Clinical Trial/Experimental Study

Medicine

OPEN

The diagnostic efficacy of diffusion tensor imaging generated by gadolinium-based magnetic resonance imaging for patients with chronic kidney disease

Liu He, MM[a], Gao Dan, MM[b], Sun Yuanbo, MD[c], Tang Fengqiong, MM[d], Hu Mingcheng, MM[a], Hongyi Li, MM[a,*]

Abstract

Background: Chronic kidney disease (CKD) can lead to systemic inflammatory responses and other cardiovascular disease. Diffusion tensor imaging findings generated by gadolinium-based MRI (DTI-GBMRI) is regarded as a standard method for assessing the pathology of CKD. To evaluate the diagnostic value of DTI-GBMRI for renal histopathology and renal efficiency, renal fibrosis and damage, noninvasive quantification of renal blood flow (RBF) were investigated in patients with CKD.

Methods: CKD patients (n = 186) were recruited and underwent diagnosis of renal diffusion tensor imaging findings generated by MRI (DTI-MRI) or DTI-GBMRI to identify the pathological characteristics and depict renal efficiency. The cortical RBFs and estimated glomerular filtration rate were compared in CKD patients undergone DTI-GBMRI (n = 92) or DTI-MRI (n = 94).

Results: Gadolinium enhanced the diagnosis generated by DTI-MRI in renal fibrosis, renal damage, and estimated glomerular filtration rate. The superiority in sensitivity and accuracy of the DTI-GBMRI method in assessing renal function and evaluating renal impairment was observed in CKD patients compared with DTI-MRI. Outcomes demonstrated that DTI-GBMRI had higher accuracy, sensitivity, and specificity than DTI-MRI in diagnosing patients with CKD.

Conclusion: In conclusion, DTI-GBMRI is a potential noninvasive method for measuring renal function, which can provide valuable information for clinical CKD diagnosis.

Abbreviations: ASCVD = atherosclerotic cardiovascular disease, BP = blood pressure, CEUS = contrast-enhanced ultrasound, CKD = chronic kidney disease, CMR = cardiovascular magnetic resonance, CNR = contrast-to-noise ratio, CT = computed tomography, DTI-GBMRI = diffusion tensor imaging findings generated by gadolinium-based MRI, DTI-MRI = diffusion tensor imaging findings generated by MRI, eGFR = estimated glomerular filtration rate, GB = gadolinium, MRI = magnetic resonance imaging, MTT = mean transit time, RBF = renal blood flow, ROC = receptor operating characteristics, US = ultrasonography.

Keywords: chronic kidney disease, diffusion tensor imaging, DTI-GBMRI, eGFR, RBF, renal function

1. Introduction

Chronic kidney disease (CKD) is a public health problem worldwide, which is a gradual impairment of renal function.[1] Patients with CKD are at an increased risk of cardiovascular disease and other chronic conditions with their daily lives.[2] Clinically, CKD is characterized by a low estimated glomerular filtration rate (eGFR, <60 mL/min/1.73 m^2), which may progress at varying rates depending on blood pressure management, history of decreased GFR, level of proteinuria.[3] CKD may result in abnormalities of multiple physiological processes including removal of waste products of metabolism, heterogeneous disorders on kidney structure and function, electrolyte balance that substantially increases mortality risk due to atherosclerotic cardiovascular disease (ASCVD).[4] Therefore, CKD patients require imaging monitoring to accurately predict the risk of declining renal function and guide therapeutic schedules.

Consent for tissue collection and use was collected prior to experimentation. All patients signed written informed consent and consent for publication.

The authors have no funding and conflicts of interest to disclose.

The present study was approved by the Committee on Human Rights Related to Research Involving Human Subjects (IRB Approval number: 20170111X).

This study was approved by the ethics committee of Hongqi Hospital Affiliated To Mudanjiang Medical University. Mechanism of BMSC transformation of NRk-52e based on the role of gsk3beta in renal interstitial fibrosis (UNPYSCT-2018120).

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

[a] Department of Magnetic Resonance, Hongqi Hospital Affiliated to Mudanjiang Medical University, Mudanjiang, China, [b] Pathological Diagnosis Center, Hongqi Hospital Affiliated to Mudanjiang Medical University, Mudanjiang, China, [c] Department of Nephrology, Hongqi Hospital Affiliated to Mudanjiang Medical University, Mudanjiang, China, [d]Department of Magnetic Resonance, Qujing First People's Hospital, Qujing, China.

** Correspondence: Li Hongyi, Department of Magnetic Resonance, Hongqi Hospital Affiliated to Mudanjiang Medcial University, No 5, Tongxiang, Road, Mudanjiang 157000, China (e-mail: hongyi_liprof@163.com).*

How to cite this article: He L, Dan G, Yuanbo S, Fengqiong T, Mingcheng H, Hongyi L. The diagnostic efficacy of diffusion tensor imaging generated by gadolinium-based magnetic resonance imaging for patients with chronic kidney disease. Medicine 2022;101:27(e29291).

Received: 11 November 2021 / Received in final form: 10 February 2022 / Accepted: 24 March 2022

http://dx.doi.org/10.1097/MD.0000000000029291

CKD is generally diagnosed by imaging of the kidney using ultrasonography (US), contrast-enhanced ultrasound (CEUS), computed tomography (CT), or magnetic resonance imaging (MRI).[5] Cardiovascular magnetic resonance (CMR) is a standard method for imaging impairment in kidney function, renal injury, and fibrosis.[6] MRI technique in particular has the potential to present both structural and functional parameters in the kidney by using targeted magnetic nanoparticles.[7] Gadolinium (GB)-based are an important aid in MRI diagnostics for improving the detection and characterization of pathologic processes.[8] Gadolinium GB-based contrast agents are frequently used to enhance the diagnostic efficacy of MRI in patients with kidney diseases.[9] In addition, GB is widely employed as a contrast agent for MRI and has generally been considered to be safe in patients with kidney disease.[10] Furthermore, a potential alternative imaging modality for evaluating GFR and renal fibrosis is diffusion tensor imaging findings generated by Gadolinium-based MRI (DTI-GBMRI).[11] Thus, DTI-GBMRI may be ideal for renal function assessment in patients with CKD.

The purpose of this study was to comprehensively assess renal histopathology and renal efficiency, renal fibrosis and damage, noninvasive quantification of renal blood flow (RBF) in patients with CKD using DTI-GBMRI. The sensitivity and accuracy between DTI-GBMRI and DTI-MRI method in assessing renal function and evaluating renal impairment was compared in CKD patients. The association between the RBF value and eGFR was analyzed in patients with CKD.

2. Materials and methods

2.1. Patients

A total of 186 CKD patients were recruited in Hongqi Hospital Affiliated To Mudanjiang Medical University between January 2017 and May 2019. The inclusion criteria were as follows: age > 18 years; and Stage 2 of CKD (60 ml/min/1.73 m^2 ≤ eGFR <90 mL/min/1.73 m^2); Stage 3a of CKD (30 mL/min/1.73 m^2 ≤ eGFR <60 mL/min/1.73 m^2); The exclusion criteria were as follows: patients with HIV infection, polycystic kidney disease, cancer; transplant recipients; pregnant and breastfeeding women; and history of adverse reaction to gadolinium. The protocol was approved by the ethics committee of Hongqi Hospital Affiliated To Mudanjiang Medical University. CKD patients received DTI-GBMRI (n = 92) or DTI-MRI (n = 94) diagnosis. All participants signed written informed consent.

2.2. Magnetic resonance imaging

MRI examinations were performed using a 3 T unit (Canon Medical Systems, Tustin, CA). Diffusion-weighted imaging/diffusion tensor imaging scans were obtained by using the following parameters: 256 diffusion directions, TR: 8000 ms, TE: 60 ms, 8 diffusion-weighted b-values in steps of 200 s/mm^2 ranging from b: 0 to 14,000 s/mm^2, flip angle: 90°; bw: 1860 Hz/px, transversal base resolution matrix: 128 × 128. For DTI-GBMRI, a bolus injection of 0.2 mL/kg body weight gadolinium (Omniscan; Bracco, Daiichi-San-kyo Co., Ltd, Tokyo, Japan) was intravenously administered, followed by a 20-mL saline flush at 2 mL/s. The location of impairment of renal structure can be observed in MRI images, where exposure to GB-based contrast agent in CKD patients. MR renography was obtained from all CKD patients to analyze renal histopathology and renal efficiency, renal fibrosis and damage, and noninvasive quantification of RBF.

2.3. Outcomes

Kidney volume, the number, diameter, and volume of glomeruli in CKD patients were automatically analyzed using MRI image data. The eGFR was calculated using the estimation equation for CKD patients determined by MRI image data. The GFR was calculated for each kidney by 3 radiologists by using Mirage software.[12] The mean transit time (MTT) was used to evaluate function of kidney in CKD patients as described previously.[13] RBF was determined by MRI image data.[14] The procedure includes preprocessing of image data, segmentation of the kidney region, segmentation of the glomeruli, and quantification of the segmented regions as described previously.[7] All parameters were automatically analyzed by Syngo software (Siemens, Erlangen, Germany).

2.4. Statistical analyses

Data are expressed means ± SD. All statistical analyses were performed using SAS software (version 9.4; SAS Institute, Inc., Tokyo, Japan). The P values were calculated via independent sample t test for continuous variables and chi-square test for categorical variables. Receiver operating characteristic (ROC) analyses were used to analyze the diagnostic performance of the DTI-GBMRI diagnosis. The cutoff was determined according to the ROC curve, and then the specificity and sensitivity of various scoring systems were calculated separately. Statistical significance was defined as a *P* value <.05.

3. Results

3.1. Characteristic of patients with CKD

A total of 186 CKD patients were enrolled in this study. All CKD patients in stage 1 or 2 were enrolled between May 2017 and June 2019. A flowchart of CKD patient recruitment is shown in Figure 1. The age of CKD patients was 46.5 years old (range, 30–65 years). CKD patients received diagnosis of DTI-GBMRI (n = 92) or DTI-MRI (n = 94) to identify the pathological characteristics and depict renal efficiency. Table 1 showed the demographics and characteristics of patients with CKD. There were no significant differences in BMI, age, sex, blood pressure, cerebrovascular disease, and intraocular pressure between 2 groups. Signalment and renal biomarkers in 2 groups were not significant difference.

3.2. The pathological characteristics and depict renal efficiency diagnosed by DTI-GBMRI

We compared the pathological characteristics and depict renal efficiency in CKD patients diagnosed by DTI-GBMRI or DTI-MRI. CKD patients diagnosed by DTI-GBMRI showed more renal vascular lesions and bigger diameters of lesions than those patients in DTI-MRI group. The average diameter diagnosed by DTI-GBMRI was 3.28 cm, while was in 3.02 cm in CKD patients diagnosed by DTI-MRI. DTI-GBMRI had significantly better performance than DTI-MRI in measuring lumen depiction scores (4.8 ± 0.2 vs 3.2 ± 0.2 for arterial inflow, 4.2 ± 0.1 vs

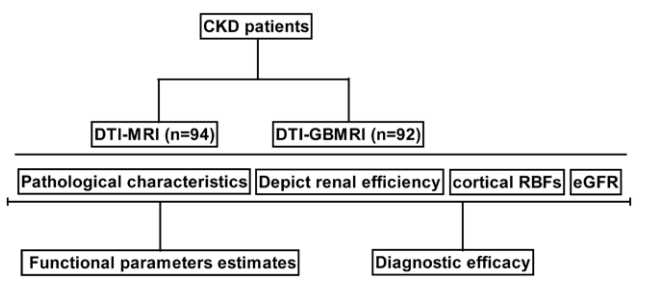

Figure 1. Flow diagram showing CKD patients in this study. CKD = chronic kidney disease.

Table 1

Characteristic of CKD patients.

	DTI-MRI	DTI-GBMRI
Number	94	92
Male/female	54/40	53/39
Age (y)	52 ± 10	52 ± 10
BMI (kg/m^2)	25.2 ± 2.6	25.8 ± 3.1
Blood pressure (mm Hg)		
Systolic	132.3 ± 8.5	130.8 ± 9.0
Diastolic	82.6 ± 5.8	84.2 ± 6.5
Cerebrovascular disease	10 (10.6%)	9 (9.8%)
Intraocular pressure (mm Hg)	14.5 ± 2.6	14.8 ± 3.1
Smoking, n (%)	10 (10.6%)	10 (10.9%)
CKD stages		
2 (mild)	50 (53.2%)	50 (54.3%)
3a (mild to moderate)	44 (46.8%)	42 (45.7%)

Data are expressed as mean ± or n (%). The *P* values were calculated via independent sample *t* test for continuous variables and chi-square test for categorical variables.
BMI = body mass index, CKD = chronic kidney disease, DTI-GBMRI = diffusion tensor imaging findings generated by gadolinium-based MRI, DTI-MRI = diffusion tensor imaging findings generated by MRI.

1.8 ± 0.2 for arterial outflow, 3.8 ± 0.3 vs 2.0 ± 0.3 for anastomosis, and 4.4 ± 0.2 vs 2.2 ± 0.2 for venous outflow; $P < .01$), intraluminal signal homogeneity (0.24 ± 0.03 vs 0.40 ± 0.05, $P < .01$), and contrast-to-noise ratio efficiency in the venous outflow (5.2 ± 0.3 vs 2.6 ± 0.3, $P < .01$) (Table 2).

3.3. Kidney volume and functional parameters estimates

Kidney volumes and functional parameters estimates were compared in CKD patients between DTI-GBMRI and DTI-MRI groups (Table 3). The mean kidney volumes of CKD patients in DTI-GBMRI and DTI-MRI were 2046 ± 214 and 1868 ± 224 mL, respectively ($P < .01$). Creatinine levels were not significantly different between DTI-GBMRI and DTI-MRI groups. The total glomerular count in CKD patients diagnosed by DTI-GBMRI and DTI-MRI was around 16,320 ± 12,350 and 14,560 ± 10,180, respectively ($P < .01$). MTT_K was significantly higher in the DTI-MRI group (186.2 ± 40.5 seconds) than in the DTI-GBMRI group (137.6 ± 30.6 seconds). DTI-GBMRI revealed stronger impairment of renal perfusion (156 ± 7 vs 293 ± 44 mL/[min × 100 g]; $P < .01$) and more pronounced increases in T2 (60.1 ± 2.0 vs 45.7 ± 1.2 ms, $P < .01$) and T1 relaxation times (1938 ± 53 vs 1350 ± 27 ms, $P < .01$) than DTI-MRI. Apparent diffusion coefficient was $1.39 \pm 0.14 \times 10^{-3}$ and $1.83 \pm 0.05 \times 10^{-3}$ mm^2/s in kidneys in the DTI-GBMRI group and DTI-MRI group, respectively ($P < .05$).

3.4. Cortical RBFs and eGFR

The cortical RBFs and eGFR were compared in CKD patients undergone DTI-GBMRI (n = 92) or DTI-MRI (n = 94). The cortical RBF values of CKD patients in the DTI-GBMRI group were lower than patients in DTI-MRI group (315.8 ± 23.6 vs 503.5 ± 32.4, $P < .01$). Outcomes demonstrated that eGFR was significantly lower in CKD patients who undergone DTI-GBMRI than those undergone DTI-MRI (36.4 ± 20.8 vs 44.7 ± 16.5 mL/min) (Table 4). Results showed that gadolinium enhanced the diagnosis generated by DTI-MRI in renal fibrosis, renal damage, and eGFR.

Table 2

The pathological characteristics and depict renal efficiency diagnosed by DTI-GBMRI.

	DTI-MRI	DTI-GBMRI	*p* value
Diameters of lesions (cm)	3.02 ± 0.32	3.28 ± 0.24	.0045
Depiction scores	3.2 ± 0.2	4.8 ± 0.2	.0032
Arterial inflow	1.8 ± 0.2	4.2 ± 0.1	.0010
Arterial outflow	2.0 ± 0.3	3.8 ± 0.3	.0041
Venous outflow	2.2 ± 0.2	4.4 ± 0.2	.0036
Intraluminal signal homogeneity	0.40 ± 0.05	0.24 ± 0.03	.0057
CNR efficiency	2.6 ± 0.3	5.2 ± 0.3	.0028

Data are reported as mean ± SD. The *P* values were analyzed using independent sample *t* test.
CNR = contrast-to-noise ratio, DTI-GBMRI = diffusion tensor imaging findings generated by gadolinium-based MRI, DTI-MRI = diffusion tensor imaging findings generated by MRI.

Table 3

Kidney volume and functional parameters estimates diagnosed by DTI-GBMRI.

	DTI-MRI	DTI-GBMRI	*P* value
Kidney volumes (mL)	1868 ± 224	2046 ± 214	.0008
Creatinine (mg/dL)	1.68 ± 0.32	1.75 ± 0.40	.0091
MTT_K	186.2 ± 40.5	137.6 ± 30.6	.0025
Impairment of renal perfusion (mL/min)	293 ± 44	156 ± 7	.0010
T2 pronounce (ms)	45.7 ± 1.2	60.1 ± 2.0	.0040
T1 relaxation times (ms)	1938 ± 53	1350 ± 27	.0012
CNR efficiency (mm^2/s)	$1.83 \pm 0.05 \times 10^{-3}$	$1.39 \pm 0.14 \times 10^{-3}$	.0085

Data are reported as mean ± SD. The *P* values were analyzed using independent sample t test.
CNR = contrast-to-noise ratio, DTI-GBMRI = diffusion tensor imaging findings generated by gadolinium-based MRI, DTI-MRI = diffusion tensor imaging findings generated by MRI.

3.5. Diagnostic efficacy of DTI-GBMRI

The ROC curve was used to determine the diagnostic efficacy between DTI-MRI and DTI-GBMRI groups in CKD patients. The DTI-GBMRI method showed the superior diagnostic accuracy compared to DTI-MRI. Outcomes demonstrated that DTI-GBMRI had higher sensitivity and specificity than DTI-MRI in diagnosing patients with CKD (Table 5). From the curve, the cut-off value for and DTI-GBMRI were determined with maximum sensitivity and specificity to be 0.92 and 0.85, respectively (Fig. 2).

4. Discussion

The assessment of early CKD damage is of crucial importance in preventing CKD-induced diseases.[15] In this study, we investigated the diagnostic efficacy of DTI-GBMRI in evaluating histopathology and renal efficiency in patients with CKD. Functional parameters associated with renal impairment in kidney function were analyzed in DTI-GBMRI-diagnosed CKD patients with CKD. Findings in this study demonstrated that DTI-GBMRI clearly demonstrated the pathological characteristics and depict renal efficiency compared to MRI in CKD patients. Thus, DTI-GBMRI may be a potential noninvasive method for measuring renal function for CKD patients.

CKD has been associated with increased visual impairment and cardiovascular disease.[15] Inflammation and dysfunction of glomerular cells contributes to the cardiovascular disease burden associated with CKD, which is one of the most important

Table 4

Analysis of Cortical RBFs and eGFR in CDK patients.

	DTI-MRI	DTI-GBMRI	*P* value
Serum creatinine (mg/dL)	1.68 ± 0.32	1.75 ± 0.40	.0058
eGFR (mL/min/1.73 m^2)	36.4 ± 20.8	44.7 ± 16.5	.0072
BRF(ml/min)	503.5 ± 32.4	315.8 ± 23.6	.0020

Data are reported as mean ± SD. The *P* values were analyzed using independent sample *t* test.
CKD = chronic kidney disease, DTI-GBMRI = diffusion tensor imaging findings generated by gadolinium-based MRI, DTI-MRI = diffusion tensor imaging findings generated by MRI, eGFR = estimated glomerular filtration rate, RBF = renal blood flow.

Table 5

Diagnostic efficacy of DTI-GBMRI in CKD patients.

	DTI-MRI	DTI-GBMRI	*P* value
Sensitivity (%)	86.8	98.5	.0048
Specificity (%)	88.3	98.2	.0070

Sensitivity and specificity differences between DTI-MRI and DTI-GBMRI were analyzed using Pearson nonparameter correlation analysis.

CKD = chronic kidney disease, DTI-GBMRI = diffusion tensor imaging findings generated by gadolinium-based MRI, DTI-MRI = diffusion tensor imaging findings generated by MRI.

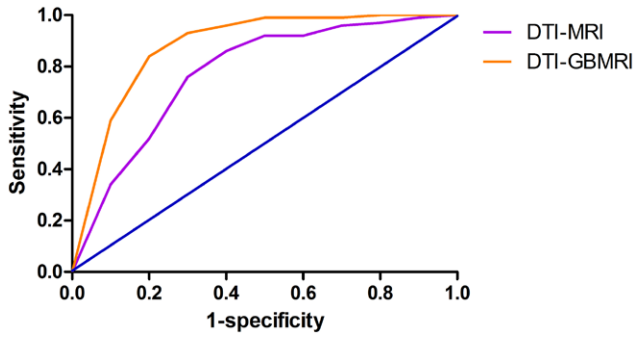

Figure 2. Receiver operating characteristic curve of DTI-GBMRI and DTI-MRI for the diagnosis of CKD patients. CKD = chronic kidney disease, DTI-GBMRI = diffusion tensor imaging findings generated by gadolinium-based MRI, DTI-MRI = diffusion tensor imaging findings generated by MRI.

risk factors for mortality and morbidity in CKD patients.[16] Thus, it is very important to evaluate the degree of CKD and analyze abnormalities of kidney structure or function.[17] MRI methods have become available for renal functional evaluation for patients with CKD, which can access renal function combined with high-resolution morphological evaluation of the kidneys and the entire urinary tract.[18] In this study, we found that DTI-GBMRI presented higher efficacy in evaluating renal histopathology and renal efficiency, renal fibrosis and damage, and noninvasive quantification of RBF than DTI-MRI (Table 2). Data reported that DTI-GBMRI clearly showed the diameters of lesions, good performance in measuring lumen depiction scores, intraluminal signal homogeneity, and contrast-to-noise ratio efficiency in CKD patients compared to DTI-MRI, suggesting DTI-GBMRI provided the possible origins of differences in estimates of CKD prevalence, and presented possible solutions for tackling the factors responsible for the reported variations in renal injury measurements (Table 3).

Previously, MRI allows the assessment of markers of perfusion without the use of contrast media.[19] A study highlighted the potential clinical benefits of early detection in patients predisposed to CKD by using MRI techniques, which provided structural and functional information in the kidney.[7] Zhao et al[20] found that diffusion-weighted MRI can be used to assess renal fibrosis in CKD patients. Data in this study observed that DTI-GBMRI-diagnosed CKD patients had higher MTT_K, stronger impairment of renal perfusion and more pronounced increases in T2 and T1 relaxation times than DTI-MRI in CKD patients. However, there was no significant difference in evaluating kidney volumes between DTI-GBMRI and DTI-MRI groups. A previous study demonstrated that MRI could classify renal function, identify eGFR and functional renal parenchyma RBF in CKD patients.[20,21] Findings in the current study demonstrated that DTI-GBMRI-diagnosed CKD patients showed lower cortical RBF values and eGFR than those patients diagnosed by DTI-MRI.

The MRI method has been used in diagnosing CKD because it is a noninvasive and accessible method.[22–24] However, its operator dependency and low sensitivity reduce its utility in research. This study introduced gadolinium-based MRI to improve operator dependency and low sensitivity in diagnosing cortical RBFs, eGFR, renal fibrosis, renal damage, and eGFR in CKD patients. The strategies of this study compared the diagnostic efficacy between DTI-GBMRI and DTI-MRI, and outcomes found that the DTI-GBMRI method showed the superior diagnostic accuracy, sensitivity and specificity compared to DTI-MRI in patients with CKD.

Limitations of our study included the absence of pathologic correlation with MRI findings. In addition, as with most published articles investigating GB deposition, any GB contrast agent injections in addition to the ones reported in clinical records could not be excluded in the study population. Furthermore, this study did not investigate the potential safety/toxicity issues of DTI-GBMRI. Moreover, the sample size is small.

In conclusion, this study demonstrates the benefits of DTI-GBMRI in measuring renal histopathology and renal efficiency, renal fibrosis and damage, and noninvasive quantification of RBF in CKD patients. Outcomes find that DTI-GBMRI improves testing methodologies for more accurate assessment of cortical RBFs, GFR, pathological characteristics, and depict renal efficiency than DTI-MRI, which further contributes to high sensitivity and specificity. These data suggest that DTI-GBMRI may be a reliable assessment of renal function combined with high-resolution morphological evaluation of the kidneys, as well as accurately identify stage CKD in certain clinical patients.

Author Contributions

Conceptualization: Liu He.
Data curation: Gao Dan.
Formal analysis: Sun Yuanbo.
Investigation: Tang Fengqiong.
Methodology: Liu He, Gao Dan, Li Hongyi.
Project administration: Li Hongyi.
Software: Liu He, Suan Yuanbo.
Supervision: Hu Mingcheng.
Validation: Hu Mingcheng.
Visualization: Hu Mingcheng.
Writing – original draft: Li Hongyi.
Writing – review & editing: Li Hongyi.

References

[1] Hildegard Stancu S, Stanciu A, Lipan M, et al. Renal anemia and hydration status in non-dialysis chronic kidney disease: is there a link? J Med Life. 2018;11:293–8.
[2] Bhatia HS, Hsu JC, Kim RJ. Atrial fibrillation and chronic kidney disease: a review of options for therapeutic anticoagulation to reduce thromboembolism risk. Clin Cardiol. 2018;41:1395–402.
[3] Bouya S, Balouchi A, Rafiemanesh H, et al. Prevalence of chronic kidney disease in Iranian general population: a meta-analysis and systematic review. Ther Apher Dial. 2018;22:594–99.
[4] Afsar B, Siriopol D, Aslan G, et al. The impact of exercise on physical function, cardiovascular outcomes and quality of life in chronic kidney disease patients: a systematic review. Int Urol Nephrol. 2018;50:885–904.
[5] Ketteler M, Block GA, Evenepoel P, et al. Diagnosis, evaluation, prevention, and treatment of chronic kidney disease-mineral and bone disorder: synopsis of the kidney disease: improving global outcomes 2017 clinical practice guideline update. Ann Intern Med. 2018;168:422–430.
[6] Prasad GVR, Yan AT, Nash MM, et al. Determinants of left ventricular characteristics assessed by cardiac magnetic resonance imaging and cardiovascular biomarkers related to kidney transplantation. Can J Kidney Health Dis 2018;5:2054358118809974.
[7] Charlton JR, Beeman SC, Bennett KM. MRI-detectable nanoparticles: the potential role in the diagnosis of and therapy for chronic kidney disease. Adv Chronic Kidney Dis. 2013;20:479–87.

[8] Forslin Y, Shams S, Hashim F, et al. Retention of gadolinium-based contrast agents in multiple sclerosis: retrospective analysis of an 18-year longitudinal study. AJNR Am J Neuroradiol 2017;38:1311–6.
[9] Bhave G, Lewis JB, Chang SS. Association of gadolinium based magnetic resonance imaging contrast agents and nephrogenic systemic fibrosis. J Urol. 2008;180:830–5; discussion 835.
[10] Perazella MA. Gadolinium-contrast toxicity in patients with kidney disease: nephrotoxicity and nephrogenic systemic fibrosis. Curr Drug Saf 2008;3:67–75.
[11] Yantasee W, Fryxell GE, Porter GA, et al. Novel sorbents for removal of gadolinium-based contrast agents in sorbent dialysis and hemoperfusion: preventive approaches to nephrogenic systemic fibrosis. Nanomed: Nanotechnol Biol Med. 2010;6:1–8.
[12] Yu Y, Shumway KL, Matheson JS, Edwards ME, Kline TL, Lyons LA. Kidney and cystic volume imaging for disease presentation and progression in the cat autosomal dominant polycystic kidney disease large animal model. BMC Nephrol. 2019;20:259.
[13] Yamamoto A, Zhang JL, Rusinek H, et al. Quantitative evaluation of acute renal transplant dysfunction with low-dose three-dimensional MR renography. Radiology. 2011;260:781–9.
[14] Kim DW, Shim WH, Yoon SK, et al. Measurement of arterial transit time and renal blood flow using pseudocontinuous ASL MRI with multiple post-labeling delays: feasibility, reproducibility, and variation. J Magn Reson Imaging. 2017;46:813–19.
[15] Liu X, Liu K, Sun Q, et al. Efficacy and safety of febuxostat for treating hyperuricemia in patients with chronic kidney disease and in renal transplant recipients: a systematic review and meta-analysis. Exp Ther Med. 2018;16:1859–65.
[16] Aomatsu A, Ookawara S, Ishibashi K, et al. Protective effects of diuretics against the development of cardiovascular disease in patients with chronic kidney disease: a systematic review. Cardiovasc Hematol Agents Med Chem. 2018;16:12–9.
[17] Manski-Nankervis JE, Thuraisingam S, Lau P, et al. Screening and diagnosis of chronic kidney disease in people with type 2 diabetes attending Australian general practice. Aust J Prim Health. 2018;24:280–6.
[18] Kirsch H, Mentzel HJ. Renal functional diagnostics using magnetic resonance imaging. Der Radiologe. 2018;58:914–24.
[19] Odudu A, Francis ST, McIntyre CW. MRI for the assessment of organ perfusion in patients with chronic kidney disease. Curr Opin Nephrol Hypertens. 2012;21:647–54.
[20] Zhao J, Wang ZJ, Liu M, et al. Assessment of renal fibrosis in chronic kidney disease using diffusion-weighted MRI. Clin Radiol. 2014;69:1117–22.
[21] Li C, Liu H, Li X, et al. Application of BOLD-MRI in the classification of renal function in chronic kidney disease. Abdom Radiol (NY). 2019;44:604–11.
[22] Wang CY, Peng YJ, Hsu YJ, et al. Cartilage MRI T2(*) relaxation time and perfusion changes of the knee in a 5/6 nephrectomy rat model of chronic kidney disease. Osteoarthr Cartil. 2017;25:976–85.
[23] Albayrak E, Ozmen Z, Sahin S, Demir O, Erken E. Evaluation of cisterna chyli diameter with MRI in patients with chronic kidney disease. J Magn Reson Imaging. 2016;44:890–6.
[24] Inoue T, Kozawa E, Ishikawa M, Okada H. Assessment of chronic kidney disease using functional MRI. Nihon Jinzo Gakkai Shi. 2015;57:1225–32.