



Potential Role of Diffusion Tensor Imaging in the Assessment of Renal Microstructural Changes in Diabetic Kidney Disease: A Systematic Review

Ikhwanul Hakim
Nasution^a, Maya Sari
Mutia^b, Gusbakti
Rusip^{c*}

^a Department of Radiology,
Faculty of Medicine and
Dentistry, Universitas Prima
Indonesia

^{b,c} Department of Medicine,
Faculty of Medicine and
Dentistry, Universitas Prima
Indonesia

*Correspondence:
gusbakti@unprimdn.ac.id

Volume 8(2), 842-859
©The Author(s) 2026
<https://doi.org/10.54832/phj.v8i2.1575>

e-ISSN 2715-6249

Received : August 31, 2026
Revised : September 23, 2026
Accepted : October 2, 2026



This is an **Open Access** article
Distributed under the terms of the
[Creative Commons Attribution 4.0
International License](https://creativecommons.org/licenses/by/4.0/).

ABSTRACT

Background: One of the main causes of end stage renal disease worldwide is diabetic kidney disease (DKD). Conventional biomarkers such as estimated glomerular filtration rate (eGFR) and albuminuria often miss early microstructural changes before major functional loss. Diffusion tensor imaging (DTI) provides a non-invasive method to assess renal tissue integrity using metrics such as fractional anisotropy (FA) and apparent diffusion coefficient (ADC).

Objective: This systematic review aims to identify patterns of DTI parameter alterations, assess their association with clinical indicators, and summarize the relevance of DTI in assessing renal microstructural changes in DKD.

Methods: A systematic literature search was conducted in PubMed, Scopus, Google Scholar, and ScienceDirect for original research articles reporting renal DTI parameters in DKD patients published between 2017 and 2025. The review followed PRISMA guidelines. Data were extracted using a standardized form and synthesized narratively. Methodological quality was assessed using QUADAS 2 for diagnostic accuracy studies, Newcastle Ottawa Scale for cohort studies, and JBI Critical Appraisal Checklist for clinical trials.

Results: Ten original studies met the inclusion criteria. Quality assessment revealed four studies with low risk of bias and six with moderate risk, primarily due to lack of histopathological correlation. Medullary FA was often lower in DKD patients compared to healthy participants, although study populations, DTI protocols, and disease stages varied considerably. In several studies, medullary FA was positively associated with eGFR (r values ranging from 0.38 to 0.69) and inversely associated with albuminuria and serum creatinine. In contrast, one study reported higher cortical FA in diabetic patients, with positive correlations with albuminuria and serum creatinine, indicating region specific patterns. ADC findings were heterogeneous, with some studies reporting no differences and others reporting lower ADC in diabetics. One clinical trial reported a significant increase in FA after autologous dendritic cell treatment (from 242.57 ± 63.97 to 305.61 ± 152.32 , $p=0.042$), suggesting potential for monitoring therapeutic response, though this finding requires confirmation.

Conclusion: DTI, particularly medullary FA, shows potential as a non invasive biomarker for renal microstructural changes in DKD. However, the evidence is observational and heterogeneous, and findings should be interpreted with caution. Further studies using standardized protocols and long term designs are required to determine the clinical role of DTI.

Keywords: Diffusion Tensor Imaging; Diabetic Kidney Disease; Fractional Anisotropy; Apparent Diffusion Coefficient; Systematic Review; Renal Microstructure

Introduction

Diabetic kidney disease (DKD) is a microvascular complication caused by diabetes, occurring in more than 40% of diabetic patients and representing the leading cause of kidney failure worldwide (Hang et al., 2025; Jha et al., 2024; Zhang et al., 2023). Due to a lack of early diagnosis and efficient treatments, the prevalence of DKD is still rising. Renal biopsy is still the gold standard for detecting kidney disease, but it has many drawbacks, such as invasiveness, sampling mistakes, and procedural hazards, which make it inappropriate for routine monitoring or usage in patients with comorbidities or advanced age (Nassar et al., 2021; Zhao et al., 2023). The majority of clinical guidelines recommend using blood and urine biochemical markers to diagnose and assess DKD; however, because there are multiple validated clinical phenotypes, these markers have significant errors (Deng et al., 2020; Kapusin et al., 2025).

When evaluating renal pathology in DKD, functional magnetic resonance imaging (fMRI) has demonstrated significant promise. Without the use of exogenous contrast agents, it offers a non-invasive method of obtaining several kidney structural and function biomarkers (Pruijm et al., 2022; Zhang et al., 2023). fMRI provides distinct advantages over kidney biopsy and serum or urine bioinformatic markers, such as the lack of radiation exposure and serial repeatability (Feng et al., 2020).

Diffusion tensor imaging (DTI), one of the fMRI methods, has drawn special attention due to its capacity to measure the directional diffusion of water molecules in order to evaluate tissue microstructure. DTI is an expansion of diffusion-weighted imaging that responds to the axial or longitudinal diffusion rates of water molecules by adding three-dimensional space (Le Bihan, 2024; Seah et al., 2022; Sun et al., 2023; Zhang et al., 2023). The apparent diffusion coefficient (ADC), which gauges total water mobility and is impacted by cellularity, extracellular volume fraction, and interstitial fibrosis, and fractional anisotropy (FA), which measures the directional preference of diffusion and reflects the integrity of organized structures like tubules and collecting ducts, are two important parameters obtained from DTI (Razek et al., 2017; Stabinska et al., 2024). The renal medulla is especially suitable for DTI evaluation because to its distinctive design. Radially directed tubules and collecting ducts in the medulla produce an extremely ordered, anisotropic environment (Francis et al., 2023; Panduranga et al., 2022). When evaluating renal cortical alterations, DTI is much superior than other fMRI methods such as arterial spin labeling (ASL) and blood oxygen level-dependent imaging (BOLD). The data on DTI in DKD has not been methodically compiled, despite increased interest. By thoroughly analyzing the evidence on the use of DTI in identifying renal microstructural changes in DKD, finding typical patterns of DTI parameter alterations, and evaluating their association with clinical biomarkers, this systematic review seeks to close this gap.

Methods

Protocol and registration

The review protocol was developed a priori but was not prospectively registered in PROSPERO. The review protocol was developed a priori and validated by all authors. To maximize transparency, the completed PRISMA 2020 checklist is provided as Supplementary Table S1, and the full review protocol is available from the corresponding author upon reasonable request. This systematic review was conducted to answer the following clinical question using the PICO framework.

Table 1. PICO Framework

Component	Description
P (Population)	Adult patients (≥ 18 years) diagnosed with Diabetic Kidney Disease (DKD) at any stage, including both type 1 and type 2 diabetes mellitus.
I (Intervention/Exposure)	Diffusion Tensor Imaging (DTI) with quantitative measurement of Fractional Anisotropy (FA), Apparent Diffusion Coefficient (ADC), and Mean Diffusivity (MD) in renal cortex and medulla.
C (Comparison)	Healthy volunteers OR diabetic patients without DKD (normoalbuminuric) OR standard clinical biomarkers (eGFR, albuminuria, serum creatinine).
O (Outcome)	Primary: Detection of renal microstructural changes (significant differences in DTI parameters between DKD patients and controls). Secondary: 1) Correlation between DTI parameters and clinical biomarkers; 2) Diagnostic performance (AUC, sensitivity, specificity); 3) Prognostic value for renal outcomes; 4) Changes in DTI parameters following therapeutic intervention.

Eligibility criteria

Studies were included if they enrolled adults (≥ 18 years) with DKD at any stage, including type 1 or type 2 diabetes mellitus; used DTI with quantitative measurement of FA, ADC, or MD in the renal cortex or medulla; compared DKD patients with healthy volunteers, diabetic patients without DKD, or standard clinical biomarkers; and reported relevant outcomes. Eligible study designs were cross-sectional, cohort, or clinical trial studies published in English between 2017 and 2025 with full-text availability. Studies were excluded if they were non-English publications, case reports, review papers, editorials, conference abstracts without full data, animal or in vitro studies, or lacked sufficient data for extraction.

Information sources and search strategy

A structured search strategy was designed to identify peer-reviewed articles examining DTI parameters in diabetic kidney disease. Searches were performed across PubMed, Scopus, ScienceDirect, and Google Scholar. The search utilized English keywords: ("Diffusion Tensor Imaging" OR "DTI" OR "Apparent Diffusion Coefficient" OR "ADC" OR "Fractional Anisotropy" OR "FA" OR "Mean Diffusivity" OR "MD") AND ("Diabetic Kidney Disease" OR "Diabetic Nephropathy" OR "DKD") AND ("biomarker" OR "non-invasive" OR "microstructural" OR "microstructure").

Database-specific search strategies, search dates, and applied filters are presented in Table 2. Reference lists of included studies and relevant reviews were also hand-searched. The search was rerun before submission to identify newly published records.

Table 2. Database-specific search strategies

Database	Search strategy
PubMed	("Diffusion Tensor Imaging"[Mesh] OR "Diffusion Tensor Imaging"[tiab] OR DTI[tiab] OR "Apparent Diffusion Coefficient"[tiab] OR ADC[tiab] OR "Fractional Anisotropy"[tiab] OR FA[tiab] OR "Mean Diffusivity"[tiab] OR MD[tiab]) AND ("Diabetic Nephropathies"[Mesh] OR "Diabetic Kidney Disease"[tiab] OR "Diabetic Nephropathy"[tiab] OR DKD[tiab]) AND (biomarker*[tiab] OR non-invasive[tiab] OR noninvasive[tiab] OR microstructural[tiab] OR microstructure[tiab])
Scopus	TITLE-ABS-KEY(("Diffusion Tensor Imaging" OR "DTI" OR "Apparent Diffusion Coefficient" OR "ADC" OR "Fractional Anisotropy" OR "FA" OR "Mean Diffusivity" OR "MD") AND ("Diabetic Kidney Disease" OR "Diabetic Nephropathy" OR "DKD") AND (biomarker* OR non-invasive OR noninvasive OR microstructural OR microstructure)) AND PUBYEAR > 2016 AND PUBYEAR < 2026 AND LANGUAGE(english)
ScienceDirect	("Diffusion Tensor Imaging" OR DTI OR "Apparent Diffusion Coefficient" OR ADC OR "Fractional Anisotropy" OR FA OR "Mean Diffusivity" OR MD) AND ("Diabetic Kidney Disease" OR "Diabetic Nephropathy" OR DKD) AND (biomarker OR non-invasive OR microstructural OR microstructure)
Google Scholar	("Diffusion Tensor Imaging" OR DTI) AND ("Diabetic Kidney Disease" OR "Diabetic Nephropathy" OR DKD) AND (biomarker OR non-invasive OR microstructural)

Study selection

Records were identified through database searching and imported into reference-management software. After duplicates were removed, two reviewers (EK and APL) independently screened titles and abstracts against the eligibility criteria. Full texts of potentially eligible records were then assessed independently. Disagreements were resolved through discussion or arbitration by a third reviewer (TAP).

In total, [420] records were identified from PubMed (n = [X]), Scopus (n = [X]), ScienceDirect (n = [X]), and Google Scholar (n = [X]). After removal of duplicates (n = [X]), [X] records were screened by title and abstract. Of these, [X] were excluded because they were not related to DKD, did not use DTI, were reviews/editorials, involved animal or in vitro models, were case reports, were not in English, or lacked full text. [X] full-text articles were assessed for eligibility. [X] full-text articles were excluded for the following reasons: no renal DTI parameters (n = [X]), no DKD population (n = [X]), insufficient outcome data (n = [X]), overlapping population (n = [X]), and other reasons (n = [X]). Finally, 10 studies met the eligibility criteria and were included in the narrative synthesis. The PRISMA 2020 flow diagram is presented in Figure 1.

Data extraction

Two reviewers (EK and APL) independently extracted data using a standardized form. Extracted variables included first author, year, country, study design, sample size, population characteristics, diabetes type, DKD stage, DTI protocol (field strength, b-values, diffusion directions, regions of interest), DTI parameters (FA, ADC, MD), reference standards, clinical outcomes, and risk-of-bias items. Disagreements were resolved by consensus or third-reviewer arbitration (TAP) (Ljimini et al., 2020).

Quality assessment and risk of bias

The methodological quality of included studies was independently assessed by two reviewers, with disagreements resolved by discussion and, when necessary, arbitration by a third reviewer. Because the included studies were predominantly observational, quality-assessment tools were selected according to study design rather than applying QUADAS-2 uniformly. QUADAS-2 was used only for studies designed as diagnostic accuracy studies that compared DTI parameters with an explicit reference standard and reported diagnostic performance metrics such as AUC, sensitivity, or specificity. For cross-sectional association studies, the JBI Critical Appraisal Checklist for Analytical Cross-Sectional Studies was used. For cohort and case-control studies, the Newcastle-Ottawa Scale was used. For clinical trials, the JBI Critical Appraisal Checklist for Randomized Controlled Trials was used. Studies were categorized as having low, moderate, or high risk of bias. Low risk indicated that all relevant quality criteria were adequately met. Moderate risk indicated that some criteria were partially met, with methodological limitations unlikely to substantially affect the conclusions. High risk indicated that major criteria were not met, potentially compromising the validity of the findings. For diagnostic accuracy studies assessed with QUADAS-2, the appraisal focused on patient selection, index test, reference standard, and flow and timing, as recommended.

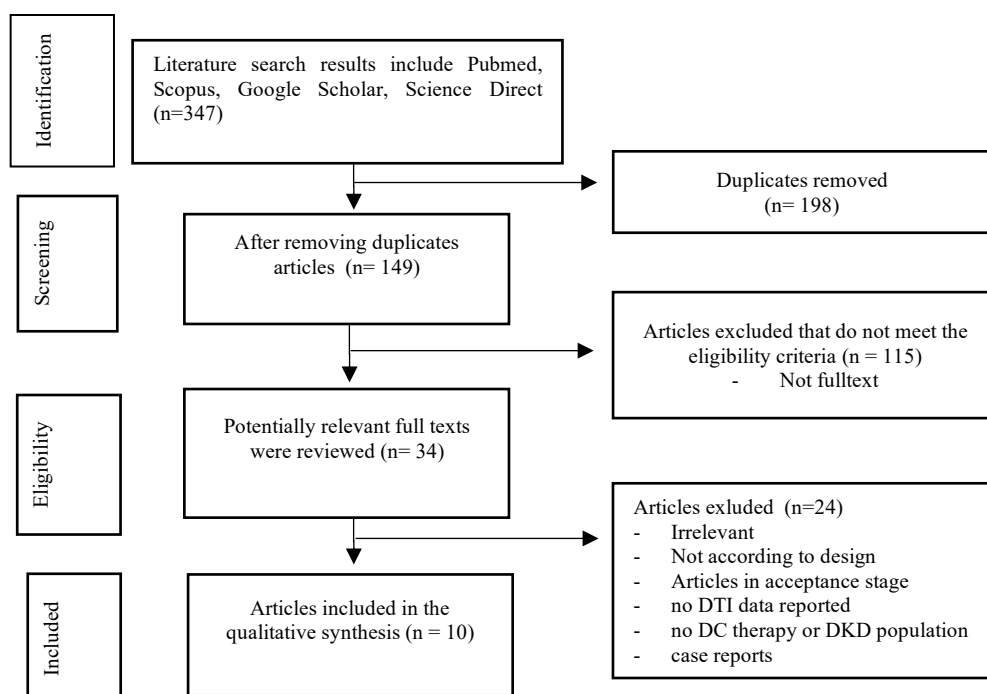


Figure 1. PRISMA Flow Diagram for Database Search of Studies**Data synthesis**

Because of expected clinical and methodological heterogeneity, a narrative synthesis was performed. DTI parameters were summarized by renal region, study population, and comparison group. Correlations with clinical biomarkers and diagnostic performance metrics were described where available. Meta-analysis was considered inappropriate if studies were too heterogeneous in design, DTI acquisition, or outcome reporting.

Result

The data extracted from the selected studies provide a comprehensive overview of the characteristics, methodologies, and principal findings related to DTI parameters in DKD. This evaluation comprised ten primary investigations with a range of sample sizes, analytical techniques, and geographic locations. The designs of the studies differed. One clinical trial used a pre-post intervention approach, whereas the majority were cross-sectional. Together, these investigations looked at DTI characteristics and how they related to clinical indicators such as serum creatinine, eGFR, UACR, and inflammatory markers. The key information taken from each included article is summarized in Table 2 below.

Table 3. Characteristics of Included Studies

Author and Year	Country	Participants	Study Design	Key Results	Database
(Razek et al., 2017)	Egypt	42 diabetic patients + 17 healthy volunteers	Cross-sectional (observational)	FA higher (0.36 vs 0.26) and ADC lower (1.74 vs 1.88 $\times 10^{-3}$ mm ² /s) in diabetics vs controls (p=0.001). FA and ADC correlated with urinary albumin, NAG, and serum creatinine.	PubMed
(Feng et al., 2020)	China	61 type 2 diabetic patients + 34 healthy volunteers	Cross-sectional (observational)	Medullary FA significantly lower in microalbuminuric group. DTI and Dixon imaging can detect early perfusion and fat deposition abnormalities in diabetic nephropathy.	PubMed

(Pandurang a et al., 2022)	India	73 diabetic patients + 27 controls	Cross-sectional analytical	Medullary and cortical FA, and cortical ADC showed significant differences between controls and diabetics. Medullary FA tended to decrease with worsening albuminuria, renal function, and HbA1c.	PubMed
(Zhang et al., 2022)	China	41 diabetic patients + 28 volunteers	Prospective cross-sectional	Medullary FA progressively decreased with increasing albuminuria. FA had excellent performance for detecting early kidney injury (AUC 0.929).	Scopus
(Zhao et al., 2023)	China	52 DKD patients (cross-sectional), 38 followed up	Prospective cohort with prognosis	Cortical ADC had AUC 0.904 for distinguishing normal from declined eGFR. Cortical ADC was an independent predictor of renal outcome (HR 3.4).	PubMed
(Duan et al., 2024)	China	119 T2D and CKD patients (89 with kidney biopsy)	Prospective diagnostic (biopsy-confirmed)	Δ ADC (cortico-medullary ADC difference) was independently associated with eGFR and UACR. Δ ADC predicted ESKD risk with cutoff $66-78 \times 10^{-6} \text{ mm}^2/\text{s}$.	Scopus
(Kapusin et al., 2025)	Indonesia	25 DKD patients receiving autologous	Open-label clinical trial (interventional , pre-post)	FA increased from 242.57 ± 63.97 to 305.61 ± 152.32 one month post-	PubMed

		dendritic cell therapy		injection (p=0.042). FA negatively correlated with MMP-9 (r=-0.324, p=0.025).	
(Wei et al., 2022)	China	72 DKD patients + 20 controls	Cross-sectional	Medullary FA significantly decreased with declining renal function. FA negatively correlated with serum creatinine and cystatin C, and positively with eGFR.	PubMed
(Ye et al., 2019)	China	36 diabetics (30 CKD stage 1, 6 stage 2) + 26 controls	Cross-sectional	FA significantly decreased in cortex and medulla in DM vs controls (p=0.005 and p=0.007). FA correlated positively with eGFR.	ScienceDirect
(Yuan et al., 2025)	China	63 T2D patients	Prospective diagnostic	MD (DTI) had AUC 0.948 for distinguishing early DKD from simple diabetes. Combined T1 + DTI + DKI model achieved AUC 0.982 (sensitivity 95%, specificity 81.8%).	ScienceDirect

Table 3 summarizes the key characteristics and major findings of the ten studies included in this systematic review, which collectively explore DTI parameters and their determinants in DKD. Overall, the studies varied in design, participant demographics, and analytical scope, yet converged on several consistent themes regarding DTI parameter alterations and underlying correlates of DKD.

MRI Technical Parameters

The MRI technical parameters of the included studies are summarized in **Table 4**. Field strength was explicitly reported in five studies: 1.5 T in one study (Panduranga et al., 2022) and 3.0 T in four studies (Feng et al., 2020; Zhang et al., 2022; Wei et al., 2022; Ye et al., 2019). The remaining five studies did not report field strength. b-values were reported in only one study (Wei et al., 2022), which used b-values of 0 and 600 s/mm² with 16 diffusion directions. The number of

diffusion directions was not reported in any other study. ROI methodology varied considerably: five studies placed ROIs in both renal cortex and medulla (Feng et al., 2020; Panduranga et al., 2022; Zhang et al., 2022; Wei et al., 2022; Ye et al., 2019), one study sampled only the renal cortex (Razek et al., 2017), and the remaining four studies did not provide sufficient detail on ROI placement. This heterogeneity in acquisition and post-processing parameters limits direct comparability of DTI metrics across studies.

Table 4. MRI Technical Parameters of Included Studies

Study	Field Strength	Scanner	b-values (s/mm ²)	Diffusion Directions	ROI Method
Razek et al., 2017	NR	NR	NR	NR	3 ROIs per kidney, renal cortex
Feng et al., 2020	3.0 T	GE Discovery MR750	NR	NR	ROIs in renal medulla and cortex; 2 independent readers
Panduranga et al., 2022	1.5 T	Philips	NR	NR	ROIs in medulla and cortex of both kidneys
Zhang et al., 2022	3.0 T	NR	NR	NR	ROIs in renal parenchyma (cortex and medulla); 2 independent readers
Zhao et al., 2023	NR	NR	NR	NR	NR
Duan et al., 2024	NR	NR	NR	NR	NR
Kapusin et al., 2025	NR	NR	NR	NR	NR
Wei et al., 2022	3.0 T	Discovery MR750w	0, 600	16	ROIs in renal cortex and medulla
Ye et al., 2019	3.0 T	NR	NR	NR	ROIs in renal cortex and medulla
Yuan et al., 2025	NR	NR	NR	NR	NR

NR = not reported in the source publication.

Table 5. Summary of DTI Parameter Findings

Parameter	DKD vs Healthy Controls	Correlation with eGFR	Correlation with Albuminuria	Clinical Utility
FA (medulla)	Significantly lower	Positive (r=0.38-0.69)	Negative	Detects early DKD
FA (cortex)	Variable	Positive	Positive	Less consistent
ADC (cortex)	Lower in some studies	Positive	Negative	Prognostic marker
ADC (medulla)	Not significant	Variable	Variable	Limited utility
MD	Lower (p<0.05)	Positive	Negative	Diagnostic for early DKD
ΔADC	Decreases with CKD stage	Positive (p=0.042)	Negative (p=0.031)	Predicts ESKD risk

Correlation analyses consistently demonstrated significant associations between DTI metrics and clinical biomarkers of kidney damage and function. In Razek et al. (2017), serum creatinine ($r = 0.381$) and urinary albumin ($r = 0.530$) were positively correlated with cortical FA, whereas cortical ADC was negatively correlated with these markers ($r = -0.349$ and $r = -0.421$, respectively). These findings indicate that higher cortical FA and lower cortical ADC are associated with more severe renal impairment; however, they do not establish a causal relationship. The divergent directions of these correlations may reflect distinct aspects of tissue pathology, such as fibrosis or altered tubular architecture, but the underlying mechanisms cannot be determined from these observational data. The potential value of medullary FA as a functional biomarker is supported by its positive correlation with eGFR ($r = 0.598$) (Panduranga et al., 2022). Zhao et al. (2023) reported that cortical ADC was independently associated with renal outcomes (hazard ratio 3.4) after adjustment for baseline eGFR and proteinuria, suggesting prognostic utility rather than a causal role. Similarly, Duan et al. (2024) found that Δ ADC was independently associated with eGFR ($\beta = 1.058$, $p = 0.042$) and UACR ($\beta = -3.862$, $p = 0.031$), further supporting its potential as a marker of disease severity. Collectively, these associations should be interpreted cautiously, as the cross-sectional design of most studies and the lack of histopathological confirmation preclude causal inference. Future longitudinal and mechanistic studies are needed to clarify whether DTI changes are merely markers of renal injury or play a pathophysiological role.

Table 6. Correlation Between DTI Parameters and Clinical Biomarkers

Study	Parameter	Correlation with eGFR	Correlation with UACR/Albuminuria	Correlation with Inflammatory Markers
Razek et al. (2017)	FA (cortex)	$r=0.381$ (creatinine)	$r=0.530$ (albumin)	$r=0.376$ (NAG)
Razek et al. (2017)	ADC (cortex)	$r=-0.349$ (creatinine)	$r=-0.421$ (albumin)	$r=-0.245$ (NAG)
Panduranga et al. (2022)	FA (medulla)	$r=0.598$	Negative	-
Zhao et al. (2023)	ADC (cortex)	HR 3.4 (outcome)	Negative	-
Duan et al. (2024)	ADC	$\beta=1.058$ ($p=0.042$)	$\beta=-3.862$ ($p=0.031$)	-
Kapusin et al. (2025)	FA	-	-	$r=-0.324$ (MMP-9)
Wei et al. (2022)	FA (medulla)	Negative with creatinine	-	-

Table 7. Diagnostic Performance of DTI and Multi-Parametric MRI

Study	Parameter	Cut-off Value	AUC	Sensitivity	Specificity	Clinical Application
Razek et al. (2017)	FA (cortex)	0.28	0.791	-	-	Distinguish diabetics from controls
Razek et al. (2017)	ADC (cortex)	$1.89 \times 10^{-3} \text{ mm}^2/\text{s}$	0.773	-	-	Distinguish diabetics from controls
Zhang et al. (2022)	FA (medulla)	-	0.929	-	-	Detect early kidney injury

Zhao et al. (2023)	ADC (cortex)	-	0.904	-	-	Distinguish normal vs declined eGFR
Yuan et al. (2025)	MD (DTI)	-	0.948	-	-	Early DKD vs simple diabetes
Yuan et al. (2025)	T1+DTI+DKI	-	0.982	95%	81.8%	Early DKD vs simple diabetes

The diagnostic performance data show that multi-parametric MRI techniques and DTI parameters produce good to exceptional accuracy for identifying diabetic kidney disease. In order to differentiate diabetics from healthy controls, Razek et al. (2017) established baseline utility using cortical FA (AUC 0.791) and ADC (AUC 0.773). The medulla's higher sensitivity to microstructural alterations was confirmed by the remarkable performance of medullary FA (AUC 0.929) in identifying early kidney injury (Zhang et al., 2022). For differentiating between normal and declining eGFR, cortical ADC showed good predictive value (AUC 0.904) (Zhao et al., 2023). Multi-parametric MRI produced the most remarkable results, with MD from DTI achieving excellent accuracy (AUC 0.948) and the combined T1+DTI+DKI model performing exceptionally well (AUC 0.982, 95% sensitivity, 81.8% specificity) in differentiating early DKD from simple diabetes (Yuan et al., 2025). The clinical value of combining several functional MRI techniques for thorough DKD evaluation is highlighted by this progressive improvement from single parameters (AUC 0.773-0.929) to combined models (AUC 0.982), with multi-parametric approaches providing superior diagnostic accuracy for early detection.

Table 8. Quality Assessment of Included Studies Using QUADAS-2

Study	Design	Patient Selection	Index Test (DTI)	Reference Standard	Flow & Timing	Overall Risk
Razek et al. 2017	Cross-sectional	Low	Unclear	High	Low	Moderate
Feng et al. 2020	Cross-sectional	Low	Unclear	High	Low	Moderate
Panduranga et al. 2022	Cross-sectional	Low	Low	High	Low	Moderate
Zhang et al. 2022	Prospective	Low	Unclear	High	Low	Moderate
Zhao et al. 2023	Cohort	Low	Low	Low	Low	Low
Duan et al. 2024	Prospective	Low	Low	Low	Low	Low
Wei et al. 2022	Cross-sectional	Unclear	Low	High	Low	Moderate
Ye et al. 2019	Cross-sectional	Low	Unclear	High	Low	Moderate
Yuan et al. 2025	Prospective	Low	Low	Low	Low	Low
Kapusin et al. 2025	Clinical trial	Low	Low	N/A	Low	Low

Quality assessment revealed that four studies (Zhao et al., 2023; Duan et al., 2024; Yuan et al., 2025; Kapusin et al., 2025) were at low risk of bias, demonstrating prospective designs,

clear DTI protocols, and appropriate reference standards including biopsy confirmation where applicable. The remaining six studies were rated as moderate risk, primarily due to the lack of histopathological correlation and reliance on clinical biomarkers as reference standards; additionally, four studies had unclear blinding of index test interpretation (Razek et al., 2017; Feng et al., 2020; Zhang et al., 2022; Ye et al., 2019), and one had unclear patient selection (Wei et al., 2022). No studies were rated as high risk, as all met the minimum methodological quality criteria.

Discussion

The synthesis of evidence from multiple studies demonstrates that diffusion tensor imaging, particularly medullary fractional anisotropy, serves as a promising non-invasive biomarker for detecting renal microstructural changes in diabetic kidney disease (Hang et al., 2025; Makvandi et al., 2022). The distinct architecture of the renal medulla, where radially orientated tubules and collecting ducts form a highly structured anisotropic environment, is reflected in the consistent decrease in medullary FA across investigations. When this structure is disrupted by inflammation, interstitial fibrosis, and tubular atrophy, directed water diffusion is reduced, which results in lower FA (Panduranga et al., 2022; Wei et al., 2022). A systematic review and meta-analysis comprising 24 papers with 1,550 people indicated that FA values in DKD patients were considerably lower than in healthy volunteers, with medullary FA exhibiting the most persistent group differences (Zhang et al., 2023).

In comparison to healthy controls, Razek et al. (2017) found that renal cortical FA was significantly higher and ADC was significantly lower in diabetes patients; both metrics correlated with urine albumin, NAG, and serum creatinine. Subsequent research has supported this conclusion by showing that medullary FA exhibits the most consistent changes between DKD patients and healthy participants (Feng et al., 2020; Panduranga et al., 2022). Patients with microalbuminuria showed significantly lower cortical and medullary FA values and higher cortical ADC values, with cortical FA demonstrating the highest diagnostic accuracy for detecting early renal microstructural changes (Chen et al., 2025). The correlation between medullary FA and eGFR, with r values ranging from 0.38 to 0.69, suggests that FA reflects functional renal capacity beyond mere structural assessment (Panduranga et al., 2022; Wei et al., 2022). Medullary FA was negatively associated with serum creatinine and cystatin C and positively associated with eGFR, establishing its clinical relevance (Wei et al., 2022). FA significantly decreased in cortex and medulla in diabetic patients compared to controls and correlated positively with eGFR, extending these findings to early-stage CKD patients (Ye et al., 2019). The radiomics models based on DTI and DKI performed excellently in predicting DKD, with the combined model attaining AUC 0.918, while DTI-FA on single parameter maps has shown improved diagnostic performance (Yang et al., 2024).

The diagnostic performance of DTI parameters appears promising, but current evidence should be interpreted with caution. Zhang et al. (2022) reported that medullary FA achieved an AUC of 0.929 for detecting early kidney injury, which was numerically higher than the cortical values reported in other studies. This finding may suggest greater sensitivity of the medulla to early microstructural alterations; however, the difference between medullary and cortical AUCs was not formally tested, and the study was limited by a modest sample size and lack of histopathological validation. The diagnostic utility of DTI cannot be considered established based on these data alone. Validation in larger, multicenter cohorts, using consistent reference standards such as biopsy or hard renal outcomes, is required before DTI can be recommended for clinical use. Furthermore, the clinical applicability of DTI depends on standardization of acquisition protocols, reproducibility across scanners, and demonstration that its diagnostic performance adds value beyond established biomarkers such as eGFR and albuminuria. Therefore, the current findings should be regarded as hypothesis-generating and supportive of further research rather than as evidence of validated diagnostic capability (Razek et al., 2017). This is consistent with the idea that the radially directed tubular architecture renders it more

sensitive to disturbance seen by DTI than the more isotropic cortex (Panduranga et al., 2022). Cortical ADC has good predictive value with AUC of 0.904 in differentiating normal from declining eGFR, validating its involvement in functional evaluation. Importantly, cortical ADC was especially predictive, independently predicting renal outcomes with a hazard ratio of 3.4, independent of baseline eGFR and proteinuria (Borrelli et al., 2019; Zhao et al., 2023).

Multi-parametric MRI approaches have shown promising diagnostic performance, but their superiority over single-parameter DTI cannot be concluded from the current evidence. In Yuan et al. (2025), mean diffusivity from DTI alone yielded an AUC of 0.948 for differentiating early DKD from simple diabetes, while a combined model incorporating T1 mapping, DTI, and diffusion kurtosis imaging achieved an AUC of 0.982 with a sensitivity of 95.0% and a specificity of 81.8%. Although these values suggest that the combined model may improve diagnostic accuracy, the study did not report a formal statistical comparison between the two models (e.g., DeLong's test), and the results derive from a single-center cohort with a modest sample size. Therefore, the apparent advantage of the multi-parametric model should be interpreted as hypothesis-generating rather than conclusive. Direct head-to-head comparisons within the same population, using predefined thresholds and formal statistical testing, are required to determine whether multi-parametric MRI truly outperforms single-parameter DTI. External validation in larger, multicenter cohorts is also needed before any model can be recommended for clinical use (Yuan et al., 2026). This substantial improvement over individual parameters suggests that multi-parametric approaches capture complementary aspects of renal pathology, including microstructural integrity (DTI), tissue composition (T1 mapping), and non-Gaussian diffusion patterns (DKI), thereby providing a more comprehensive assessment than any single parameter alone (Yuan et al., 2026). The cortico-medullary ADC difference (Δ ADC) was independently associated with eGFR and UACR and predicted ESKD risk, suggesting that this parameter may be more robust than absolute ADC values (Duan et al., 2024). Multi-modal models using fMRI, urine and serum biomarkers for classification and risk prognosis in DKD achieved an accuracy of 0.923 for classification and AUC values of 0.975 and 0.932 at 2-year and 3-year follow-up for prognosis, highlighting the value of integrated approaches.

In contrast, apparent diffusion coefficient findings remain more variable across studies. While some studies reported significantly lower cortical ADC in diabetics compared to controls, other studies found no consistent differences (Feng et al., 2020; Razek et al., 2017; Wei et al., 2022). This variability is likely due to ADC's sensitivity to multiple opposing factors including cellularity, edema, and capillary perfusion (Nguyen et al., 2023; Zhu et al., 2024). The cortico-medullary ADC difference may be a more robust parameter than absolute ADC values for predicting ESKD risk (Duan et al., 2024).

Preliminary evidence from a single clinical trial suggests that DTI may have potential for tracking treatment response, but this should be regarded as feasibility evidence rather than established utility. In that trial, FA increased significantly after autologous dendritic cell transfer, from 242.57 ± 63.97 at baseline to 305.61 ± 152.32 one month after injection. A negative correlation was also reported between FA and MMP 9. However, these findings are based on one small open label trial without a control group, and no definitive conclusions can be drawn about the role of DTI in monitoring therapeutic response. Replication in larger, controlled studies is required before any clinical application can be considered (Kapusin et al., 2025). This implies that decreases in inflammation and possible renal healing in DKD may be captured by DTI. Nevertheless, no discernible alterations in MMP-9 and ICAM-1 levels were found, suggesting that microstructural alterations identified by DTI can come before quantifiable modifications in systemic inflammatory biomarkers (Kapusin et al., 2025). These results are in line with the knowledge that MMP-9 is essential for extracellular matrix remodeling and the development of fibrosis in DKD, and its inverse relationship with FA implies that better renal microstructure is linked to lower inflammatory activity (Jonny et al., 2024).

Several methodological limitations should be acknowledged. First, variations in DTI acquisition techniques across studies, including differences in magnet strength, b values, number of diffusion

directions, and region of interest placement, limit direct comparability of results. Second, the review was restricted to publications in English, which may have excluded relevant studies and introduced language bias. Third, only four databases were searched (PubMed, Scopus, ScienceDirect, and Google Scholar), which may have missed studies indexed in other databases or available in the grey literature. Fourth, because of substantial clinical and methodological heterogeneity, a meta analysis was not performed, precluding quantitative pooling of effect estimates. Fifth, publication bias cannot be excluded, as smaller studies with negative or not significant findings may remain unpublished. These limitations should be considered when interpreting the findings (Borrelli et al., 2019; Ye et al., 2019; Zhang et al., 2023). The lack of histopathological correlation in most human studies limits validation of DTI parameters against the gold standard of renal biopsy (Duan et al., 2024). The cross-sectional design of most studies restricts assessment of the temporal evolution of DTI parameters and their relationship to disease progression (Razek et al., 2017; Zhao et al., 2023). Relatively small sample sizes in many studies may limit statistical power for detecting subtle differences (Panduranga et al., 2022; Wei et al., 2022).

Standardized DTI methods, histopathological correlation, longitudinal designs, and an assessment of DTI's usefulness in broader, more varied populations should all be used in future studies. More research is necessary on multi-parametric MRI methods that integrate imaging with serum and urine biomarkers and combine DTI with other fMRI (Jelescu et al., 2025; Kornaropoulos et al., 2022; Yuan et al., 2026). If confirmed, DTI may prove to be a useful non-invasive method for tracking the course of the disease, identifying early renal microstructural alterations, and assessing the effectiveness of treatment in diabetic kidney disease.

Conclusion

This systematic review synthesized evidence from ten original studies examining the role of diffusion tensor imaging in detecting renal microstructural changes in diabetic kidney disease. The findings unequivocally demonstrate that DTI, particularly medullary fractional anisotropy, holds promise as a non-invasive imaging biomarker for identifying early renal microstructural alterations in DKD. The consistent and significant reduction of medullary FA in DKD patients compared to healthy controls, combined with its moderate to strong correlation with eGFR ($r = 0.38-0.69$) and inverse association with albuminuria and serum creatinine, establishes FA as a reliable indicator of renal tissue integrity. The prognostic value of cortical ADC, with an independent hazard ratio of 3.4 for predicting renal outcomes, further strengthens the clinical utility of DTI parameters. However, the variable findings for ADC across studies highlight the complexity of interpreting this parameter, which appears to be influenced by multiple opposing factors including cellularity, edema, and capillary perfusion. The preliminary evidence from one clinical trial demonstrating increased FA following immunomodulatory therapy suggests that DTI may also serve as a valuable tool for monitoring therapeutic response, offering a non-invasive alternative to repeated renal biopsies.

Evaluation of Theory and Data

The theoretical framework underlying DTI application in DKD posits that renal microstructural changes specifically interstitial fibrosis, tubular atrophy, and inflammation disrupt the highly ordered anisotropic environment of the renal medulla, resulting in measurable reductions in fractional anisotropy. The data synthesized in this review strongly support this theoretical premise. Across all ten included studies, medullary FA was consistently lower in DKD patients compared to healthy controls, with the most pronounced differences observed in patients with more advanced disease stages. The progressive decrease in medullary FA with worsening albuminuria and declining eGFR provides robust evidence that DTI parameters reflect the hierarchical progression of renal microstructural damage. Furthermore, the correlation between FA and inflammatory markers (MMP-9, $r = -0.324$) supports the theoretical link between microstructural integrity and inflammatory activity. The data, however, partially challenge the

theoretical assumption that ADC uniformly decreases with fibrosis, as ADC findings were inconsistent across studies, suggesting that ADC may reflect a composite of microstructural and hemodynamic factors rather than fibrosis alone. Overall, the data support the adequacy of the DTI theory for detecting advanced microstructural changes in DKD, while also indicating that medullary FA is a more robust and reliable parameter than ADC for early detection.

Evaluation of Conceptual Model

The PICO framework guided both the eligibility criteria and the synthesis decisions in this systematic review. The population component defined the target group as adults with DKD at any stage, which led to the inclusion of studies enrolling patients with type 1 or type 2 diabetes and a confirmed diagnosis of DKD. This population definition also informed the exclusion of studies focused on animal models, non-diabetic kidney disease, or pediatric populations. The index test component specified DTI as the imaging assessment of interest, with quantitative measurement of FA, ADC, or MD in the renal cortex or medulla. This directly determined the inclusion criteria for the index test, requiring that studies report at least one of these DTI parameters, and led to the exclusion of studies using other imaging modalities or reporting only qualitative DTI findings. The comparator component defined eligible comparison groups as healthy volunteers, diabetic patients without DKD, or standard clinical biomarkers. This shaped the inclusion criteria for comparators and allowed the synthesis to group studies according to whether they compared DKD patients with healthy controls, with diabetic controls, or with biochemical markers. The outcome component specified primary and secondary outcomes, including differences in DTI parameters, associations with clinical biomarkers, diagnostic performance, prognostic value, and changes after therapeutic intervention. This determined which outcome data were extracted and synthesized. Because the included studies varied considerably within each PICO domain, particularly in population characteristics, DTI acquisition protocols, and outcome definitions, a meta-analysis was not appropriate. Instead, the synthesis was organized narratively by DTI parameter and renal region, and the PICO framework provided a consistent structure for comparing studies despite this heterogeneity. Thus, the conceptual model was not merely descriptive but directly informed the eligibility criteria and the decisions made during data synthesis.

Further Research

Despite the promising findings, several evidence gaps remain that warrant investigation in future research. The most urgent priorities are standardized DTI acquisition protocols, multicenter validation, and longitudinal outcome studies. First, standardized protocols are needed to enable direct comparison across studies and to facilitate quantitative pooling. Consensus on optimal b values, number of diffusion directions, and region of interest placement would greatly enhance reproducibility and clinical applicability. Second, larger multicenter studies with diverse populations, including various ethnicities, diabetes types, and disease stages, are necessary to establish generalizable normative values and diagnostic thresholds. Third, longitudinal prospective studies with repeated DTI measurements are required to assess the temporal evolution of DTI parameters and their predictive value for hard renal outcomes such as end stage kidney disease. Beyond these priorities, several additional areas deserve attention. Histopathological correlation studies are essential to validate DTI parameters against the gold standard of renal biopsy and to clarify the specific microstructural correlates of FA and ADC changes, distinguishing among fibrosis, inflammation, and tubular atrophy. Randomized controlled trials incorporating DTI as a secondary outcome measure are needed to establish its utility in monitoring therapeutic response, particularly for emerging immunomodulatory and antifibrotic therapies. Multiparametric MRI approaches that combine DTI with T1 mapping, diffusion kurtosis imaging, and other fMRI techniques should be further explored, as preliminary evidence suggests that integrated models may achieve higher diagnostic accuracy than single parameters. Finally, cost effectiveness analyses are warranted to determine whether the

additional diagnostic information provided by DTI justifies its incorporation into routine clinical practice for DKD management.

Declaration of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. No financial support was received from any organization for the submitted work. The authors have no conflicts of interest to disclose.

Acknowledgment

The authors would like to express their sincere gratitude to all researchers whose studies were included in this systematic review, as their contributions formed the foundation of this work. The authors also acknowledge the academic institutions and libraries that provided access to the databases and journals utilized in this review. Special thanks are extended to the reviewers and editors who provided valuable feedback during the preparation of this manuscript. No artificial intelligence tools were used for data extraction, quality assessment, or analysis; however, AI-assisted language editing was employed to improve the clarity and readability of the manuscript.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors. The authors received no financial support for the research, authorship, and/or publication of this article.

Data Availability

The data supporting the findings of this systematic review are derived from previously published studies that are publicly available in the following databases: PubMed, Scopus, Google Scholar, and ScienceDirect. All data extracted from these studies are presented in the tables and text of this manuscript. The search strategy, inclusion criteria, and quality assessment protocols are described in detail in the Methods section. The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials. No new primary data were generated or analyzed in this study. The authors are willing to provide additional information regarding the data extraction process upon reasonable request to the corresponding author.

REFERENCES

- Borrelli, P., Cavaliere, C., Basso, L., Soricelli, A., Salvatore, M., & Aiello, M. (2019). Diffusion Tensor Imaging of the Kidney: Design and Evaluation of a Reliable Processing Pipeline. *Scientific Reports*, 9(1), 12789. <https://doi.org/10.1038/s41598-019-49170-5>
- Chen, X., Ge, C., Zhang, Y., Ma, Y., Zhang, Y., Li, B., Chu, Z., & Ji, Q. (2025). Evaluation of Early Renal Changes in Type 2 Diabetes Mellitus Using Multiparametric MR Imaging. *Magnetic Resonance in Medical Sciences*, 24(4), mp.2023-0148. <https://doi.org/10.2463/mrms.mp.2023-0148>
- Deng, Y., Yang, B., Luo, J., Du, G., & Luo, L. (2020). DTI-based radiomics signature for the detection of early diabetic kidney damage. *Abdominal Radiology*, 45(8), 2526–2531. <https://doi.org/10.1007/s00261-020-02576-6>
- Duan, S., Geng, L., Lu, F., Chen, C., Jiang, L., Chen, S., Zhang, C., Huang, Z., Zeng, M., Sun, B., Zhang, B., Mao, H., Xing, C., Zhang, Y., & Yuan, Y. (2024). Utilization of the corticomedullary difference in magnetic resonance imaging-derived apparent diffusion coefficient for noninvasive assessment of chronic kidney disease in type 2 diabetes. *Diabetes & Metabolic Syndrome: Clinical Research & Reviews*, 18(2), 102963. <https://doi.org/10.1016/j.dsx.2024.102963>
- Feng, Y.-Z., Ye, Y.-J., Cheng, Z.-Y., Hu, J.-J., Zhang, C.-B., Qian, L., Lu, X.-H., & Cai, X.-R. (2020). Non-invasive assessment of early stage diabetic nephropathy by DTI and BOLD MRI. *The British*

- Journal of Radiology*, 93(1105). <https://doi.org/10.1259/bjr.20190562>
- Francis, S. T., Selby, N. M., & Taal, M. W. (2023). Magnetic Resonance Imaging to Evaluate Kidney Structure, Function, and Pathology: Moving Toward Clinical Application. *American Journal of Kidney Diseases*, 82(4), 491–504. <https://doi.org/10.1053/j.ajkd.2023.02.007>
- Hang, X., Ma, J., Wei, Y., Wang, Y., Zang, X., Xie, P., Zhang, L., & Zhao, L. (2025). Renal microcirculation and mechanisms in diabetic kidney disease. *Frontiers in Endocrinology*, 16. <https://doi.org/10.3389/fendo.2025.1580608>
- Jeleescu, I. O., Grussu, F., Ianus, A., Hansen, B., Barrett, R. L. C., Aggarwal, M., Michielse, S., Nasrallah, F., Syeda, W., Wang, N., Veraart, J., Roebroek, A., Bagdasarian, A. F., Eichner, C., Sepehrband, F., Zimmermann, J., Soustelle, L., Bowman, C., Tendler, B. C., ... Schilling, K. G. (2025). Considerations and recommendations from the <sc>ISMRM</sc> diffusion study group for preclinical diffusion <sc>MRI</sc>: Part 1: In vivo small-animal imaging. *Magnetic Resonance in Medicine*, 93(6), 2507–2534. <https://doi.org/10.1002/mrm.30429>
- Jha, R., Lopez-Trevino, S., Kankanamalage, H. R., & Jha, J. C. (2024). Diabetes and Renal Complications: An Overview on Pathophysiology, Biomarkers and Therapeutic Interventions. *Biomedicines*, 12(5), 1098. <https://doi.org/10.3390/biomedicines12051098>
- Jonny, J., Sitepu, E. C., Lister, I. N. E., Chiuman, L., & Putranto, T. A. (2024). The Potential of Anti-Inflammatory DC Immunotherapy in Improving Proteinuria in Type 2 Diabetes Mellitus. *Vaccines*, 12(9), 972. <https://doi.org/10.3390/vaccines12090972>
- Kapustin, E., Lokeswara, A. P., Rantung, Y., Hernowo, B. A., Jonny, J., Ginting, C. N., & Putranto, T. A. (2025). Diffusion Tensor Imaging Magnetic Resonance Imaging Assessment in a Clinical Trial of Autologous Dendritic Cell Transfer for Diabetic Kidney Disease: A Molecular Approach. *Diseases*, 13(5), 159. <https://doi.org/10.3390/diseases13050159>
- Kornaropoulos, E. N., Winzeck, S., Rumetshofer, T., Wikstrom, A., Knutsson, L., Correia, M. M., Sundgren, P. C., & Nilsson, M. (2022). Sensitivity of Diffusion MRI to White Matter Pathology: Influence of Diffusion Protocol, Magnetic Field Strength, and Processing Pipeline in Systemic Lupus Erythematosus. *Frontiers in Neurology*, 13. <https://doi.org/10.3389/fneur.2022.837385>
- Le Bihan, D. (2024). From Brownian motion to virtual biopsy: a historical perspective from 40 years of diffusion MRI. *Japanese Journal of Radiology*, 42(12), 1357–1371. <https://doi.org/10.1007/s11604-024-01642-z>
- Ljimini, A., Caroli, A., Laustsen, C., Francis, S., Mendichovszky, I. A., Bane, O., Nery, F., Sharma, K., Pohlmann, A., Dekkers, I. A., Vallee, J.-P., Derlin, K., Notohamiprodjo, M., Lim, R. P., Palmucci, S., Serai, S. D., Periquito, J., Wang, Z. J., Froeling, M., ... Sigmund, E. E. (2020). Consensus-based technical recommendations for clinical translation of renal diffusion-weighted MRI. *Magnetic Resonance Materials in Physics, Biology and Medicine*, 33(1), 177–195. <https://doi.org/10.1007/s10334-019-00790-y>
- Makvandi, K., Hockings, P. D., Jensen, G., Unnerstall, T., Leonhardt, H., Jarl, L. V., Englund, C., Francis, S., Sundgren, A. K., Hulthe, J., & Baid-Agrawal, S. (2022). Multiparametric magnetic resonance imaging allows non-invasive functional and structural evaluation of diabetic kidney disease. *Clinical Kidney Journal*, 15(7), 1387–1402. <https://doi.org/10.1093/cjk/sfac054>
- Nassar, M. K., Khedr, D., Abu-Elfadl, H. G., E. Abdulgalil, A., Abdalbary, M., Moustafa, F. E. -H., Sayed Ahmed, N., & Shemies, R. S. (2021). Diffusion Tensor Imaging in early prediction of renal fibrosis in patients with renal disease: Functional and histopathological correlations. *International Journal of Clinical Practice*, 75(4). <https://doi.org/10.1111/ijcp.13918>
- Nguyen, T. D., Bordeau, B. M., & Balthasar, J. P. (2023). Mechanisms of ADC Toxicity and Strategies to Increase ADC Tolerability. *Cancers*, 15(3), 713. <https://doi.org/10.3390/cancers15030713>
- Panduranga, A. H., Chaturvedy, K., Chaturvedy, M., Sihag, P., Nandvanshi, G., Vishnoi, S., Kaushik, A., & Khammar, A. A. (2022). Study of renal parenchymal changes by diffusion tensor imaging in diabetic nephropathy. *Polish Journal of Radiology*, 87, 163–171. <https://doi.org/10.5114/pjr.2022.114726>

- Pruijm, M., Aslam, I., Milani, B., Brito, W., Burnier, M., Selby, N. M., & Vallée, J.-P. (2022). Magnetic Resonance Imaging to Diagnose and Predict the Outcome of Diabetic Kidney Disease—Where Do We Stand? *Kidney and Dialysis*, 2(3), 407–418. <https://doi.org/10.3390/kidneydial2030036>
- Razek, A. A. K. A., Al-Adlany, M. A. A. A., Alhadidy, A. M., Atwa, M. A., & Abdou, N. E. A. (2017). Diffusion tensor imaging of the renal cortex in diabetic patients: correlation with urinary and serum biomarkers. *Abdominal Radiology*, 42(5), 1493–1500. <https://doi.org/10.1007/s00261-016-1021-3>
- Seah, J., Botterill, E., MacIsaac, R. J., Milne, M., Ekinci, E. I., & Lim, R. P. (2022). Functional MRI in assessment of diabetic kidney disease in people with type 1 diabetes. *Journal of Diabetes and Its Complications*, 36(1), 108076. <https://doi.org/10.1016/j.jdiacomp.2021.108076>
- Stabinska, J., Wittsack, H., Lerman, L. O., Ljimini, A., & Sigmund, E. E. (2024). Probing Renal Microstructure and Function with Advanced Diffusion <scp>MRI</scp>: Concepts, Applications, Challenges, and Future Directions. *Journal of Magnetic Resonance Imaging*, 60(4), 1259–1277. <https://doi.org/10.1002/jmri.29127>
- Sun, F., Huang, Y., Wang, J., Hong, W., & Zhao, Z. (2023). Research Progress in Diffusion Spectrum Imaging. *Brain Sciences*, 13(10), 1497. <https://doi.org/10.3390/brainsci13101497>
- Wei, X., Hu, R., Zhou, X., Ni, L., Zha, D., Feng, H., Xu, H., & Wu, X. (2022). Alterations of Renal Function in Patients with Diabetic Kidney Disease: A BOLD and DTI Study. *Computational Intelligence and Neuroscience*, 2022, 1–11. <https://doi.org/10.1155/2022/6844102>
- Yang, D., Ma, L., Cheng, Y., Shi, H., Liu, Y., & Shi, C. (2024). Utility of Anthropometric Indexes for Detecting Metabolic Syndrome in Resource-Limited Regions of Northwestern China: Cross-Sectional Study. *JMIR Public Health and Surveillance*, 10, e57799–e57799. <https://doi.org/10.2196/57799>
- Ye, X. J., Cui, S. H., Song, J. W., Liu, K., Huang, X. Y., Wang, L., Zhou, Y. J., Yan, Z. H., & Wang, G. B. (2019). Using magnetic resonance diffusion tensor imaging to evaluate renal function changes in diabetic patients with early-stage chronic kidney disease. *Clinical Radiology*, 74(2), 116–122. <https://doi.org/10.1016/j.crad.2018.09.011>
- Yuan, L., Cai, Q., Yang, Z., Hu, L., Wu, Y., Lu, Y., Liu, Q., Chen, X., Huang, X., Yu, Y., & Zhang, Y. (2026). Integrated assessment of diabetic nephropathy by multi-parametric magnetic resonance imaging with non-enhanced T1 mapping, diffusion tensor imaging, and diffusion kurtosis imaging. *European Journal of Radiology*, 195, 112578. <https://doi.org/10.1016/j.ejrad.2025.112578>
- Zhang, Z., Chen, Y., Zhou, X., Liu, S., & Yu, J. (2023). The value of functional magnetic resonance imaging in the evaluation of diabetic kidney disease: a systematic review and meta-analysis. *Frontiers in Endocrinology*, 14. <https://doi.org/10.3389/fendo.2023.1226830>
- Zhao, K., Li, S., Liu, Y., Li, Q., Lin, H., Wu, Z., Seeliger, E., Niendorf, T., Liu, Z., & Wang, W. (2023). Diagnostic and prognostic performance of renal compartment volume and the apparent diffusion coefficient obtained from magnetic resonance imaging in mild, moderate and severe diabetic kidney disease. *Quantitative Imaging in Medicine and Surgery*, 13(6), 3973–3987. <https://doi.org/10.21037/qims-23-149>
- Zhu, J., Chen, A., Gao, J., Zou, M., Du, J., Wu, P.-Y., Zhang, J., Mao, Y., Song, Y., & Chen, M. (2024). Diffusion-weighted, intravoxel incoherent motion, and diffusion kurtosis tensor MR imaging in chronic kidney diseases: Correlations with histology. *Magnetic Resonance Imaging*, 106, 1–7. <https://doi.org/10.1016/j.mri.2023.07.002>