






The use of fetal MRI for renal and urogenital tract anomalies

Gihad E. Chalouhi^{1,9,11}  | Anne-Élodie Millischer¹  | Houman Mahallati^{1,10} |
 Nathalie Siauve² | Andrew Melbourne^{1,3,4}  | David Grevent¹ | Nicolas Vinit⁵  |
 Laurence Heidet^{1,6,7} | Yves Aigrain^{1,5} | Yves Ville¹ | Thomas Blanc^{1,5,8,11} |
 Laurent J. Salomon^{1,11} 

¹Hôpital Necker-Enfants Malades, Assistance Publique-Hôpitaux de Paris, Université Paris Descartes and Fetus & LUMIERE team, Paris, France

²Imagerie Médicale, Hôpital Louis Mourier APHP, Colombes, France

³School of Biomedical Engineering and Imaging Sciences, King's College London, London, United Kingdom

⁴Medical Physics and Biomedical Engineering, University College London, London, United Kingdom

⁵Hôpital Necker-Enfants Malades, Assistance Publique-Hôpitaux de Paris, Department of Pediatric Surgery and Urology, Paris, France

⁶Centre de référence des Maladies Rénales Héritaires de l'Enfant et de l'Adulte (MARHEA), Paris, France

⁷Pediatric Nephrology Department, Hôpital Universitaire Necker-Enfants Malades, Sorbonne Paris Cité University, Paris, France

⁸INSERM U1151-CNRS UMR 8253, Université de Paris, Institut Necker-Enfants Malades, Paris, France

⁹Division of Fetal Medicine, Department of Obstetrics and Gynecology, American University of Beirut Medical Center, American University of Beirut, Beirut, Lebanon

¹⁰Department of Radiology, University of Calgary, Calgary, Canada

¹¹Université de Paris, Paris, France

Correspondence

Laurent J. Salomon, Hôpital Necker-Enfants Malades, 149 rue de Sevres, 75015 Paris, France.
 Email: laurentsalomon@gmail.com

Abstract

Fetal anomalies are detected in approximately 2% of all fetuses and, among these, genitourinary tract abnormalities account for 30% to 50% of all structural anomalies present at birth. Although ultrasound remains the first line diagnostic modality, fetal MRI provides important additional structural and functional information, especially with the development of faster sequences and the use of functional sequences. The added value of MRI-based imaging is three-fold: (a) improvement of diagnostic accuracy by adequate morphological examination, (b) detection of additional anomalies, and (c) in addition, MRI has the potential to provide information regarding renal function. In this review, we describe the role of fetal MRI in the anatomical evaluation of renal and urogenital tract anomalies, and we also touch upon the contribution of functional MRI to the diagnostic workup of these conditions.

1 | INTRODUCTION

Since the implementation of routine prenatal ultrasound (US) screening during pregnancy 40 years ago, studies have shown that fetal anomalies are detected in approximately 2% of all fetuses. Genitourinary (GU) tract abnormalities are the most common among these, accounting for 30% to 50% of all structural anomalies present at birth or identified at the time of prenatal US.^{1,2} These include a wide range of abnormalities both morphologically as well as in terms of severity, for example, from mild pyelectasis over bilateral multicystic dysplastic kidneys to

bilateral renal agenesis. At the most severe end of the spectrum, GU anomalies may have a high morbidity and mortality (up to 45%), mainly because of anhydramnios, pulmonary hypoplasia, early kidney failure, or even pathologies incompatible with life, such as renal agenesis.³⁻⁵ Early diagnosis alongside precise characterization is of utmost importance in order to appropriately counsel parents and, where appropriate, offer in utero intervention to prevent renal dysfunction and improve the future child's quality of life.⁶

US is an accurate method for evaluating the fetal urinary tract⁷ and can provide the correct diagnosis in the majority of cases.^{8,9} However,

there may be technical limitations that can hamper the use of US such as fetal positioning, maternal obesity, shadowing from bone, and oligohydramnios⁶; the latter being more frequently associated with urinary tract anomalies. In these circumstances, or when sonography is inconclusive, MRI provides important additional information, certainly as faster sequences become available, which minimize motion hence improve image quality.^{2,10,11} There are three areas where MRI can add value: (a) adequate morphological examination and additional tissue contrast^{11,12} from MRI to improve the diagnostic accuracy, (b) the detection of additional anomalies not detected by sonography,¹³ and (c) the provision of information regarding renal function.^{14,15} Herein, we aimed to review the role of fetal MRI in the anatomical and functional evaluation of renal and urogenital tract anomalies.

2 | FETAL MRI OF THE GENITO-URINARY TRACT

Fetal MR imaging using fast and ultrafast pulse sequences enables the acquisition of high-quality images regardless of maternal body habitus, fetal position, or amniotic fluid index. Fetal MRI is also not hampered by the acoustic shadowing from fetal pelvic bones, thereby allowing multiplanar imaging and a better differentiation of kidneys and pelvic organs compared to US, especially late in pregnancy.¹³

The genitourinary structures can already be correctly identified and examined from about 20 weeks onwards with MRI, unlike the fetal central nervous system imaging where robust analysis of gyrification is only possible later on. T2-weighted (T2W) images are the backbone of MR imaging of the urinary tract, and any standard fetal MR GU protocol should be based on fast T2W sequences which demonstrate amniotic fluid and the fluid filled urinary tract very well, due to the long T2 signal of fluid. T1-weighted (T1W) sequences are more useful to study anatomy, particularly in evaluating the gastrointestinal tract and liver. Fetal MRI is also considered more accurate than US in the visualization of genital (external and internal) and adjacent pelvic organs, which is crucial for an accurate diagnosis in case of GU pathology.¹⁶ The hyperintense signal of meconium on T1W sequences is particularly useful in determining the anatomy, and content of the rectum, and its relationship to other pelvic organs.

Once the fetal position is determined on localizer sequences, T2W images in the axial, coronal, and sagittal planes of the fetus should be obtained. The thorax and abdomen are in the same plane and can be studied together. A GU-focused protocol can include Single Shot Fast Spin Echo T2W sequences, both static and dynamic Steady State Fast Precession (SSFP) sequences, and fat suppressed 3D T1W fast spoiled gradient echo sequences. These basic sequences can be complemented with additional specific sequences tailored to clinical questions, such as 3D T2W or SSFP sequences for virtual urography.

3 | NORMAL ANATOMY

Standard anatomical evaluation should include: assessment of amniotic fluid volume, appearance, size, and position of both kidneys, with

What's already known about this topic?

- Fetal anomalies are detected in approximately 2% of all fetuses.
- Genitourinary tract abnormalities account for 30 to 50% of all structural anomalies present at birth. Although ultrasound remains the first line diagnostic modality, fetal MRI provides important additional structural and functional information.

What does this study add?

The added value of MRI-based imaging is three-fold:

- (i) improvement of diagnostic accuracy by adequate morphological examination.
- (ii) detection of additional anomalies.
- (iii) MRI has the potential to provide information regarding renal function.

special emphasis on the parenchyma and the renal cortex; assessment of the ureters, bladder (size, wall thickness, regularity), and urethra.

The amount of amniotic fluid can be easily and accurately assessed with ultrafast, T2W, and volumetric sequences. Interpretation of the urinary abnormalities must take into account the quantity of amniotic fluid which is used as a proxy for fetal diuresis.¹⁷ In case of oligohydramnios, diagnostic and prognostic accuracy of US imaging is diminished, whereas the image quality of fetal MRI is not affected.^{16,18-21}

MRI with its superior tissue contrast and large field of view facilitates visualization of the kidneys.²² On T2W sequences, fetal kidneys are identified as oval structures of intermediate signal intensity on both sides of the spine. A long-T2 rim surrounds the kidney, caused by the peri-renal fat.^{22,23} The renal cortex has a slightly lower T2 signal when compared to the medulla. The renal pelvis and calyces appear as high-signal T2 structures in the middle of the kidneys, due to the presence of urine (Figure 1).

Fetal ureters are very thin, around 1 mm in diameter, and normally not visible on T2W images unless dilated¹⁷ (Figure 1). This may be due to obstruction or to vesico-ureteral reflux. Real time cine MRI can be particularly useful as it permits visualization of peristalsis²⁴ of the ureters. However, inappropriate temporal resolution may generate a false appearance of reflux. In rare cases, T1W sequences can be useful to differentiate dilated ureters from bowel loops. Dilated ureters are hypointense T1 tubular structures, whereas distal bowel loops are hyperintense because of the presence of intraluminal meconium.²⁵

The bladder appears as a fluid-filled oval structure in the anterior part of the pelvis and can be easily identified in all planes (Figure 1). The trigone has a high T2 signal, yet cannot be visualized when the bladder is empty. The adjacent umbilical arteries appear as T2 hypointense bands.²⁶ Normally, the urethra cannot be visualized.

The normal rectum exhibits meconium-like high intensity signal on T1W images and low intensity signal on T2W images after 24 weeks. The rectum is located close to the bladder with the peritoneum's cul-

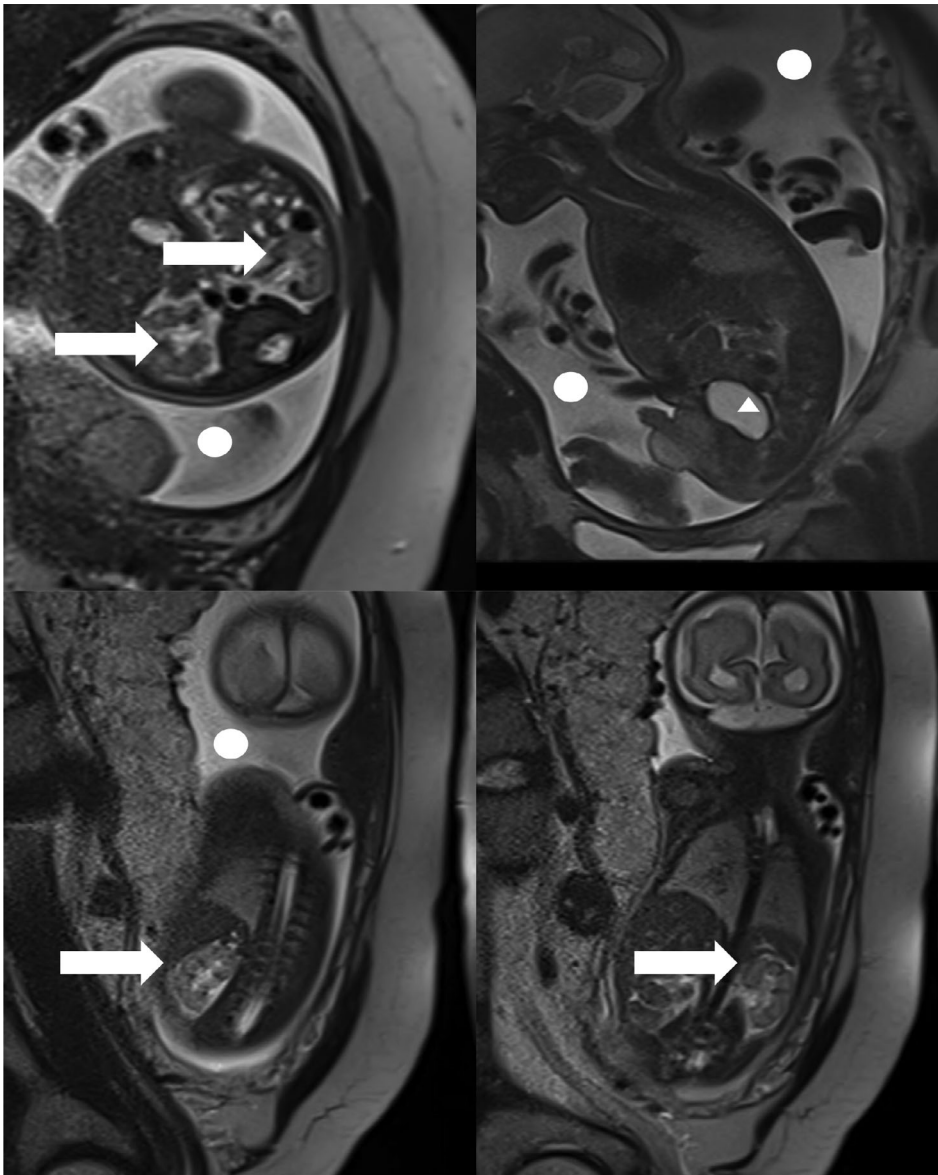


FIGURE 1 Normal appearance of the urinary tract on T2W images. Note the kidneys (arrows), bladder (triangle), and amniotic fluid (circle). The male genitalia can also be well recognized on the upper right image

de-sac going down at least 10 mm below the bladder neck, confirming its normal anatomy and ruling out rectal atresia^{13,27} (Figure 2).

4 | IMAGING OF THE PATHOLOGIC URINARY TRACT

The most frequently diagnosed urinary tract abnormalities are ureteropelvic junction obstruction, multi-cystic dysplastic kidneys, posterior urethral valves, ureterocele, vesicoureteral reflux, hydronephrosis, and a primary megaureter.²⁸ The definition and delineation of these abnormalities is usually not challenging on fetal MRI. An example of a urinary tract malformation secondary to ureterocele is displayed in Figure 3 to illustrate how different urinary structures are well identifiable on fetal MRI, including ureterocele, multicystic kidneys, and a dilated bladder, etc., as well as adjacent organs (rectum).

In most of these anomalies, MRI complements US.^{18,29} Renal parenchymal abnormalities such as absent or cystic kidneys, or

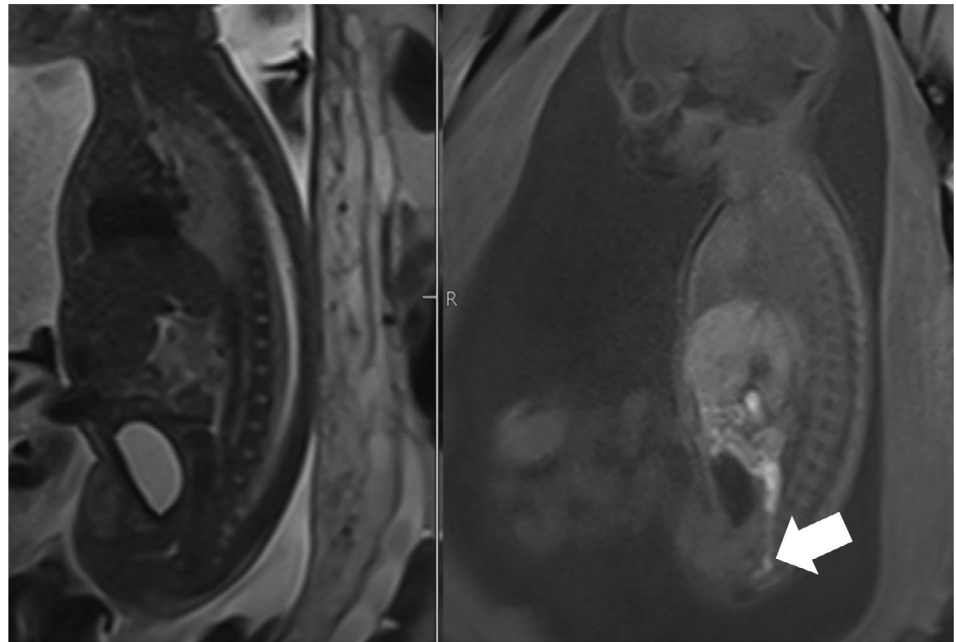
hydronephrosis are easily recognized on T2W structural imaging, yet for that type condition, the advantages of MRI over US is unclear.²⁹⁻³¹

Any dilatation of the bladder or upper urinary tract is amenable for volumetric measurement. Some have claimed that MRI may help in choosing the in utero treatment modality, such as fetal cystoscopic ablation or via vesico-amniotic shunting.³²

4.1 | 3D reconstruction and 3D virtual cystoscopy

Virtual fetal cystoscopy provides a novel perspective as it is capable of generating a 3D cystoscopic-like view of the urethra and bladder, for instance to demonstrate the distal extension of ureterocele or bladder outlet obstruction (Figure 4) (Video 1). This technique is based on a three-dimensional (3D) acquisition, using a SSFP sequence. Virtual cystoscopy may provide a clear and precise evaluation of the obstructive pathology and assist in planning treatment. It has been occasionally used to guide treatment of a ureterocele using the double

FIGURE 2 Normal appearance of the rectum on T2W image (left) and on T1W image (right). Normal rectum exhibits meconium-like high intensity signal on T1W images and low intensity signal on T2W images after 24 weeks. It is located close to the bladder with its cul-de-sac being at least 10 mm below the bladder neck, confirming its normal anatomy and ruling out rectal atresia



puncture technique,^{33,34} or to document posterior urethral valves.³⁵ The quality of virtual cystoscopy is directly related to the quality of the MR images, which can be hampered by fetal movements and the artefacts these induce.

4.2 | Functional imaging

One of the challenges in the management of obstructive uropathies is proper function assessment, which ideally is noninvasive and should be amenable for longitudinal monitoring.³⁶ The use of MRI for this purpose is relatively recent³⁷ and the understanding of renal physiology is now rapidly evolving,³⁸ for instance in renovascular disease, diabetic nephropathy, renal transplants, renal masses, acute kidney injury, and pediatric anomalies.³⁷ However, the role of MRI in assessment of fetal renal function has not yet been well investigated. For instance, renal impairment has been demonstrated in cases with fetal growth restriction,³⁹ having long-term consequences.⁴⁰⁻⁴² In these cases MRI may have a role in predicting outcome.⁴³

4.3 | Diffusion weighted imaging

Diffusion weighted imaging (DWI) is widespread in many areas of clinical MRI, including fetal renal assessment.^{44,45} An apparent diffusion coefficient (ADC) value is calculated for each voxel within an image. Fetal kidney ADC decreases with increasing gestation, but the pattern may be quite different in urinary tract anomalies.^{45,46} Normally, the fetal kidney shows restricted diffusion similar to that of the mother's kidneys. Conversely, a functionally impaired kidney demonstrates higher signal on ADC.²² When DWI is performed with low diffusion sensitization in capillarized tissue, the measured signal attenuation has

a second component caused by the microcirculation within the capillary network (intra-voxel incoherent motion).⁴⁷ The two-compartment model fitting in this case may be influenced by noise and other tissue properties of the cortex, medulla, and renal pelvis fluid.^{48,49} Diffusion measurements can be enhanced by including directional sensitization and there is now some evidence of directionality of flow in the kidney.⁵⁰ Measurements may therefore provide a marker of glomerular filtration rate. Multi-compartment models such as used in adult and pediatric populations are also suitable for fetal applications,⁵¹ but to the best of our knowledge have not yet been attempted. DWI can also be a helpful adjunct to US to confirm an ectopic kidney, in the differential diagnosis of renal agenesis.^{22,45,52} Lack of a normal DWI bright signal in the renal fossae without evident renal signal elsewhere is consistent with renal agenesis rather than ectopic kidneys.^{22,45} It has also been suggested that DWI with ADC determination is useful for predicting renal function in the presence of posterior urethral valves.⁴⁶

4.4 | Other functional MRI techniques with potential clinical importance

4.4.1 | Blood oxygen level-dependent (BOLD) MRI

The BOLD effect is a functional MRI technique, based on the paramagnetic properties of hemoglobin and extensively used in functional brain imaging.^{53,54} While deoxyhemoglobin has a paramagnetic effect, and induces a local inhomogeneity in the magnetic field, oxyhemoglobin does not. Shifts from states of hyper- or hypo-oxygenation to a normal or resting state induces a BOLD effect which varies according to the level of oxygenation of the tissue. The BOLD effect is directly obtained by analyzing the variation of signal intensity between the

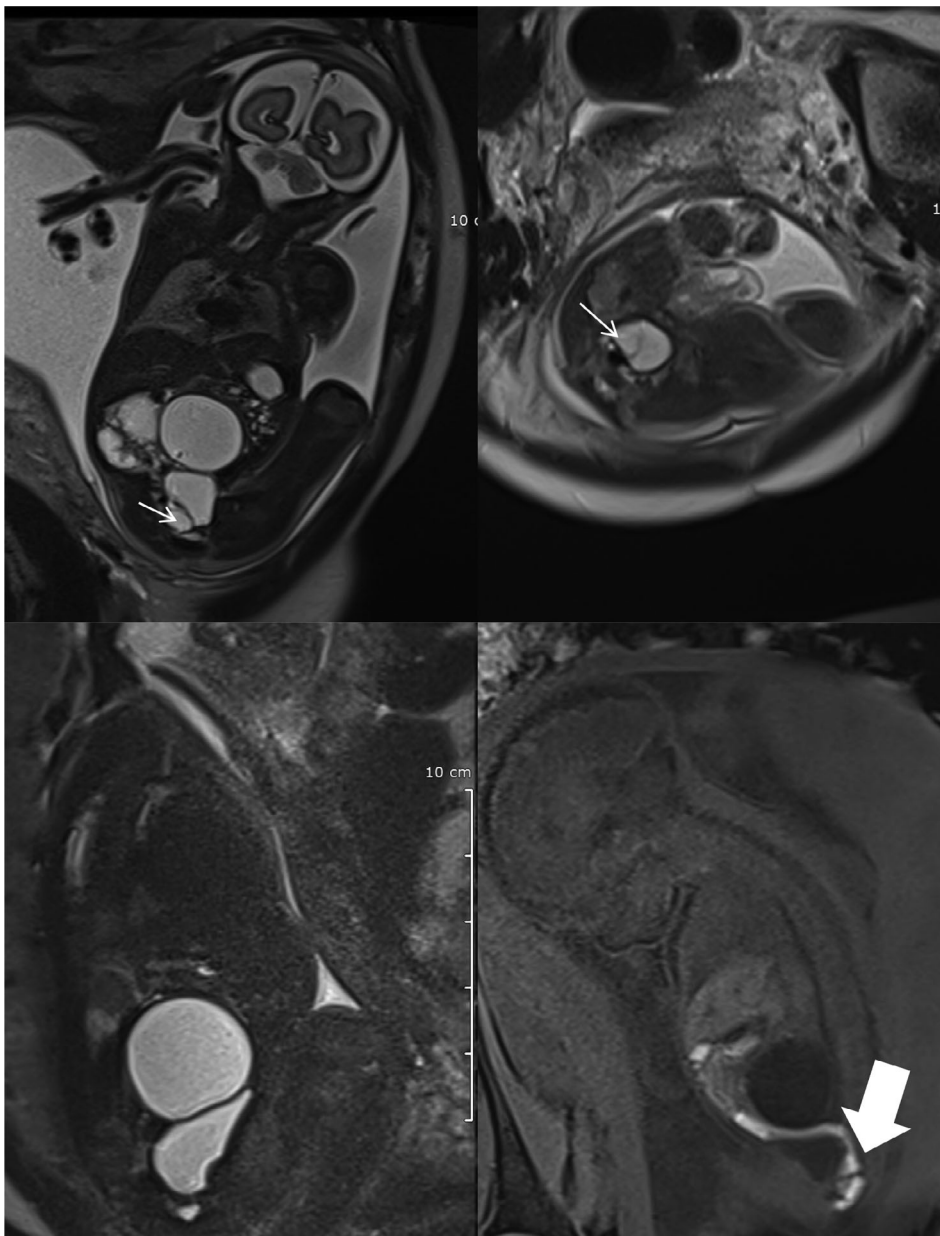


FIGURE 3 Urinary tract malformation secondary to a ureterocele (small arrow) with a multicystic kidney on T2W images. Note the normal appearance of the rectum on T1W images (large arrow, lower right image)

two oxygenation states, or by measuring the $T2^*$ relaxation time when a multi-echo spoiled gradient echo sequence is performed.

The BOLD technique has been used in human adults in a wide variety of renal pathologies to evaluate that organ's function.^{9,53,55-57} It seems also logic to attempt to evaluate the effectiveness of fetal therapeutic interventions as a function of changes in renal oxygen content. BOLD MRI could be used for this purpose to document renal oxygenation, hence replace invasive techniques, including microelectrodes⁵⁸ or laser probes.⁵⁹

Sorenson et al demonstrated that during maternal hyperoxia, oxygenation changes could be measured in a number of fetal organs,⁶⁰ including the liver, spleen, kidneys as well as the placenta. Within a few minutes, the MRI signal reached a steady-state plateau. We have started a preliminary study on a rat model of unilateral obstructive uropathy with the aim of evaluating the chronology of renal function deterioration in the ligated kidney. We hence compared the evolution

of the BOLD effect between the normal and the obstructed kidney on days 0, 2, 4, 6, and 8 after ligating the right ureter (unpublished data). We measured the BOLD effect longitudinally in both kidneys (normal and ligated) ($\Delta T2^* = 100 \times (T2^*O_2 - T2^*AA) / T2^*AA$) and adjusted it to the BOLD effect in the liver (Chart 1).

In the obstructed kidney, there was a brief period of slightly increased O_2 consumption, evidenced by a drop in the BOLD effect. Thereafter, that kidney gradually decreased its oxygen consumption and concomitantly increased the BOLD effect (Chart 1). From the 6th day after ligation the BOLD effect decreased. This could be explained in two ways: (a) the pressure secondary to the dilatation impedes the flow to the renal tissue, thus compromising oxygen supply or (b) the renal tissue becomes ischemic and is no longer perfused. In the contralateral kidney, oxygen consumption was initially significantly increased, to compensate for the contralateral renal impairment, reducing the BOLD effect for most of the

duration of the experiment. By the 8th day, the oxygen consumption in that kidney increases with a further fall in the BOLD effect. Moreover, Avni et al demonstrated the BOLD effect to be a potential tool to overcome the need for direct sampling of fetal or maternal blood: he was able to generate oxygen-hemoglobin dissociation curves and to map fetoplacental oxygen-hemoglobin affinity in pregnant mice at 9.4-T MR, derived from the relaxation rates R1 and R2*.⁶¹

Knowledge of the normal BOLD effect in fetal kidneys and appropriate recognition of the natural history of its changes in obstructive pathologies may permit improved assessment, eventually perhaps also counseling and follow-up of renal diseases.

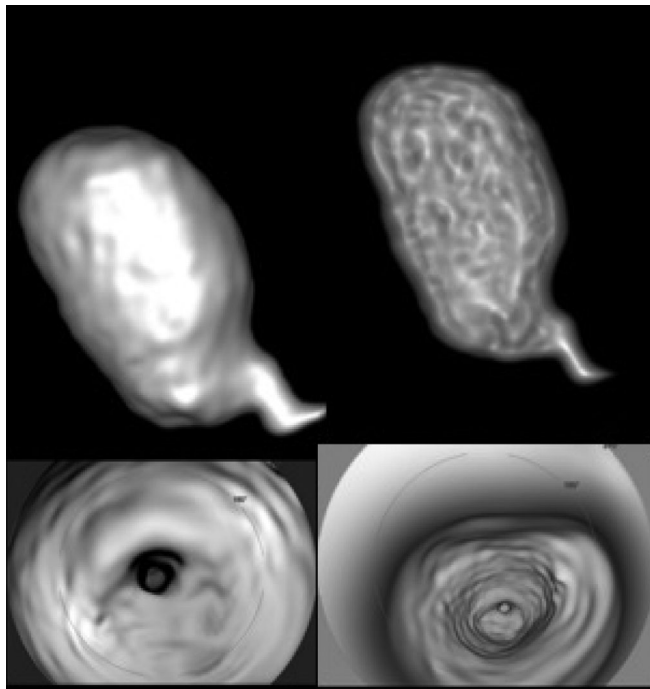


FIGURE 4 Virtual fetal cystoscopy using MRI showing a 3D reconstructed obstructed bladder with its trabeculation (upper images) and a cystoscopic-like view of urethra and bladder outlet obstruction(lower images). For more visual content check Video 1

4.4.2 | Functional MRI techniques as potential tools

Dynamic contrast enhanced (DCE) MRI, arterial spin labeling (ASL), magnetic resonance spectroscopy, and relaxometry are functional MRI techniques with applications for renal function evaluation.⁶⁴⁻⁷¹ Although DCE has been investigated in the kidneys of developing mice,⁶² it still is not clinically used. Conversely, magnetic resonance spectroscopy of fetal and neonatal urine has been attempted and may allow noninvasive longitudinal follow up, as an alternative to serial vesicocentesis.⁶³

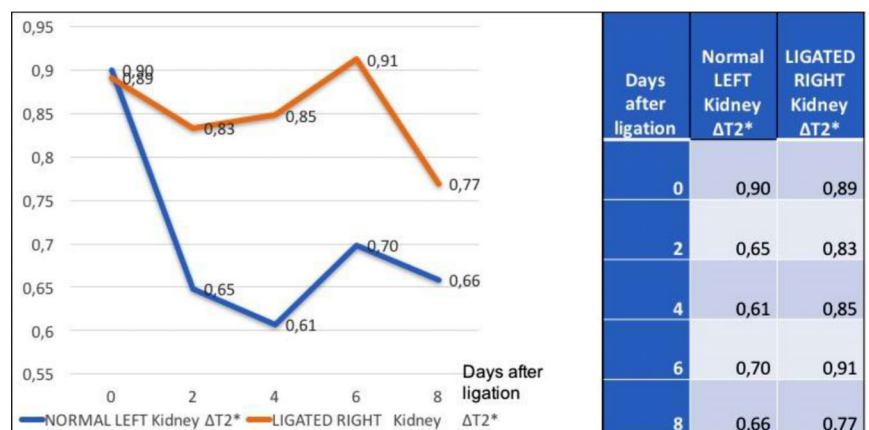
Despite the promise of functional MRI for extracting quantitative physiological information, many challenges remain and a validation process will be required before these techniques can be clinically implemented.

4.5 | Imaging of genital anomalies

Abnormal genitalia and obstructive disorders of the vagina are much less frequent than urinary anomalies. They can be diagnosed at various gestational ages depending on their severity, yet some occur typically during the third trimester such as ovarian cysts. Fetal genital malformations include disorders of sexual development (DSD), complex pelvic malformations such as a cloaca with or without exstrophy, urogenital sinus, and female hypospadias, obstructive conditions such as vaginal atresia, imperforate hymen, or a vaginal septum. These malformations are often identified as a cystic dilatation of the vagina (hydrocolpos) (Figure 5) due to the accumulation of cervical secretions or urine in case of a persistent urogenital sinus or cloacal dysgenesis. It is important to differentiate simple from more complex obstructive diseases and cloacal and urogenital sinus pathology. Precise knowledge of the anatomy is necessary to adjust prenatal counseling.¹⁰

The cause of the cystic dilatation is often difficult to determine on US.¹¹ Fetal MRI is useful to locate and characterize the rectum as well as to diagnose associated anomalies (Figure 5). Fetal MRI can refine an US diagnosis, modifying further management.^{10,12} For instance, MRI helps excluding the diagnosis of cloacal malformation by identifying the normal rectum, because of the presence of a normal

CHART 1 Evolution of the BOLD effect $\Delta T2^*$ at the level of the normal left and the right ligated kidney adjusted to the $\Delta T2^*$ of the liver after the ligation of the right ureter [Colour figure can be viewed at wileyonlinelibrary.com]



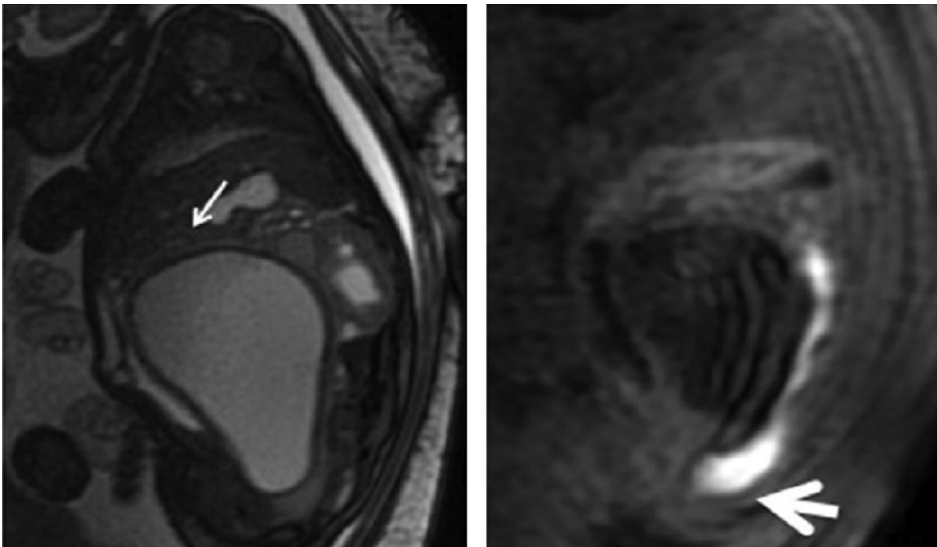


FIGURE 5 Hydrocolpos. The dilated cystic vagina displaces the uterus in the upper abdomen (small arrow). Note the normal appearance of the rectum on T1W images (large arrow, lower right image)

meconium signal (hyperintense on T1W and hypointense on T2W images) because of the absence of urogenital secretions in the rectum. In a consecutive series of 20 MRIs in obstructive urogenital anomalies, MRI was found to facilitate evaluation of major pelvic organs and to provide significant additional information, optimizing the prenatal management, when compared to US.¹³ In particular, MRI facilitated the exclusion of a cloaca.¹³

DSD can be suspected based on the atypical appearance of the external genitalia on US (eg, “tulip sign” in posterior hypospadias or clitoromegaly) or a discrepancy between the phenotype and genotype. MRI can be added to genetic and hormonal testing, and permit the exact location of the gonads and Mullerian duct remnants.²⁴

4.6 | Relevant clinical information from MRI examination

Fetal MRI has several advantages.

a. For the fetal medicine specialist

The added value of MRI for urinary tract abnormalities is:

- to confirm the diagnosis raised by US^{11,12} especially in the differentiation of complex urogenital pathology.
- to diagnose or rule out additional abnormalities, which occurs in up to 75% of cases, and modifies prenatal management in 70%.¹³ In particular, MRI allows good differentiation between the urinary tract and the distal meconium-filled intestine.

Over time, MRI may provide functional information and play a role in selecting patients for fetal intervention, next to provide anatomical information, which with the current tools is not very effective.⁶⁴

b. For the pediatric nephrologist

Prenatal counseling in case of congenital anomalies of the kidney and urinary tract (CAKUT) during screening fetal US is mainly based (a) on the presence or absence of extra-renal associated anomalies⁶⁵ and (b) on the evaluation of the risk of postnatal renal failure.

Fetal MRI provides useful information regarding extra-renal involvement in cases of syndromic CAKUT. This is the case not only for CNS anomalies,^{66,67} but also for spinal,⁶⁸ pulmonary,⁶⁹ hepatic,⁷⁰ ophthalmic,⁷¹ genital,¹³ digestive,⁷² and branchial⁷³ defects. MRI is hence an important adjunct to US examination in the anatomical characterization of CAKUT.^{16,18,19} MRI can also assess renal parenchymal differentiation and thickness, caliceal dilation, presence or absence of a urinoma, as well as urinary tract anatomy. In the future, it is hoped that MRI can provide reliable functional information.

c. For the pediatric surgeon

Accurate anatomical characterization of a fetal malformation is required for the pediatric surgeon to provide appropriate counseling to the parents.⁷⁴ For most isolated unilateral urinary tract anomalies, the prognosis is favorable, and US is typically sufficient.^{75,76} Most newborns will eventually be asymptomatic⁷⁷ and performing a post-natal US at 7 to 10 days of life is sufficient.⁷⁸ However, MRI will help in more complex diagnoses, such as the diagnosis of megacystis microcolon intestinal hypoperistalsis syndrome,⁷⁹ obstructive pathology, or the suspicion of a cloaca.⁸⁰

Next to ruling out associated anomalies or absence of the rectum,⁸¹ estimating of the length of the common channel may be helpful for the pediatric surgeon in parental counseling, given it affects urinary prognosis.⁸² The use of fetal MRI in simple conditions, such as isolated hypospadias is questionable, since it does not impact management nor counseling.⁸³

5 | CONCLUSION

MRI provides excellent resolution, anatomical detail, multiplanar acquisition, and permits 3D reconstruction in normal and pathological settings.^{6,13} With the advent of rapid sequences and short acquisition times, the use of fetal MRI has evolved exponentially. It has become key in the optimization of prenatal counseling, as it often refines or modifies the US based prenatal diagnosis thus altering the management of the pregnancy.¹³ The ability of MRI to help plan complex fetal

procedures could also increase its utility in the near future.^{16,84,85} It is hoped that MRI will permit noninvasive, longitudinal estimation of renal function. However, this still faces many challenges, such as validation and technical limitations, such as the need for compensation for both maternal and fetal motion and models that account for the rapid changes with gestational age. This will require new tools for advanced image registration, segmentation, and model-fitting, which can only be developed through close cross-disciplinary collaboration and sharing of data and software.

CONFLICT OF INTEREST

The authors report no conflict of interest with this work.

DATA AVAILABILITY STATEMENT

N/A

ORCID

Gihad E. Chalouhi  <https://orcid.org/0000-0002-3302-416X>

Anne-Élodie Millischer  <https://orcid.org/0000-0002-3692-0998>

Andrew Melbourne  <https://orcid.org/0000-0001-7667-3947>

Nicolas Vinit  <https://orcid.org/0000-0002-2453-9620>

Laurent J. Salomon  <https://orcid.org/0000-0003-0627-4347>

REFERENCES

- Davenport MT, Merguerian PA, Koyle M. Antenatally diagnosed hydronephrosis: current postnatal management. *Pediatr Surg Int*. 2013;29(3):207-214.
- Gomez Huertas M, Culiarez Casas M, Molina Garcia FS, Carrillo Badillo MP, Pastor Pons E. Complementary role of magnetic resonance imaging in the study of the fetal urinary system. *Radiologia*. 2016;58(2):101-110.
- Mouriquand PD, Whitten M, Pracros JP. Pathophysiology, diagnosis and management of prenatal upper tract dilatation. *Prenat Diagn*. 2001;21(11):942-951.
- Parkhouse HF, Barratt TM, Dillon MJ, et al. Long-term outcome of boys with posterior urethral valves. *Br J Urol*. 1988;62(1):59-62.
- Samnakay N, Orford J, Barker A, et al. Timing of morphologic and apoptotic changes in the sheep fetal kidney in response to bladder outflow obstruction. *J Pediatr Urol*. 2006;2(4):216-224.
- Fazecas TM, Araujo Junior E, Werner H, et al. Applicability of magnetic resonance imaging in the assessment of fetal urinary tract malformations. *Can Assoc Radiol J*. 2019;70(1):83-95.
- Sinha A, Bagga A, Krishna A, et al. Revised guidelines on management of antenatal hydronephrosis. *Indian J Nephrol*. 2013;23(2):83-97.
- Baba K, Okai T, Kozuma S, Taketani Y. Fetal abnormalities: evaluation with real-time-processible three-dimensional US--preliminary report. *Radiology*. 1999;211(2):441-446.
- Peralta CF, Cavoretto P, Csapo B, Falcon O, Nicolaidis KH. Lung and heart volumes by three-dimensional ultrasound in normal fetuses at 12-32 weeks' gestation. *Ultrasound Obstetr Gynecol*. 2006;27(2):128-133.
- Amini H, Wikstrom J, Ahlstrom H, Axelsson O. Second trimester fetal magnetic resonance imaging improves diagnosis of non-central nervous system anomalies. *Acta Obstet Gynecol Scand*. 2011;90(4):380-389.
- Chapman T. Fetal genitourinary imaging. *Pediatr Radiol*. 2012;42 (Suppl 1):S115-S123.
- Chauvin NA, Epelman M, Victoria T, Johnson AM. Complex genitourinary abnormalities on fetal MRI: imaging findings and approach to diagnosis. *AJR Am J Roentgenol*. 2012;199(2):W222-W231.
- Millischer AE, Grevent D, Rousseau V, et al. Fetal MRI compared with ultrasound for the diagnosis of obstructive genital malformations. *Prenat Diagn*. 2017;37(11):1138-1145.
- Riccabona M. Imaging of the neonatal genito-urinary tract. *Eur J Radiol*. 2006;60(2):187-198.
- Gordon I, Riccabona M. Investigating the newborn kidney: update on imaging techniques. *Semin Neonatol*. 2003;8(4):269-278.
- Alamo L, Laswad T, Schnyder P, et al. Fetal MRI as complement to US in the diagnosis and characterization of anomalies of the genito-urinary tract. *Eur J Radiol*. 2010;76(2):258-264.
- Martin C, Darnell A, Duran C, Bermudez P, Mellado F, Rigol S. Magnetic resonance imaging of the intrauterine fetal genitourinary tract: normal anatomy and pathology. *Abdom Imaging*. 2004;29(3):286-302.
- Hormann M, Brugger PC, Balassy C, Witzani L, Prayer D. Fetal MRI of the urinary system. *Eur J Radiol*. 2006;57(2):303-311.
- Cassart M, Majoub N, Irtan S, et al. Prenatal evaluation and postnatal follow-up of ureteral ectopic insertion in multicystic dysplastic kidneys. *Fetal Diagn Ther*. 2019;45(6):373-380.
- Pico H, Dabadie A, Bourliere-Najean B, et al. Contribution of the foetal uro-MRI in the prenatal diagnosis of uronephropathies. *Diagn Interv Imaging*. 2014;95(6):573-578.
- Cannie M, Jani J, Dymarkowski S, Deprest J. Fetal magnetic resonance imaging: luxury or necessity? *Ultrasound Obstetr Gynecol*. 2006;27(5):471-476.
- Faghihimehr A, Gharavi M, Mancuso M, Sreedher G. Fetal MR imaging in urogenital system anomalies. *J Matern Fetal Neonatal Med*. 2019;32(20):3487-3494.
- Millischer AE, Sonigo P, Ville Y, Brunelle F, Boddaert N, Salomon LJ. Standardized fetal anatomical examination using magnetic resonance imaging: a feasibility study. *Ultrasound Obstetr Gynecol*. 2013;42(5):553-559.
- Salomon LJ, Sonigo P, Ou P, Ville Y, Brunelle F. Real-time fetal magnetic resonance imaging for the dynamic visualization of the pouch in esophageal atresia. *Ultrasound Obstetr Gynecol*. 2009;34(4):471-474.
- Furey EA, Bailey AA, Twickler DM. Fetal MR imaging of gastrointestinal abnormalities. *Radiographics*. 2016;36(3):904-917.
- McHugo J, Whittle M. Enlarged fetal bladders: aetiology, management and outcome. *Prenat Diagn*. 2001;21(11):958-963.
- Pugash D, Brugger PC, Bettelheim D, Prayer D. Prenatal ultrasound and fetal MRI: the comparative value of each modality in prenatal diagnosis. *Eur J Radiol*. 2008;68(2):214-226.
- Dias CS, Silva JM, Marciano RC, et al. Imaging for evaluation of urologic abnormalities in infants with fetal hydronephrosis: advances and controversies. *J Bras Nefrol*. 2012;34(4):395-400.
- Hawkins JS, Dashe JS, Twickler DM. Magnetic resonance imaging diagnosis of severe fetal renal anomalies. *Am J Obstet Gynecol*. 2008;198(3):328.e1-5.
- Gupta P, Kumar S, Sharma R, Gadodia A, Roy KK, Sharma JB. The role of magnetic resonance imaging in fetal renal anomalies. *Int J Gynaecol Obstet*. 2010;111(3):209-212.
- Abdelazim IA, Abdelrazak KM, Ramy AR, Mounib AM. Complementary roles of prenatal sonography and magnetic resonance imaging in diagnosis of fetal renal anomalies. *Aust N Z J Obstet Gynaecol*. 2010;50(3):237-241.
- Wu S, Johnson MP. Fetal lower urinary tract obstruction. *Clin Perinatol*. 2009;36(2):377-390. x.
- Kajbafzadeh AM, Nabavizadeh B, Seyed Hossein Beigi R, Alinia P, Mirshahvalad SA. Virtual three-dimensional magnetic resonance fetal cystoscopy: a novel modality for precise in utero evaluation of urinary tract. *Urol J*. 2018. <https://doi.org/10.22037/uj.v0i0.4569>. [Epub ahead of print].
- Kajbafzadeh A, Salmasi AH, Payabvash S, Arshadi H, Akbari HR, Moosavi S. Evolution of endoscopic management of ectopic ureterocele: a new approach. *J Urol*. 2007;177(3):1118-1123. discussion 23.

35. Werner H, Lopes J, Ribeiro G, et al. Three-dimensional virtual cystoscopy: noninvasive approach for the assessment of urinary tract in fetuses with lower urinary tract obstruction. *Prenat Diagn.* 2017;37(13):1350-1352.
36. Wang ZJ, Yeh BM. Is assessing renal oxygenation by using blood oxygen level-dependent MR imaging a clinical reality? *Radiology.* 2008;247(3):595-596.
37. Zhang JL, Morrell G, Rusinek H, et al. New magnetic resonance imaging methods in nephrology. *Kidney Int.* 2014;85(4):768-778.
38. Haque ME, Franklin T, Bokhary U, et al. Longitudinal changes in MRI markers in a reversible UO mouse model: preliminary experience. *J Magn Reson Imaging.* 2014;39(4):835-841.
39. Kent AL, Jyoti R, Robertson C, et al. Does extreme prematurity affect kidney volume at term corrected age? *J Matern Fetal Neonatal Med.* 2009;22(5):435-438.
40. Chan PY, Morris JM, Leslie GI, Kelly PJ, Gallery ED. The long-term effects of prematurity and intrauterine growth restriction on cardiovascular, renal, and metabolic function. *Int J Pediatr.* 2010;2010:280402.
41. Stritzke A, Thomas S, Amin H, Fusch C, Lodha A. Renal consequences of preterm birth. *Mol Cell Pediatr.* 2017;4(1):2.
42. Beck M, Graf C, Ellenrieder B, et al. Long-term outcome of kidney function after twin-twin transfusion syndrome treated by intrauterine laser coagulation. *Pediatr Nephrol.* 2005;20(11):1657-1659.
43. Damodaram MS, Story L, Eixarch E, et al. Foetal volumetry using magnetic resonance imaging in intrauterine growth restriction. *Early Hum Dev.* 2012;88(Suppl 1):S35-S40.
44. Manganaro L, Vinci V, Giancotti A, et al. Bi-parametric magnetic resonance imaging applied to obstetrics. *J Obstet Gynaecol.* 2017;37(5):670-672.
45. Savelli S, Di Maurizio M, Perrone A, et al. MRI with diffusion-weighted imaging (DWI) and apparent diffusion coefficient (ADC) assessment in the evaluation of normal and abnormal fetal kidneys: preliminary experience. *Prenat Diagn.* 2007;27(12):1104-1111.
46. Faure A, Panait N, Panuel M, et al. Predicting postnatal renal function of prenatally detected posterior urethral valves using fetal diffusion-weighted magnetic resonance imaging with apparent diffusion coefficient determination. *Prenat Diagn.* 2017;37(7):666-672.
47. Le Bihan D, Breton E, Lallemand D, Aubin ML, Vignaud J, Laval-Jeantet M. Separation of diffusion and perfusion in intravoxel incoherent motion MR imaging. *Radiology.* 1988;168(2):497-505.
48. Orton MR, Collins DJ, Koh DM, Leach MO. Improved intravoxel incoherent motion analysis of diffusion weighted imaging by data driven Bayesian modeling. *Magn Reson Med.* 2014;71(1):411-420.
49. Jerome NP, d'Arcy JA, Feiweier T, et al. Extended T2-IVIM model for correction of TE dependence of pseudo-diffusion volume fraction in clinical diffusion-weighted magnetic resonance imaging. *Phys Med Biol.* 2016;61(24):N667-N680.
50. Jaimes C, Darge K, Khrichenko D, Carson RH, Berman JI. Diffusion tensor imaging and tractography of the kidney in children: feasibility and preliminary experience. *Pediatr Radiol.* 2014;44(1):30-41.
51. Notohamiprodjo M, Reiser MF, Sourbron SP. Diffusion and perfusion of the kidney. *Eur J Radiol.* 2010;76(3):337-347.
52. Manganaro L, Francioso A, Savelli S, et al. Fetal MRI with diffusion-weighted imaging (DWI) and apparent diffusion coefficient (ADC) assessment in the evaluation of renal development: preliminary experience in normal kidneys. *Radiol Med.* 2009;114(3):403-413.
53. Pedersen M, Dissing TH, Morkenborg J, et al. Validation of quantitative BOLD MRI measurements in kidney: application to unilateral ureteral obstruction. *Kidney Int.* 2005;67(6):2305-2312.
54. Vincent K, Moore J, Kennedy S, Tracey I. Blood oxygenation level dependent functional magnetic resonance imaging: current and potential uses in obstetrics and gynaecology. *BJOG Int J Obstet Gynaecol.* 2009;116(2):240-246.
55. Rognant N, Lemoine S, Laville M, Juillard L. Evaluation of renal oxygen content by BOLD MRI. *Nephrol Ther.* 2012;8(4):212-215.
56. Eckardt KU, Bernhardt WM, Weidemann A, et al. Role of hypoxia in the pathogenesis of renal disease. *Kidney Int Suppl.* 2005;99:S46-S51.
57. Thoeny HC, Zumstein D, Simon-Zoula S, et al. Functional evaluation of transplanted kidneys with diffusion-weighted and BOLD MR imaging: initial experience. *Radiology.* 2006;241(3):812-821.
58. Brezis M, Agmon Y, Epstein FH. Determinants of intrarenal oxygenation. I. Effects of diuretics. *Am J Physiol.* 1994;267(6 Pt 2):F1059-F1062.
59. Braun RD, Lanzen JL, Snyder SA, Dewhirst MW. Comparison of tumor and normal tissue oxygen tension measurements using OxyLite or microelectrodes in rodents. *Am J Physiol Heart Circ Physiol.* 2001;280(6):H2533-H2544.
60. Sorensen A, Peters D, Simonsen C, et al. Changes in human fetal oxygenation during maternal hyperoxia as estimated by BOLD MRI. *Prenat Diagn.* 2013;33(2):141-145.
61. Avni R, Golani O, Akselrod-Ballin A, et al. MR Imaging-derived oxygen-hemoglobin dissociation curves and fetal-placental oxygen-hemoglobin affinities. *Radiology.* 2016;280(1):68-77.
62. Xie L, Subashi E, Qi Y, Knepper MA, Johnson GA. Four-dimensional MRI of renal function in the developing mouse. *NMR Biomed.* 2014;27(9):1094-1102.
63. Foxall PJ, Bewley S, Neild GH, Rodeck CH, Nicholson JK. Analysis of fetal and neonatal urine using proton nuclear magnetic resonance spectroscopy. *Arch Dis Child Fetal Neonatal Ed.* 1995;73(3):F153-F157.
64. Matsell DG, Tarantal AF. Experimental models of fetal obstructive nephropathy. *Pediatr Nephrol.* 2002;17(7):470-476.
65. Millischer AE, Sonigo P, Attie T, et al. Fetal MRI findings in a retrospective cohort of 26 cases of prenatally diagnosed charge syndrome individuals. *Prenat Diagn.* 2019;39(9):781-791.
66. Celedin S, Kau T, Gasser J, Kraschl R, Sinzig M. Fetal MRI of a hypothalamic hamartoma in Pallister-Hall syndrome. *Pediatr Neurol.* 2010;42(1):59-60.
67. Reilly ML, Stokman MF, Magry V, et al. Loss of function mutations in KIF14 cause severe microcephaly and kidney development defects in humans and zebrafish. *Hum Mol Genet.* 2019;28(5):778-795.
68. Hong R, Lim SC, Jang JW, et al. OEIS complex with glomerulocystic kidney disease: a case report. *Pediatr Dev Pathol.* 2007;10(2):121-124.
69. Wall J, Coates A. Prenatal imaging and postnatal presentation, diagnosis and management of congenital lung malformations. *Curr Opin Pediatr.* 2014;26(3):315-319.
70. Sciard C, Collardeau-Frachon S, Atallah A, et al. Prenatal imaging features suggestive of liver gestational allo immune disease. *J Gynecol Obstet Hum Reprod.* 2019;48(1):61-64.
71. Araujo Junior E, Kawanami TE, Nardoza LM, Milani HJ, Oliveira PS, Moron AF. Prenatal diagnosis of bilateral anophthalmia by 3D "reverse face" view ultrasound and magnetic resonance imaging. *Taiwan J Obstet Gynecol.* 2012;51(4):616-619.
72. Garel C, Dreux S, Philippe-Chomette P, Vuillard E, Oury JF, Muller F. Contribution of fetal magnetic resonance imaging and amniotic fluid digestive enzyme assays to the evaluation of gastrointestinal tract abnormalities. *Ultrasound Obstet Gynecol.* 2006;28(3):282-291.
73. Jiang ZY, Wood J, Schindel D, Berg E. Abnormal fetal cystic left neck mass. *JAMA Otolaryngol Head Neck Surg.* 2014;140(6):573-574.
74. Benachi A, Sarnacki S. Prenatal counselling and the role of the paediatric surgeon. *Semin Pediatr Surg.* 2014;23(5):240-243.
75. Sidhu G, Beyene J, Rosenblum ND. Outcome of isolated antenatal hydronephrosis: a systematic review and meta-analysis. *Pediatr Nephrol.* 2006;21(2):218-224.

76. Lee RS, Cendron M, Kinnamon DD, Nguyen HT. Antenatal hydronephrosis as a predictor of postnatal outcome: a meta-analysis. *Pediatrics*. 2006;118(2):586-593.
77. Epelman M, Daneman A, Donnelly LF, Averill LW, Chauvin NA. Neonatal imaging evaluation of common prenatally diagnosed genitourinary abnormalities. *Semin Ultrasound CT MR*. 2014;35(6):528-554.
78. Wiener JS, O'Hara SM. Optimal timing of initial postnatal ultrasonography in newborns with prenatal hydronephrosis. *J Urol*. 2002;168(4 Pt 2):1826-1829. discussion 9.
79. Garel C, Leger J. Contribution of magnetic resonance imaging in non-tumoral hypopituitarism in children. *Horm Res*. 2007;67(4):194-202.
80. Picone O, Laperelle J, Sonigo P, Levailant JM, Frydman R, Senat MV. Fetal magnetic resonance imaging in the antenatal diagnosis and management of hydrocolpos. *Ultrasound Obstetr Gynecol*. 2007;30(1):105-109.
81. Capito C, Belarbi N, Paye Jaouen A, et al. Prenatal pelvic MRI: additional clues for assessment of urogenital obstructive anomalies. *J Pediatr Urol*. 2014;10(1):162-166.
82. Bischoff A, Calvo-Garcia MA, Baregamian N, et al. Prenatal counseling for cloaca and cloacal exstrophy-challenges faced by pediatric surgeons. *Pediatr Surg Int*. 2012;28(8):781-788.
83. Nemeč SF, Kasprian G, Brugger PC, et al. Abnormalities of the penis in utero--hypospadias on fetal MRI. *J Perinat Med*. 2011;39(4):451-456.
84. Aghwane R, Ingram E, Johnstone ED, Salomon LJ, David AL, Melbourne A. Placental MRI and its application to fetal intervention. *Prenat Diagn*. 2019 Jul 15. <https://doi.org/10.1002/pd.5526> [Epub ahead of print].
85. Luo J, Abaci Turk E, Bibbo C, et al. In vivo quantification of placental insufficiency by BOLD MRI: a human study. *Sci Rep*. 2017;7(1):3713.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

How to cite this article: Chalouhi GE, Millischer A, Mahallati H, et al. The use of fetal MRI for renal and urogenital tract anomalies. *Prenatal Diagnosis*. 2020;40:100–109. <https://doi.org/10.1002/pd.5610>