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Renal scintigraphy for post-transplant monitoring after kidney transplantation[☆]

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ABSTRACT

Background: Clinicians use several diagnostic modalities to recognize post-transplant complications, such as acute tubular necrosis, acute rejection, urologic and vascular complications. Currently, there is no consensus about the best procedural approach to evaluate post-transplant renal dysfunction. Renal needle-biopsy is often required, however, this is invasive and may lead to sample errors and complications, and most clinicians prefer using one of the noninvasive diagnostic modalities.

Methods: A systematic literature search was performed using PubMed, EMBASE, the Cochrane Library, MEDLINE (OvidSP), Web of Science, and Google Scholar to identify relevant articles. This review provides a literature overview of the technical aspects, new developments and clinical value of renal scintigraphy (RS), after kidney transplantation. Additionally, the advantages and limitations of RS in comparison to other diagnostic modalities are addressed. The study protocol is registered with PROSPERO, protocol number CRD42017078391.

Results: A total of 32 studies were included. Studies were categorized in the following groups: tracer pharmacokinetics; acute rejection and acute tubular necrosis; vascular complications; urological complications; post-operative fluid collections; early transplant outcomes; one-year transplant outcomes.

Conclusions: Several studies have described the use of RS for the diagnosis of acute rejection, however, differentiating between rejection and acute tubular necrosis remains difficult. For the diagnosis of vascular complications, RS has been described as an alternative for invasive procedures. For urologic complications, studies support the use of RS in combination with routine ultrasonography (US) surveillance. For the diagnosis of postoperative fluid collections, RS provides information to differentiate lymphoceles and urinomas. Altogether, RS should be considered in case of non-acute complications, and if US provides insufficient results.

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1. Introduction

To recognize post-transplant complications, such as urologic and vascular complications, acute tubular necrosis (ATN) and acute rejection (AR), clinicians can choose from several diagnostic modalities. Currently, there is no consensus regarding the best procedural approach to evaluate post-transplant renal dysfunction. Renal needle-biopsy, which generally is considered the gold standard for the diagnosis of AR, is often

required. However, this is invasive and may lead to sample errors or complications. Most clinicians prefer using one of the noninvasive methods, such as ultrasonography (US), computed tomography (CT), magnetic resonance imaging (MRI) and renal scintigraphy (RS).

US is a noninvasive and non-nephrotoxic diagnostic test with relatively low costs. However, US results are difficult to interpret and showed to have a high inter-observer variability. CT provides detailed images of the renal transplant anatomy and the surrounding tissue but has limitations due to the nephrotoxic agents used. The use of MRI, for both anatomical and functional evaluation, has increased in the past years, but is mainly described as a second-line diagnostic modality.

RS, first introduced in 1965 for post-transplant assessment, is a non-invasive diagnostic test using radioactive isotopes. The most commonly used technique for RS is a dynamic planar procedure using a radioactive isotope which is imaged on a gamma camera, producing two-dimensional images. Radioactive isotopes (gamma ray-emitting

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radioactive nuclides) are used to visualize the physiological pathway from the renal artery to the urinary tract. This method is considered a sensitive diagnostic tool for the assessment of renal transplant dysfunction, urological and vascular complications, and postoperative fluid collections, particular in the early post-transplant period.

The aim of this review is to provide a literature overview of the technical aspects, new developments and clinical value of RS, after kidney transplantation. This review also addresses the advantages and limitations of RS in comparison with other imaging modalities.

2. Literature search

A literature search with predefined search terms was performed using the following databases: PubMed (Biomedical research articles), Embase (Medicine and Pharmacology), the Cochrane Library (Systematic reviews and controlled trials), MEDLINE (OvidSP), Web of Science, and Google Scholar. To identify all relevant publications, we used a search strategy consisting of Medical Subject Headings (MeSH) and “Title and Abstract” (TiAb) terms: “kidney transplantation”, “renal transplantation”, “radioisotope renography”, “renal (transplant) scan”, “radionuclide imaging”, “renogram”, “technetium”, “Tc 99 m and 99mTc mertiatide”, and “MAG3”. We used verified electronic search strategies, with database specific formats and the reference lists from the selected articles were manually checked for additional relevant studies. Specific search terms for each database are provided in Supplement 1. In Pubmed, the “related article” algorithm was employed to identify additional articles. Papers written in a non-English language, non-human trials, including <30 patients, when no full text was available or only supplements were excluded (Fig. 1). Additionally, we included the recommendations of the five most relevant guidelines for kidney transplantation [1–5]. The study protocol is registered with PROSPERO, protocol number CRD42017078391.

A total of 32 studies were included. Studies were categorized in the following groups: tracer pharmacokinetics; acute rejection and acute tubular necrosis; vascular complications; urological complications; postoperative fluid collections; early transplant outcomes; one-year transplant outcomes.

3. Radiopharmaceuticals

Several radiopharmaceuticals are available for the assessment of renal function after kidney transplantation. Technetium-99 m-labelled mercaptoacetyl triglycine (^{99m}Tc -MAG3) is nowadays the most commonly used radiopharmaceutical [6]. The high plasma protein binding capacity (90%) causes rapid excretion and a low percentage of irrelevant tracer distribution, leading to a high imaging quality [7]. The second-most used tracer is technetium-99 m diethylene-triamine-pentaacetic acid (^{99m}Tc -DTPA). ^{99m}Tc -DTPA is only filtered by glomerular filtration, making it very suitable for the direct measurement of the glomerular filtration rate (GFR) [8]. Despite the lower imaging quality and lower renal extraction fraction (20%) compared to ^{99m}Tc -MAG3 (40–50%), quantitative ^{99m}Tc -DTPA measurements correlate well with short and long-term transplant outcomes [9]. Iodine-131 labeled o-iodohippuric acid (^{131}I -OIH) is a tubular excreted tracer, comparable to ^{99m}Tc -MAG3. ^{131}I -OIH is characterized by high energy emission and concomitant high radiation exposure [6]. The maximum dose of ^{131}I -OIH is 30 times lower than ^{99m}Tc -MAG3 due to the long half-life time and high β -emission rate, resulting in a lower count rate and therefore lower imaging quality [6]. The functioning renal proximal tubular mass and the cortical renal part are most optimally detected by Tc-99 m-labelled dimercaptosuccinic acid (^{99m}Tc -DMSA) [10]. ^{99m}Tc -DMSA is found to have a high sensitivity for the detection of renal scarring and diffuse structural abnormalities, possibly related to increased tracer uptake in affected renal transplant parenchyma, and is generally used in combination with 3-D single-photon emission computed tomography (SPECT) [11].

4. Interpretation

RS is used to assess the structure, blood flow, and function of renal grafts, allowing the imaging of reduced flow, obstructions, or leaks. The various techniques of interpretation, being visual, qualitative and quantitative analysis, describe the three sequential phases of renal function: (I) The vascular phase, or flow study, shows the transit of radiotracer through the blood vessels; (II) the parenchymal or function phase is the period in which the nephrons extract the tracer from the blood and excrete it by glomerular filtration or tubular secretion; (III) the washout or excretory phase is the period during which the tracer drains through the renal pelvis to the bladder.

4.1. Visual interpretation

Visual inspection focuses on the arterial patency, perfusion of the native kidneys and excludes occlusion of the ureter, renal transplant artery and/or vein. Fast and high uptake is an indication of good perfusion and the absence of pre-renal complications, fast plasma clearance and parenchymal washout indicates normal tubular function, and rapid excretion from the pelvic region excludes complications in the post-renal structures [12]. Signs of hydronephrosis or progressive RS tracer activity surrounding the ureter indicate respectively urinary tract obstruction and urinary leaks. Some factors can hamper the visual interpretation of the scans. First, visualisation of urological complications can be difficult in dehydrated patients. Second, inspection can be difficult due to procedure artefacts, such as patients' motion, a wrong detector position, and a low dose of the used radiopharmaceutical. Third, the interpretation can be troubled by patient specific characteristics, such as renal transplant cysts and deviations from the standard vascular and urological post-transplant anatomy.

4.2. Qualitative assessment

Tracer uptake and perfusion is visualized using time-activity curves derived from graft regions of interest. Through the grading of these curves with the grading scale of Heaf and Iversen, renal function can be assessed qualitatively (Fig. 2) [13]. Normal renal transplant function (grade 0) is characterized by a fast-rising curve, reaching its maximum within 5 min, and nearly complete excretion within thirty minutes. Reduced renal transplant function, as seen in a majority of renal transplants in the early post-operative period, is characterized by a reduced or absent excretion with normal perfusion (grade 1–2). A time-activity curve during ATN or AR shows a slowly rising curve without a downslope phase (grade 3–4). A minimal uptake of the tracer, as seen in grade 5, reflects a renal transplant with very limited function and/or perfusion.

4.3. Quantitative assessment

A quantitative analysis is preferable since it is less affected by inter-observer variability compared to a visual analysis with/without the use of a curve grading scale [14]. Over the years, several methods have been introduced with varying degrees of success, due to lack of diagnostic power and the inability to distinguish AR from ATN [12, 15]. In general, most quantitative indices describe the extraction/uptake and excretion/clearance. The largest retrospective studies have focused on the use of *tubular function slope* (TFS), reflecting the curves upslope, *MUC10*, representing kidney activity as a fraction of the injected dose, *R20/3*, dividing one-minute time intervals ending at 20 and 3 min, and *GI*, combining both time-based indices and counts-based indices (Table 1) [16–19].

Fig. 1. Flowchart, selection of studies.

5. Assessment of complications

5.1. Differentiating acute rejection from acute tubular necrosis

Differentiating between AR and ATN is important though challenging since AR will result in permanent damage if left untreated. Additionally, complicated by the fact that both entities can be present at the same time (Table 2) [20]. In case of both AR and ATN, the perfusion, uptake, parenchymal transit, and excretion of the renal transplant are all impaired. Needle biopsy is considered the golden standard for evaluating morphologic changes in the renal transplant tissue and diagnosing

causes of renal transplant dysfunction such as AR [21]. However, needle biopsy cannot always be performed due to several contraindications, such as uncontrolled hypertension, active renal or perirenal infection, hydronephrosis, and an INR ≥ 1.5 [22]. Combined with a risk of major complications (need for intervention or intensive care admittance) between 1.1%–1.9%, with a three times increased risk within the first week after transplantation [22–24]. Additionally, sample errors are seen in 0.5% of US-guided procedures [25]. A study including 43 transplant recipients with multiple RS procedures, showed a significant difference in quantitative RS indices between recipients with slow renal transplant function and recipients with renal transplant pathology

Fig. 2. Renal scintigraphy grading scale. Grade 0: normal renal scintigraphy; Grade 1: normal uptake, reduced excretion; Grade 2: normal uptake, flat excretion curve; Grade 3: rising curve; Grade 4: reduced rate of uptake, rising curve and reduced absolute uptake; Grade 5: minimal uptake.

(both AR and ATN) [26]. However, quantitative RS analyses (Hilson's perfusion index and Kirchner's kidney/aorta ratio) could not unequivocally differentiate between renal transplants with ATN and cases of AR. The

quantitative index $R20/3$ is the most commonly described quantitative index, which can be calculated for both ^{99m}Tc -MAG3 and ^{99m}Tc -DTPA by dividing the renal activity at 20 min by the activity at 3 min. In a large retrospective cohort of 307 transplant recipients, the index $R20/3$ was shown to have a strong correlation with the severity of both ATN and AR [27]. A retrospective study comparing US with the intra-renal resistive index (RI), and RS using the index $R20/3$ and a qualitative grading, found a sensitivity and specificity of respectively 93% and 73% for RS and 76% and 66% for US, for the prediction of renal transplant pathology (both AR and ATN) within seven days post-RS [15]. The clinical relevance of these findings is questionable as needle biopsy remains the 'golden standard'. However, the potential ability of RS to differentiate AR from ATN is important, since unnecessary biopsies and/or treatment procedures of acute rejection should be avoided.

5.2. Vascular complications

Vascular complications occur in 10% of renal transplant recipients and are an important cause of renal graft dysfunction and graft loss [28]. Transplant renal artery stenosis (TRAS) is the most common vascular complication, followed by transplant renal artery thrombosis (TRAT) and transplant renal vein thrombosis (TRVT) (Table 2) [28–30]. Angiography is the gold-standard invasive modality for the diagnosis of TRAS, TRAT and TRVT, however, various reports have suggested a role for RS and US [31]. The major drawbacks of angiography are the complications such as contrast-induced nephropathy and thromboembolism [29]. Colour Doppler US is used to evaluate the renal vascular flow and the RI is used to give quantitative results [32]. Large studies comparing invasive and non-invasive procedures are lacking. A study in 47 transplant recipients showed that computed tomography angiography (CTA) and

Table 1
Literature overview renal scintigraphy, grouped according to renal transplant end-points.

End-point	First author (Ref)	Publication (Year)	Patients (number)	Index	Days post-KTX	Results (sensitivity/specificity)
AR/ATN	Yazici [15]	2013	107	$R20/3$	2	93%/73% for AR/ATN within 7 days.
				RS		94%/86% for AR/ATN within 7 days.
	El Maghraby [26]	1998	43	grade	2	Significant difference in patients with slow graft function compared to patients with AR or ATN.
	Bajen [55]	1997	43	$K3/20$	1–3	Significant lower uptake in case of AR/ATN
	Li [27]	1994	307	MTT	Suspicion of AR/ATN	Correlation with the clinically assessed severity of AR/ATN.
	Gedroyc [56]	1986	43	$R20/3$	Suspicion of AR/ATN	No significant difference between AR and cyclosporine nephrotoxicity
Early renal transplant outcome	Yazici [19]	2016	179	HI	2	86%/86% for period of dialysis-dependence in first week.
	Majima [57]	2012	31	GI	4	Significant correlation with period of dialysis-dependence in first week.
	Obeidat [20]	2011	143	cTER	1–2	86%/84% for period of dialysis-dependence in first week.
	El Maghraby [16]	2002	42	RS	1	Significant difference in patients with DGF at day 7 compared to patients with immediate renal transplant function.
	Stevens [17]	2001	256	Grade	2	Significant correlation with period of dialysis-dependence in first week.
	Heaf [13]	2000	201	TFS	1–21	76% sensitivity for 10% sCr rise within 2 days.
1-Year renal transplant outcome	Yazici [19]	2016	179	RS	2	74%/76% for 1 year renal transplant function. ^a
	Yazici [40]	2015	111	grade	2	54%/78% for 1 year renal transplant function. ^a
				$R20/3$	2	54%/79% for 1 year renal transplant function. ^a
				T1/2		31%/92% for 1 year renal transplant function. ^a
				RS		
	Gupta [41]	2012	214	grade	2	73%/72% for 1 year renal transplant survival. ^b
				HI	4	88%/59% for 1 year renal transplant survival. ^b
	Guignard [58]	2011	100	TFS	3	67%/67% for 1 year renal transplant survival. ^b
	Ngai [59]	2008	64	HI	3	90%/36% for 1 year renal transplant function. ^a
	Russel [18]	2000	200	$R20/3$	3	Significant correlation with the 1y renal transplant survival.

KTX = kidney transplantation

^a Worsened renal transplant function defined as sCr >1.5 mg/dL.

^b Renal transplant survival, number of functioning renal transplants.

Table 2
Complications after kidney transplantation.

	Complication	Incidence (%)
Renal complications	Acute rejection (AR)	8%–10% [60, 61]
	Acute tubular necrosis (ATN)	22% [62]
Vascular complications	Transplant renal artery stenosis (TRAS)	1–23% [28, 29]
	Transplant renal artery thrombosis (TRAT)	0.8%–3% [28, 30]
	Transplant renal vein thrombosis (TRVT)	1.0%–1.8% [28, 30]
Urological complications	Urinary tract obstruction	4.5–4.7 [35, 36]
	Urinary leak	1.5–1.6 [35, 36]
Postoperative fluid collections	Urinoma	— ^a
	Hematoma	4.9% [63]
	Abscess	0.3% [64]
	Lymphocele	5.2% [65]

^a No data available.

gadolinium enhanced magnetic resonance angiography (MRA) are superior to ultrasound and captopril ^{99m}Tc-DTPA RS for diagnosing morphological stenosis [33]. A study evaluating 133 ^{99m}Tc-DTPA RS procedures, with 7 cases of TRVT and 2 cases of TRAT, concluded that both complications show a similar pattern of photo-deficient areas at the anatomical location of the transplant [34]. Unfortunately, studies comparing non-invasive diagnostic modalities for TRAT and TRVT are lacking.

5.3. Urological complications

Urological complications after transplantation generally consist of urinary tract obstruction and/or urinary leaks and can be determined with RS as signs of hydronephrosis or progressive RS tracer activity surrounding the ureter (Supplement 2). There is currently a lack of evidence to express a preference for either RS or US in diagnosing urological complications. However, RS provides dynamic images, which can provide elaborate information about the nature, intensity, and location of an obstruction or leak. Two retrospective studies including 1525 and 965 transplant recipients, with a 4.5%–4.7% incidence of urinary tract obstruction and a 1.5%–1.6% incidence of urinary leaks (Table 2), support the use of dynamic renal ^{99m}Tc-DTPA RS in combination with routine US surveillance [35, 36]. A study evaluating 133 ^{99m}Tc-DTPA RS procedures, with 12 cases of urinary leaks and 2 cases of urinary obstruction, described no false-negative and -positive outcomes [34]. While a more recent study including 211 pediatric transplant recipients, with a 7.6% incidence of urological obstructions and extravasations, supports the use of ^{99m}Tc-MAG3 [37].

Table 3
Future alternatives.

	Methods
Ultrasonography (US)	Contract-enhanced ultrasound (CEUS) [66] Ultrasound elastography (UE) [45]
Magnetic resonance imaging (MRI)	MR renography [46]
	Blood oxygenation level-dependent MRI (BOLD-MRI) [48]
	Diffusion-weighted MRI (DWI MRI) [49]
Positron emission tomography -computer tomography (PET-CT)	Fluor-18 FDG T-lymphocyte PET-CT (¹⁸ F-FDG PET-CT) [67]
	Rubidium-82 chloride PET-CT (⁸² Rb-chloride PET-CT) [53]
	Oxygen-15-water PET-CT (¹⁵ O-H ₂ O PET-CT) [54]

5.4. Postoperative fluid collections

Clinically significant postoperative fluid collections are commonly seen in the earlier and late postoperative period. These collections include urinomas or hematomas in the immediate post-transplant period, and abscesses or lymphoceles, in the following months (Table 2). US is mostly used as primary diagnostic modality and was shown to have a high sensitivity, although the results are non-specific. Studies comparing the sensitivity of US and RS are lacking, but with visual RS analysis the distinction between lymphoceles and urinomas can be made. However, lymphoceles and urinomas, at the anterior/posterior side of the renal transplant, could be missed with RS due to the planar (2-dimensional) view. In these cases, 3-dimensional images should be obtained using SPECT. In a retrospective analysis of 2000 transplant recipients undergoing both ^{99m}Tc-DTPA RS and US, lymphoceles were detected in 13 transplant recipients with a similar accuracy [38]. The visual analyses of these lymphoceles showed photopenic ‘cold’ areas in the first RS phase, representing an area without tracer uptake, in contrary to images of urinomas which show ‘hot’ areas with tracer uptake [38, 39].

6. Correlation with short- and long-term outcomes

In general, early post-transplant RS is performed in cases of delayed graft function (DGF) or suspicion of surgical complications. In addition to their current contribution to clinical decision-making, several studies have focused on the predictive potential of baseline RS procedures for early and one year transplant outcomes.

6.1. Early renal transplant outcome

The quantitative *GI* index has been developed for the analyses of ^{99m}Tc-DTPA, which resulted in a high sensitivity and specificity for the need of dialysis in the first week post-transplant (86% and 86%, respectively) (Table 1) [19]. The counts-based indices *tubular function slope* (*TFS*) and *MUC10* have shown to correlate significantly with the occurrence of dialysis dependence in the first postoperative week [16, 17]. The grading scale of Heaf and Iversen has a sensitivity of 76% regarding the prediction of a 10% rise in serum creatinine levels between two following days [13]. To date it has not been proven that this early predictive potential of RS is superior to the simple measurement of serum creatinine.

6.2. One year renal transplant outcome

The *GI* index described earlier, showed a moderate sensitivity and specificity for the prediction of renal transplant function, based on serum creatinine, at one year post-transplantation (74% and 76%, respectively) (Table 2) [19]. The use of the quantitative index *T1/2*, from RS procedures within two days post-transplantation, yield a relatively poor sensitivity and specificity of 54% and 79% for renal transplant function at one year based on serum creatinine [40]. The *Hilson's perfusion index* and the grading scale of Heaf and Iversen showed to have a low predictive value for one-year renal transplant function, with a sensitivity/specificity of respectively 73%/72% and 31%/92% [40, 41]. On the contrary, a recent study focusing on long-term transplant function showed no significant correlation between *RI* results of US procedures results and serum creatinine at one year post-transplantation [40]. A result which is in line with the conclusion that *RI* results during the first two years post-transplantation are not accurate enough to predict renal transplant outcome, although they reflect recipient characteristics and patient mortality [42].

7. Current guideline recommendations

The five reviewed kidney transplantation guidelines did not provide recommendations and did not mention the use of postoperative RS. The use of US was the only mentioned procedure for postoperative transplant imaging. However, recommendations with regard to this topic were all based on low-degree evidence or expert opinions, with level of evidence between 3 and 5 (Oxford Centre for Evidence-Based Medicine, Levels of Evidence) [43]. To reach a balanced recommendation for the use of either RS or US, more elaborate studies comparing both procedures are needed.

8. Discussion

In this review, we described the technical and clinical aspects of RS after kidney transplantation. The available qualitative curves grading scales, for the different possible shapes of renal time-activity curves, have a high sensitivity and somewhat low specificity for changes in renal transplant function. Moreover, several methods for a quantitative analysis are available from which *GI*, *T1/2*, *R20/3* and *Hilson's perfusion index* were shown to have moderate predictive values for the occurrence of DGF, AR or ATN, and short- or long term renal transplant outcomes.

RS is used to make a comprehensive dynamic evaluation of renal perfusion, excretion patterns, and leakage, while US is used to evaluate both the internal renal morphology, such as heterogeneity of renal cortex and hypo-echogenicity of renal pyramids. Both procedures provide comprehensive information on pre- and post-renal complications, such as postoperative fluid collections, urological-, and vascular complications. RS is less hampered by inter-observer variability and this advantage of RS leads to a higher sensitivity and specificity for the diagnosis of early graft dysfunction. However, a differentiation between AR and ATN cannot be made by either RS or US alone. For the diagnosis of urologic complications, there is currently no clear preference for either RS or US, partly because a proper comparison between both tests is lacking. However, lymphoceles and urinomas, at the anterior/posterior side of the renal transplant, could be missed with RS due to the planar (2-dimensional) view. In these cases, 3-dimensional images should be obtained using SPECT. The availability and applications of SPECT have increased in the past years. Future studies should provide more information on the advantages of SPECT compared to both conventional RS and US. Possible disadvantages of RS compared to US are higher costs, limited availability of tracers and equipment, and radiation exposure. In more detail, the costs of a RS procedure is approximately 450,00 USD ($\pm$ 400,00 EUR) compared to approximately 175,00 USD ($\pm$ 150 EUR) for an US procedure, and approximately USD (+/– EUR) for a SPECT procedure 580,00 USD ($\pm$ 500,00 EUR), in The Netherlands.

9. Future perspectives

Future research should provide more information about the feasibility to differentiate AR from ATN with improved scoring methodologies for RS images. To improve clinical value, future studies should focus on the characterization and value of different curve shapes, reliable quantification techniques, and the introduction and renewing of visualisation techniques. Furthermore, the use of SPECT-measured ^{99m}Tc -DMSA could provide more comprehensive results, however, studies comparing the use of regular RS and SPECT are not available [10].

Various new and promising imaging techniques could be useful for the follow-up of patients after kidney transplantation. The introduction of contrast-enhanced ultrasound (CEUS), a combination of microbubble technology and complementary US, could improve the clinical value of post-transplant US (Table 3) [44]. Further research

is necessary to assess the detection of hemodynamic changes and usefulness of quantification techniques, such as the resistive index used for conventional US. Several studies described the use of ultrasound elastography (UE), a method of measuring shear wave velocity to determine the extent of tissue stiffness. However, its use for post-transplant monitoring is still limited to the diagnosis of renal transplant fibrosis, for which UE provides reliable measurements in 70% of patients [45]. The use of dynamic contrast-enhanced MRI (MR renography) has been explored for renal evaluation with promising results for TRAS and urological obstruction [46]. Large studies focusing on the accuracy of MR renography for the distinction between AR and ATN are lacking. More recent developments use bodily substances such as hemoglobin for Blood Oxygenation Level-Dependent magnetic resonance imaging (BOLD MRI) and water molecules for Diffusion-Weighted Imaging (DWI MRI) [47]. Promising results have been published using BOLD MRI, showing a significant difference between AR and ATN MRI results [48]. For DWI MRI, more research is necessary in order to determine whether different causes of renal transplant dysfunction could be differentiated [49, 50]. The wide introduction of positron emission tomography-computer tomography (PET-CT) provides the opportunity for higher-resolution images and more reliable quantitative measurements. Fluor-18 (^{18}F) FDG-labelled T-lymphocytes PET-CT was shown to make a distinction between AR and ATN in a rat model of kidney transplantation [51]. In a prospective human-trial including 31 patients with suspected AR, (^{18}F) FDG PET-CT was shown to prevent avoidable transplant biopsies [52]. Studies focusing on renal blood flow, including healthy volunteers, have been performed with Oxygen-15-water (^{15}O -H₂O) PET-CT ($n = 6$) and rubidium-82 chloride (^{82}Rb) PET-CT ($n = 8$) [53, 54]. Ongoing research into tracer binding to intracellular targets or leukocytes could fulfill the demand for methods for non-invasive diagnosis of AR.

10. Conclusion

RS has its merits for the evaluation of complications after kidney transplantation, especially for vascular and/or urological complications. However, providing a clear recommendation for the use of either RS or US during the early postoperative period is not possible, based on the available literature. Several studies have described the use of RS for the diagnosis of acute rejection, however, differentiating between rejection and acute tubular necrosis remains difficult. For the diagnosis of vascular complications, RS has been described as an alternative for invasive procedures. For urologic complications, studies support the use of RS in combination with routine ultrasonography (US) surveillance. For the diagnosis of postoperative fluid collections, lymphoceles show areas with lack of tracer uptake in contrast to the accumulated tracer uptake in urinomas. Altogether, RS should be considered in case of non-acute complications, and if US provides insufficient results. Early diagnosis of vascular and urological complications can contribute to a more specific surgical approach and better post-transplant outcomes.

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Conflicts of interest

None.

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