial T2w spin echo sequence to visualize the renal parenchyma, heavily T2-weighted 3D sequences in oblique coronal orientation are acquired to evaluate the urinary tract. Additional high-resolution static radially acquired T2 sequences show the urine-filled urinary tract structures and are primarily used to evaluate ectopic ureters. The field of view of coronal sequences must extend from the upper pole of the kidney to the pelvic floor and include the complete kidneys and bladder. Coronal T1-weighted 3D sequences with high temporal and acceptable spatial resolution are used to evaluate contrast dynamics. Fat-saturated gradient echo sequences (GRE), which are not particularly sensitive to movement, in oblique coronal orientation with respect to the kidney and ureters have become established. At least 50 series with 20–30 images each and a slice thickness of 2–3 mm are acquired and then analyzed individually or as a maximum intensity projection (MIP). Combined with parallel imaging to make imaging faster, the acquisition time is approx. 5–10 seconds per block. GRASP-VIBE (Golden Angle Radial Sparse Parallel, Volume Interpolated Breath Hold Examination) combined with acceleration techniques like compressed sensing is becoming an attractive technique for dynamic contrast-enhanced fMRU [6]. The dynamic series are started before contrast administration to collect anatomical information. Imaging continues for at least 10 minutes after contrast administration. The first series make it possible to identify vessels and to acquire information about the renal vessels, scarring, and other abnormalities of the parenchyma based on the uptake and excretion of the contrast agent. Subsequent series are used to analyze contrast agent excretion and washout and to determine functional parameters. Following the dynamic contrast-enhanced series, additional scans may be needed in the case of delayed or absent contrast excretion. In the case of absent or minimal dilation of the urinary tract, high-resolution

▶ **Table 1** Example of sequence protocol for functional MR urography on a 1.5 T MRI scanner.

Sequence/orientation	TR/TE/FA/SD/FS/3D	Breath trigger	Scan time	Information
HASTE T2w/transverse	1200/92/150/4/–/–	Free	40 s	Organ location
HASTE T2w/sagittal	1800/97/180/3/–/–	Free	54 s	Organ location
TSE T2w high-res/transverse	6000/140/150/3/FS/–	Free	6 min 52 s	Visualization of the renal parenchyma
SPACE T2w/transverse	1500/136/160/1.5/–/3D	Free	4 min 59 s	Anatomy of the bladder/ureteral orifice
TSE T2w 3D/coronal	1800/599/170/2/FS/3D	Triggered	4 min 35 s	Visualization of the urinary tract
FLASH T1w (VIBE)/coronal	4.9/2.38/10/2.5/FS/3D	Free	12 s	Localizer sequence for contrast dynamics
Contrast agent administration				
FLASH T1w (VIBE)/coronal	4.9/2.38/10/2.5/FS/3D	Free	15 min 29 s	Contrast dynamics
FLASH T1w (VIBE)/coronal	3.2/1.25/41/2.0/FS/3D	Free	16 s	Optional (late images of contrast dynamics in the case of delayed or absent excretion)
FLASH T1w (VIBE high-res)/coronal	4.9/2.38/10/1.2/FS/3D	Free	4 min 09 s	Visualization of renal parenchyma and urinary tract

TR = relaxation time; TE = echo time; FA = flip angle; SD = slice thickness; FS = fat saturation; 3D = three-dimensional sequence; HASTE = Half-Fourier Acquisition Single-shot Turbo spin Echo; True FISP = True fast imaging with steady state precession; TSE = turbo spin echo; FLASH = fast low angle shot; VIBE = volume interpolated breath-hold examination

T1-weighted 3D anatomical sequences are needed near the end of the examination in order to evaluate the exact course of the contrast-enhanced ureters [2].

Determination of functional parameters

To evaluate split renal function, the transit of the contrast agent through the kidneys and urinary tract is analyzed on fMRU. In addition to subjective visual analysis, a series of parameters are determined [13] (▶ **Table 2**). fMRU is analyzed with the help of free external software programs since "customized" software for fMRU is not currently available from any MRI manufacturer. "MR-Urography V5.0 Plugin for ImageJ" from Quant-IF-Labs at the University Rouen (CHU, France) [14] and "CHOP-fMRU v1.2.52" from the Children's Hospital of Philadelphia (USA) [15] are two programs for children with good agreement at least regarding relevant obstructions in comparative studies [16]. The evaluation of functional data with the semi-automate CHOP software has been performed many times and has become established [2]. This software is used as an example in the following. Data analysis takes approximately 20 to 30 minutes. In the case of complex duplex kidneys with narrowing of the parenchyma, significantly more time as well as experience may be needed to perform manual correction of the semi-automated segmentation of the renal parenchyma. As in many software applications, the interpreting and treating physicians are responsible and thus also liable for the evaluation of results.

The evaluation is based on the qualitative parameters calyx transit time (CTT; time from contrast administration to signal increase in the calyces) and renal transit time (RTT; time to signal increase in the proximal ureter at the level of the caudal pole of the kidney), which are effectively used to evaluate relevant obstructions. A delayed CTT is seen in the case of a significant obstruction as well as in hypotension, renal artery stenosis, and dehydration, while an accelerated CTT is seen in tubular concentration defects and glomerular hyperfiltration [6]. The RTT depends among other things on the location of the ureteropelvic junction in relation to the position of the patient. There is significant anatomical variability (anterior, posterior, cranial) that affects contrast transit capability and transit time. A certain stasis of the urine in a dependent renal pelvis with resulting delayed contrast transit into the proximal ureter can simulate a relevant obstruction (false positive). Therefore, the RTT can only be evaluated under consideration of the patient position and the anatomy of the ureteropelvic junction. If the RTT is less than 4 minutes, there is definitely no significant obstruction.

Signal intensity curves of the renal parenchyma per time unit (enhancement plots) and contrast excretion in the pelvicalyceal system per time unit (excretion plots) are still generated, allowing a dynamic analysis of the parenchyma and urine flow. The enhancement plots typically show a rapid increase in the vascular phase, a linear increase in the parenchymal phase, followed by a slower signal drop at the start of contrast excretion (▶ **Fig. 2**).

Dependencies of T1 and T2* times and relaxivity as well as the kinetics of the contrast agent must be taken into consideration when converting the MR signal into the contrast concentration. Based on the signal intensity-time curves of the aorta and kidney (s), Patlak plots are generated for indirect determination of the GFR [17]. The basis for functional assessment here is the Rutland-Patlak model in which the intravasal space and nephron form a two-compartment model, while the interstitium as a third space is not included. A direct linear correlation between contrast concentration and signal intensity is postulated. Three-compartment models are not preferred. A series of quantitative parameters are determined, with the ratio of the volume Patlak differential renal function (vpDRF) being best suited for evaluating the

▶ **Table 2** Functional MR urography parameters.

Parameter	Unit	Explanation
Calyx transit time (CTT)	min, s	Time between contrast administration and initial detection of contrast agent in the pelvicalyceal system
Renal transit time (RTT)	min, s	Time between contrast administration and detection of contrast agent in the proximal ureter (at the level of the lower pole of the kidney)
Time to peak (TTP)	min, s	Time between contrast administration and maximum enhancement of the renal parenchyma
Volume	ml	Parenchymal volume (without the pelvicalyceal system)
Volumetric differential renal function (vDRF)	%	Split renal function in relation to the renal parenchymal volume
Patlak differential renal function (pDRF)	%	Split renal function in relation to the GFR-based Patlak numbers of a defined parenchymal unit
Volumetric and Patlak differential renal function (vpDRF)	%	Split renal function related to renal parenchymal volume and Patlak numbers
Patlak slope (number)	(ml/min)/ml	GFR equivalent per ml renal volume

split/differential renal function [18]. The pDRF provides information about how the nephrons are functioning in the kidney (Patlak) and the vDRF provides information about the number of nephrons and the total GFR of the kidney (volume). When the two-compartment model is used, the tubular function can be evaluated based on the mean transit time (MTT) [5]. fMRU includes a (preferably standardized) report containing morphological and functional information from the examination as well as an assessment and a possible recommendation regarding the further approach (▶ **Table 3**).

Comparison to scintigraphy

There are now a number of studies comparing the two methods with respect to their accuracy and use for treatment decisions. Similar to MAG3, a classification for the evaluation of drainage curves (normal, borderline, accumulating) was described for fMRU [19]. Relevant obstructions can be evaluated with fMRU with a concordance with MAG3 scintigraphy of 81–95 % [7]. When using a cut-off value of ≥ 6 minutes for the RTT, fMRU had a specificity of 94 % and an AUC of 0.827 in the comparison to the T ½ of MAG3 in a study including 37 examinations with a significant obstruction [8]. The statements regarding split function coincide in 92–98 % of cases [16]. However, the individual results of fMRU and MAG3 are not compatible.

Indications

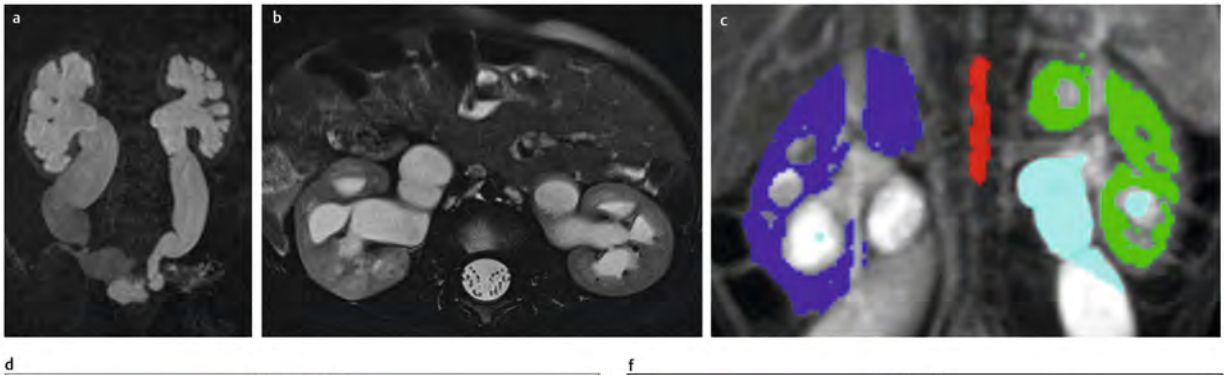
In principle, the indications for fMRU correspond to those for renal scintigraphy. However, fMRU is preferably indicated in severe unilateral or bilateral prenatally diagnosed urinary tract dilation, complicated duplex kidney, ectopic ureteral insertion, and dilated ureter [20]. A rare but very important indication is dribbling in girls in which an ectopic ureter connected to the urethra or vagina can be detected with the combination of functional and morphological imaging. These patients have usually undergone lengthy and comprehensive diagnostic testing and treatment before the often dysplastic but functional upper moiety is identified and the ectopic ureteral orifice is located [21]. The same is true for boys with an ectopic ureteral orifice, e. g., into the prostatic part of the urethra (▶ **Fig. 3**).

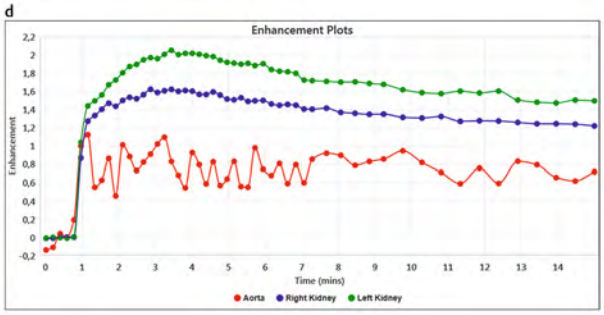
Limitation

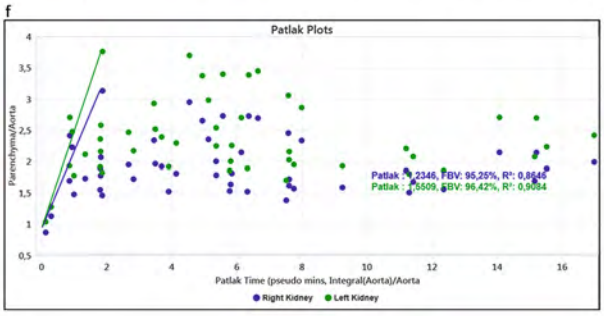
Due to the high logistical, personnel, and equipment costs of fMRU, it will not replace MAG3 scintigraphy even in the future. The long examination time that often necessitates the use of sedation or anesthesia is a disadvantage of the method. Further disadvantages include the invasive insertion of a urinary catheter, standardized hydration, and the administration of a diuretic, which are however also required for scintigraphy. The risks associated with the administration of MRI contrast agents containing gadolinium (deposits, anaphylaxis, nephrogenic systemic fibrosis) are known. Because of the immaturity of the kidney, fMRU should ideally only be performed after the third month of life. However, this is not a general contraindication for the use of gadolinium [22]. The generally known contraindications for MRI examination are also contraindications for fMRU. In the case of a reduced eGFR, it is necessary to consult with the responsible pediatric nephrologist in the individual case in order to minimize the risks of potential contrast-induced kidney damage.

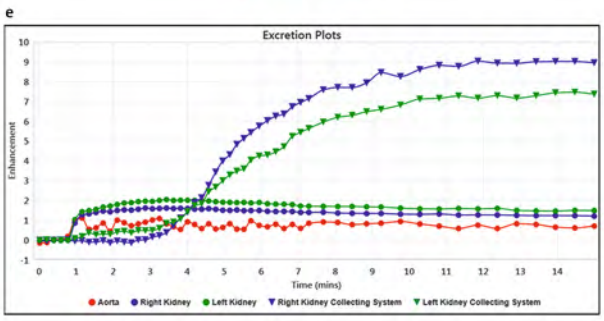
SWOT analysis

SWOT analysis shows the opportunities and risks associated with a method, with S standing for strength, W for weakness, O for opportunities, and T for threats. Static MR urography (MRU) is used for the intramodal comparison with functional MR urography (fMRU). This method, which is based on T2-weighted sequences, provides visualization of the urinary tract with high anatomical resolution and low methodological effort without the administration of contrast agent. The collecting system (pelvicalyceal system, ureter, bladder) must be filled with liquid. The method does not provide functional information. It can provide









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	Right Kidney	Left Kidney
CTT [min, sec]	1m 54s	2m 6s
RTT [min, sec]	5m 25s	4m 45s
TTP [min, sec]	1m 54s	2m 28s
Volume [mL]	48,10	27,65
vDRF [%]	63,50	36,50
pDRF [%]	44,32	55,68
vpDRF [%]	58,07	41,93
Patlak [(mL/min)/mL]	1,23461	1,55090

▶ **Fig. 2** 9-month-old male infant with bilateral urinary tract dilation IV° with hydroureters after treatment of bilateral stenosis of the ureteral orifice with Y-ureterostomy. There is no indication of a relevant obstruction in the functional analysis. Function same on both sides and contrast excreted in a timely manner. **a** MIP, reformatted from coronal post-contrast T1-weighted VIBE in the excretion phase: Pronounced dilation of the pelvicalyceal system on both side with megaureters. **b** T2 TSE transverse: Significant narrowing of the renal parenchyma is seen on both sides. **c** Semiautomatic segmentation of the aorta and the renal parenchyma with color overlay for the aorta (red), right kidney (blue), left kidney (green), and the pelvicalyceal system (turquoise). **d** Signal intensity curve of the renal parenchyma (enhancement plot) with typical enhancement of the parenchyma that is the same on both sides. **e** Signal intensity curve of the renal pelvis (excretion plot): Normal curve for both kidneys. **f** Patlak plot: Both kidneys show a sharp increase corresponding to a normal finding. **g** Overview of the split renal function parameters determined via fMRU: The determined split renal function shows at most a minimal restriction of the vpDRF on the left compared to the right (41.93 % vs. 58.07 %; red arrow) with a larger parenchymal volume of the right kidney (48.10 ml on the right vs. 27.65 ml on the left). Correlating to a regular excretion curve (E), the determined RTT of both kidneys is significantly < 8 minutes. Therefore, by definition, there is no obstruction.

excellent visualization of dilated ureters. The comparison of fMRU to MAG3 scintigraphy is evaluated intermodally in the case of CAKUT and urinary tract dilation. The decades of experience and the high degree of standardization with respect to performance are considered strengths (however, it should be mentioned that there are discrepancies between departments regarding the use of diuretics, catheterization, positioning). MAG3 scintigraphy is the method of choice in the guidelines for evaluating split kidney function. However, the method has weaknesses with respect to determining which parts are functional in duplex kidneys. There are risks due to nuclide exposure and due to the fact that sedation and catheterization are often necessary. The strengths of fMRU are the very good temporal resolution, the excellent spatial resolution, and the lack of radiation exposure. Its weaknesses are the high equipment, personnel, and time costs as well as the fact that there is not yet a definitive standard, particularly for evaluation. Artificial intelligence (deep learning, neural networks) could be helpful in the future for analysis as initial segmenting approaches have shown [23]. There are risks with respect to possible complications when using anesthesia or sedation, catheterization, and contrast administration. The informed consent discussion should be conducted with the cor-

▶ **Table 3** Structured reporting for functional MR urography.

Morphology (right/left)	Kidney	Position: orthotopic/pelvic/crossed Morphology: normal/duplex/horseshoe Lesion: none/cystic/solid Parenchyma: normal/abnormal/narrowed Corticomedullary differentiation: normal/reduced
	Pelvicalyceal system	Calyx dilation: yes/no, degree? Renal pelvis dilation: yes/no, width (ap) Ureteropelvic junction: location/sudden change in diameter
	Ureter	Diameter (ap) Ectasia: yes/no Kinking: yes/no Orifice: normal/ectopic, where?
	Bladder	Wall Diverticula Ureterocele
	Arteries	Aorta Renal artery: single/double/multiple Renal artery crosses ureteropelvic junction: yes/no
	Other findings	Thorax, abdomen, pelvis; liver, gall bladder, pancreas, spleen, adrenal glands, lymph nodes, gastrointestinal tract, musculoskeletal system
Function	Qualitative Nephrography	Symmetrical/asymmetrical Delay: yes/no
	Quantitative	CTT RTT TTP Parenchymal volume pDRF vDRF
Evaluation	Morphology of kidney and urinary tract: normal/abnormal RTT: symmetrical/asymmetrical, normal/delayed Percentages of renal function for each side/moiety(%) vpDRF in % Recommendation for further diagnostic workup, consultation, therapy	

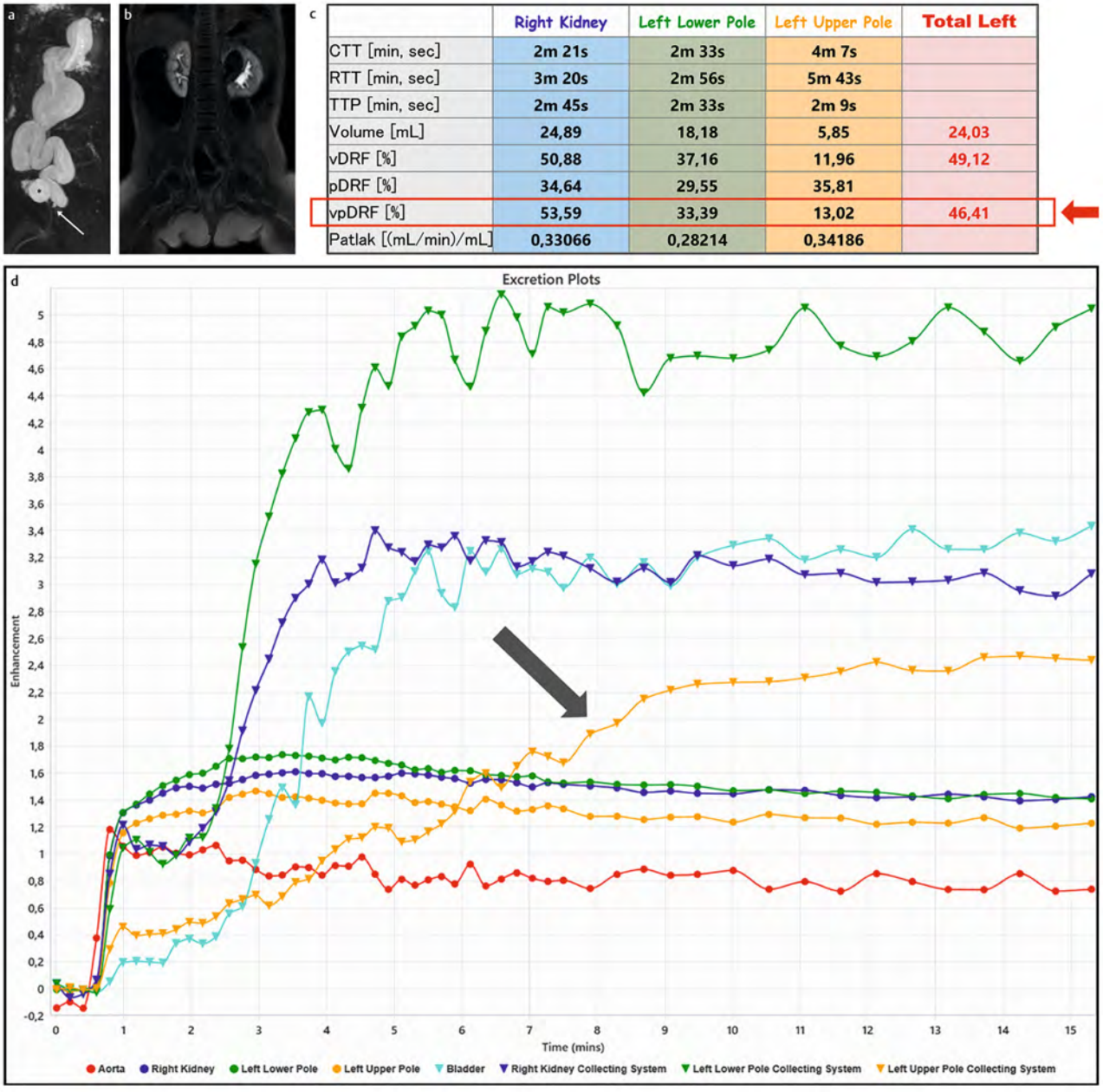
ap – anterior-posterior, MDT – gastrointestinal tract, MSK – musculoskeletal system, NB – renal pelvis, NBKS – pelvicalyceal system, UPJ – ureteropelvic junction

responding level of detail. The extent to which alternatives to contrast agents containing gadolinium like CEST (chemical exchange saturation transfer) MR urography based on pH changes with the administration of iopamidol will be able to become established in the future remains to be seen [24].

Due to the possibilities of fMRU to identify relevant obstructions and detect their cause and to facilitate (more) exact surgical planning by determining whether a laparoscopic procedure is possible, this method has become a “problem solver” in complex urinary tract anomalies (congenital anomalies of the kidney and urinary tract, CAKUT) [8].

Conclusion

- The indication for fMRU should be determined on an individual basis in an interdisciplinary team of pediatric nephrologists, pediatric surgeons/urologists, and pediatric radiologists with the help of all prior findings.
- The goal of functional MR urography is to provide three-dimensional anatomical representation of the kidneys and urinary tract with high spatial resolution and functional evaluation of the kidneys separately for each side and moiety.
- With the possibility of combining morphology and function, fMRU allows the detection, evaluation, and follow-up of congenital anomalies of the kidney and urinary tract (CAKUT) but can also be used to assess inflammation, fibrosis, and masses of the urinary tract.
- fMRU is a real alternative to MAG3 scintigraphy for surgical planning in complex anomalies.



	Right Kidney	Left Lower Pole	Left Upper Pole	Total Left
CTT [min, sec]	2m 21s	2m 33s	4m 7s	
RTT [min, sec]	3m 20s	2m 56s	5m 43s	
TTP [min, sec]	2m 45s	2m 33s	2m 9s	
Volume [mL]	24,89	18,18	5,85	24,03
vDRF [%]	50,88	37,16	11,96	49,12
pDRF [%]	34,64	29,55	35,81	
vpDRF [%]	53,59	33,39	13,02	46,41
Patlak [(mL/min)/mL]	0,33066	0,28214	0,34186	

▶ **Fig. 3** fMRU examination of a 5-month-old male infant. Duplex kidney with confirmation of the Meyer-Weigert rule (upper moiety obstructive, lower moiety refluxive). **a** 3D maximum intensity projection (MIP) reformatted from coronal T2-weighted FLASH sequence: With a clearly demarcated balloon of the inserted urinary bladder catheter (*), the ectopic ureteral orifice of the upper moiety into the pars prostatica of the urethra is shown here (white arrow). **b** MIP, reformatted from coronal post-contrast T1-weighted VIBE in the excretion phase: The dilated upper moiety is not visible because of the delayed contrast excretion. **c** Overview of the split renal function parameters determined via fMRU: Renal function is the same on both sides with a vpDRF of 53.59 % for the right kidney compared to 46.41 % for the left kidney (red arrow). Only minimal contribution of the left upper moiety (13.02 %) to overall function. **d** Signal intensity curve of the renal pelvis (excretion plot): While a normal curve is seen for the right kidney, the upper left moiety (yellow with triangles) has a “climbing curve” (gray arrow) with significant contrast accumulation in the renal pelvis.

Conflict of Interest

The authors declare that they have no conflict of interest.

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