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Tc-99m DMSA SPECT for Follow-Up of Non-Operative Treatments in Renal Injuries: A Prospective Single-Center Study

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Objective: The assessment of cortical integrity following renal injuries with planar Tc-99m dimercaptosuccinic acid (DMSA) scintigraphy depends on measuring relatively decreased cortical uptake (i.e., split renal function [SRF]). We analyzed the additive values of the volumetric and quantitative analyses of the residual cortical integrity using single-photon emission computed tomography (SPECT) compared to the planar scintigraphy.

Materials and Methods: This prospective study included 47 patients (male:female, 32:15; age, 47 ± 22 years) who had non-operatively managed renal injuries and underwent DMSA planar and SPECT imaging 3–6 months after the index injury. In addition to planar SRF, SPECT SRF, cortical volume, and absolute cortical uptake were measured for the injured kidney and both kidneys together. The correlations of planar SRF with SPECT SRF and those of SRF with volumetric/quantitative parameters obtained with SPECT were analyzed. The association of SPECT parameters with renal function, grades of renal injuries, and the risk of renal failure was also analyzed.

Results: SPECT SRF was significantly lower than planar SRF, with particularly higher biases in severe renal injuries. Planar and SPECT SRF (dichotomized with a cutoff of 45%) showed 19%–36% of discrepancies with volumetric and quantitative DMSA indices (when dichotomized as either high or low). Absolute cortical uptake of the injured kidney best correlated with glomerular filtration rate (GFR) at follow-up ($\rho = 0.687$, $P < 0.001$) with significant stepwise decreases by GFR strata (90 and 60 mL/min/1.73 m^2). Total renal cortical uptake was significantly lower in patients with moderate-to-high risk of renal failure than those with low risk. However, SRF did not reflect GFR decrease below 60 mL/min/1.73 m^2 or the risk of renal failure, regardless of planar or SPECT (count- or volume-based SRF) imaging.

Conclusion: Quantitative measurements of renal cortical integrity assessed with DMSA SPECT can provide more clinically relevant and comprehensive information than planar imaging or SRF alone.

Keywords: Tc-99m dimercaptosuccinic acid; Single-photon emission computed tomography; Renal injury

INTRODUCTION

Traumatic renal injury comprises 65%–90% of urogenital trauma, with a cumulative incidence of 10%–20% among adult and children cohorts [1]. In most cases, blunt abdominal trauma is responsible for urogenital trauma while penetrating injuries have been reported in limited cases (< 20%) [2]. Iatrogenic renal injuries are also not rare, with incidences ranging up to 15% [3], although the incidence varies with the procedure.

Regardless of the etiology, non-operative management has become the standard treatment of renal injuries unless the patient is actively bleeding or hemodynamically unstable [3,4]. Even in patients with active bleeding, selective angioembolization can be attempted if available. However, the long-term outcomes of renal injuries remain uncertain

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[3]. The cortical damages from traumatic injuries and related treatments (e.g., angioembolization) can lead to variable extent of functional consequences, which have not been clarified; the recommendations for post-traumatic assessment of renal cortical integrity also vary with guidelines [5]. The lack of information on the residual renal cortical integrity may result in suboptimal follow-up strategies with unknown risk of renal failure and patient anxiety.

Tc-99m dimercaptosuccinic acid (DMSA) scintigraphy visualizes the cortical integrity following renal injuries. As the radiotracer binds to the renal proximal tubule, cortical defects indicate the amount of damaged renal cortex, and preserved renal uptake indicates residual functional integrity. This information can help in nephrological management and counseling of patients, especially those with high-grade injuries [3,6,7]. However, the current assessment of renal cortical integrity using DMSA scintigraphy depends on the split renal function (SRF) calculation. SRF can only detect a relative decrease in cortical integrity of the injured kidney compared to the opposite side (assumed to be uninjured). It does not account for the absolute amount of residual functional cortex following injuries. Thus, SRF may be inappropriate in the follow-up of bilateral renal injuries or patients with underlying renal diseases (e.g., renal cysts or tumors) in the uninjured kidney.

DMSA single-photon emission computed tomography (SPECT) can provide three-dimensional volumetric indices and quantitative parameters of renal cortical integrity. However, its usefulness has not been elucidated in the follow-up of patients with renal injuries. Even the most recent guideline [7] does not recommend a routine use of DMSA SPECT despite its advantage over planar imaging in terms of improved image resolution and quantification. In this study, we aimed to clarify the additive value of DMSA SPECT to planar imaging in the follow-up assessment of cortical integrity of patients with renal injuries.

MATERIALS AND METHODS

Study Design

Patients with renal injuries who underwent non-operative management (including selective angioembolization) were included in the present study. Renal injury was defined as a physical injury or a wound by an extrinsic agent, including iatrogenic etiology [3]. Exclusion criteria were 1) age < 2 years, 2) history of unilateral nephrectomy, and 3) incomplete follow-up studies.

On initial assessment, the grade of renal injury was determined according to the American Association for the Surgery of Trauma (AAST) grading scale [8,9] based on the findings on contrast-enhanced computed tomography (CT). Iatrogenic injury from main renal angioembolization was considered AAST grade 4 unless active bleeding was present [9]. The management strategies were decided following the contemporary guidelines [3,4], with appropriate consultations involving trauma surgeons and urologists. The patients who underwent non-operative management were referred for regular follow-up by a urologist on an outpatient basis. The follow-up studies were performed 3–6 months following the index injury on the same day. The studies included serum creatinine measurement, estimation of glomerular filtration rate (GFR), urinalysis, and DMSA scintigraphy with SPECT imaging. The imaging protocol, analytic indices, and statistical analyses were pre-specified before patient enrollment. Patients were requested to sign the consent form to participate in this prospective study. The prospective enrollment was conducted for those who experienced renal injuries between August 2021 and July 2022. The present study was approved by the Chonnam National University Hospital Institutional Review Board (CNUH-2022-101).

Planar and SPECT DMSA Scan

Planar scintigraphy was performed in the supine position 3 hours after DMSA was intravenously injected. Administered dose of DMSA was 7.4 MBq/kg (0.2 mCi/kg) for adults and 111 MBq (3 mCi) for children; actual ranges of administered dose were 333–629 MBq (9.0–17.0 mCi) and 93–122 MBq (2.5–3.3 mCi), respectively. With a 4-mm pinhole collimator equipped on the detector, anterior and posterior planar images were obtained at the level of the kidneys (200000 counts), confirmed by a parallel-hole collimator imaging before the pinhole acquisition. SPECT images were acquired immediately after the planar imaging. A scout image was obtained to confirm that the kidneys were included in the field of view. Subsequently, a low-dose helical CT image was acquired with 120 kV of voltage, automatic current modulation (minimum 60 mA to maximum 210 mA), and a slice thickness of 3.75 mm. SPECT imaging was performed with a matrix size of 128 x 128, a zoom factor of 1.0, and 360° of total angular range (180° per detector) for 10 s per projection (3°) in a step-and-shoot mode (total acquisition time 10 min). A two-headed gamma camera (E-cam, Siemens Healthineers) and a SPECT/CT scanner

(NM-CT 670, GE Healthcare) was used for planar and SPECT imaging, respectively.

Radiation exposure (mSv) was calculated by summing the effective doses from intravenous administration of DMSA, and low-dose CT used for SPECT/CT imaging. The estimation of effective dose from radiopharmaceutical administration was based on the International Commission on Radiological Protection publication 128 [10], while that from low-dose CT was based on the k values suggested by the American Association of Physicists in Medicine [11].

Image Analyses

For planar images, the photon counts from the anterior and posterior images were averaged by calculating the geometric mean for each kidney. The planar SRF of the injured kidney was calculated as the proportion of the geometric mean from the injured kidney divided by that from both kidneys.

The renal contours were automatically delineated for SPECT images as 40% of the maximum uptake [12] using a dedicated nuclear imaging analysis software (MIM Maestro, MIM Software Inc.). The photon counts within the renal contours, and the corresponding cortical volume was measured for each kidney to calculate SRF in count-based (SRFc) and volume-based (SRFv) methods, respectively. As a per-patient analysis, the injured renal cortical volume (ICV) and total renal cortical volume (TCV) were measured as the volume of the delineated renal cortex of the injured kidney and both kidneys, respectively. These values were divided by body surface area to normalise inter-individual variation to obtain the ICV and TCV indices, respectively. Absolute volumetric renal DMSA uptake (% injected dose) [13] was quantified for the injured kidney (injured renal cortical uptake, ICU) and both kidneys (total renal cortical uptake, TCU) with decay correction, using the Q-Volumetrix MI software package (GE Healthcare).

Statistical Analyses

SRF was compared between planar and SPECT imaging using paired t-test or Wilcoxon signed-rank test. The biases and limits of agreement between planar and SPECT SRF were analyzed with Altman-Bland plots. The correlation between scintigraphic parameters and laboratory renal function tests was analyzed using Pearson's or Spearman's correlation analysis. For per-patient analyses of SRF, ICV, and ICV index in those with bilateral injuries, the kidney with the lower planar SRF was selected. The scintigraphic parameters were compared between high-grade (AAST grade 4 or 5) and low-grade (AAST grades 1 to 3) [6] renal injuries. Inter-user reproducibility was assessed for planar SRF and SPECT parameters between two independent readers. The reproducibility of planar SRF measurement was evaluated by calculating the intraclass correlation coefficient and analyzing the Bland-Altman plot. In contrast, the reproducibility of SPECT measurements was not reported because the measured values were identical between the two readers.

The statistical methods and data presentation, either mean ± standard deviation or median (interquartile range), were selected for data distribution as assessed by the Shapiro-Wilk test. R version 4.0.2 (R Foundation for Statistical Computing) was used for statistical analyses; a P-value < 0.05 was considered statistically significant.

RESULTS

Baseline Characteristics

A total of 47 patients were enrolled in the present study, with a higher number of male participants (n = 32, 68%). Fifty-one kidneys were injured, including bilateral injuries in four patients. High-grade renal injuries were observed in 27 (53%) patients. Compared to the time of index injury, renal function significantly improved (P < 0.001) at follow-up in terms of both serum creatinine and GFR. Planar DMSA scintigraphy exerted a median of 3.5 mSv of effective dose, while SPECT/CT imaging added a median of 1.2 mSv by performing a low-dose CT scan. Detailed characteristics of the enrolled patients are listed in Table 1.

SPECT vs. Planar SRF

The results of planar and SPECT imaging measurements are summarized in Table 1. Planar SRF showed an excellent intraclass correlation coefficient (0.98, 95% confidence interval, 0.97–0.99) and a small mean bias (0.5%) between two independent readers. However, the limits of agreement were beyond ± 5% (-5.3%–6.3%).

Both SRFc (ρ = 0.911, P < 0.001) and SRFv (ρ = 0.948, P < 0.001) showed excellent linear correlations with planar SRF. However, they were both significantly lower than planar SRF for the same injured kidney (both P < 0.01), with mean biases of 2.3% (limits of agreement: -11.7%–16.3%) and 2.2% (limits of agreement: -10.0%–14.4%), respectively. The differences between planar and SPECT SRF values were particularly prominent for the kidneys with SRF beyond the normal range (45%–55%). There were significant negative correlations

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Table 1. Baseline characteristics

Variables	Values
Age, yr	47 ± 22
Sex	
Male	32 (68)
Female	15 (32)
Underlying renal diseases	
Cysts	20 (43)
Unilateral	9 (19)
Bilateral	11 (23)
Stone	5 (11)
Vascular tumors	3 (6)
Others	2 (4)
Injured kidney	
Right	18 (38)
Left	25 (53)
Bilateral	4 (9)
Causes of renal injuries	
Traffic accident	19 (40)
Iatrogenic	9 (19)
Fall down	8 (17)
Slip down	8 (17)
Others	3 (6)
AAST grades	
1	5 (10)
2	9 (18)
3	10 (20)
4	23 (45)
5	4 (8)
Selective arterial embolization	20 (43)
Interval between index injury and follow-up studies, wk	17 (16–18)
Renal function	
At index injury	
Serum creatinine, mg/dL	0.90 (0.78–1.14)
GFR, mL/min/1.73 m^2	89.8 ± 33.2
Overt proteinuria*	25 (53)
Follow-up	
Serum creatinine, mg/dL†	0.86 (0.72–1.03)
GFR, mL/min/1.73 m^{2}†	98.8 ± 32.4
Overt proteinuria	4 (9)
Tc-99m DMSA scintigraphy	
Planar SRF, %‡	47.6 (42.0–50.0)
SPECT SRF	
SRFc, %	35.2 (36.0–50.2)
SRFv, %	46.5 (37.5–49.7)
ICV, mL	107.1 ± 57.1
ICV index, mL/m^2	59.2 ± 30.5
TCV, mL	246.8 ± 83.5
TCV index, mL/m^2	142.3 ± 37.2
ICU, %	11.2 ± 5.7
TCU, %	26.7 ± 8.5
Radiation exposure (effective dose, mSv)	
Total	4.7 (4.6–4.9)
Tc-99m DMSA	3.5 (3.4–3.7)
Low-dose CT	1.2 (1.2–1.2)

Data are presented as mean ± standard deviation or median (interquartile range) for continuous variables and n (%) for categorical variables.
*≥ dipstick 1+ , †*P* < 0.001 vs. at index injury, ‡SRF values were measured for the injured kidney. The kidney with the lower planar SRF value was chosen as the representative side for per-patient analysis in those with bilateral injuries.
AAST = American Association for the Surgery of Trauma, GFR = glomerular filtration rate, DMSA = dimercaptosuccinic acid, SRF = split renal function, SPECT = single-photon emission computed tomography, SRFc = count-based split renal function measured on single-photon emission computed tomography, SRFv = volume-based split renal function measured on single-photon emission computed tomography, ICV = injured renal cortical volume, TCV = total renal cortical volume, ICU = injured renal cortical uptake (absolute % injected dose), TCU = total renal cortical uptake (absolute % injected dose), CT = computed tomography

between the mean and the difference between planar and SPECT SRF: planar SRF vs. SRFc, $r = -0.611$, $P < 0.001$ and planar SRF vs. SRFv, $r = -0.626$, $P < 0.001$ (Fig. 1). Similar results were observed among the patients with unilateral injury only (Supplementary Table 1).

Volumetric/Quantitative Parameters vs. SRF

Both planar and SPECT SRF significantly correlated with ICV and ICV index (ρ 0.683–0.839; all $P < 0.001$) and less remarkably with TCV and TCV index (ρ 0.302–0.651; all $P < 0.050$). Similarly, planar and SPECT SRF significantly correlated only with ICU (ρ 0.596–0.646; $P < 0.001$) but not with TCU (all $\rho < 0.200$; $P > 0.10$).

When volumetric (ICV and TCV indices) and quantitative (ICU and TCU) parameters were dichotomized as high or low by the averages, there were 19%–36% (n = 9–17) of discrepancies with planar and SPECT SRF (dichotomized with a cutoff of 45%). ICV index-TCV index discrepancy was observed in twenty-four (51%) patients, while ICU-TCU discrepancy was observed in six (13%) (Supplementary Tables 2-6).

Correlation of DMSA Parameters with Renal Function and Risk of Renal Failure

Among the SRF and volumetric parameters, SRFv showed the best correlation with serum creatinine at follow-up, while the TCV index best correlated with that at index injury. ICU showed the highest correlation coefficient with

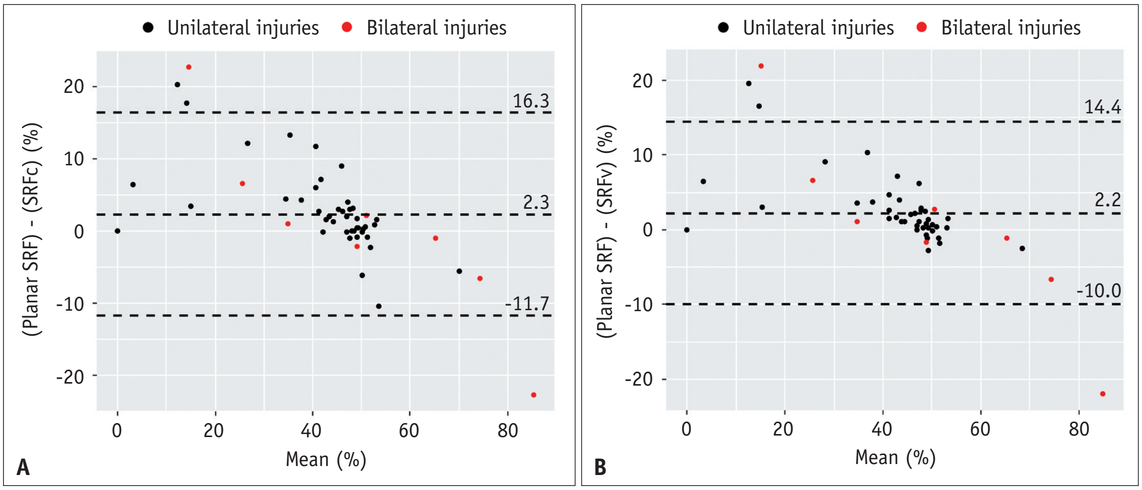

Fig. 1. Bland-Altman plot of split renal function measured by planar and SPECT DMSA imaging. The mean bias is approximately 2%, with minimal difference in SRF between planar and SPECT imaging within the normal range (45%–55%). However, SRF values show significant biases beyond the normal range; a negative correlation between the mean and difference of SRF is noted for both count-based (SRFc, **A**) and volume-based (SRFv, **B**) SPECT SRF. The results did not significantly change when only unilateral injuries were included in the analyses. SPECT = single-photon emission computed tomography, DMSA = dimercaptosuccinic acid, SRF = split renal function, SRFc = count-based split renal function, SRFv = volume-based split renal function

Table 2. Correlations between DMSA scintigraphic parameters and laboratory markers of renal function

	Laboratory markers of renal function			
	vs. serum creatinine		vs. GFR	
	At index injury	Follow-up	At index injury	Follow-up
Planar SRF	-0.380*	-0.498†	0.444*	0.433*
SPECT parameters				
SRFc	-0.450*	-0.554†	0.499†	0.492†
SRFv	-0.457*	-0.581†	0.504†	0.505†
ICV	-0.386*	-0.328	0.489†	0.390
ICV index	-0.616†	-0.549†	0.653†	0.568†
TCV	-0.283	-0.089	0.407*	0.255
TCV index	-0.635†	-0.453*	0.684†	0.552†
ICU	-0.596†	-0.532†	0.687†	0.610†
TCU	-0.562†	-0.449*	0.586†	0.477*

*$P < 0.01$, †$P < 0.001$.
DMSA = dimercaptosuccinic acid, GFR = glomerular filtration rate, SRF = split renal function, SPECT = single-photon emission computed tomography, SRFc = count-based split renal function measured on single-photon emission computed tomography, SRFv = volume-based split renal function measured on single-photon emission computed tomography, ICV = injured renal cortical volume, TCV = total renal cortical volume, ICU = injured renal cortical uptake (absolute % injected dose), TCU = total renal cortical uptake (absolute % injected dose)

GFR at follow-up (Table 2). Significant stepwise decreases were observed in TCV index and ICU for patients with GFR ≥ 90, 60–90, and < 60 mL/min/1.73 m^2 regardless of planar or SPECT imaging (Fig. 2A-D). However, SRF did not differ between those with GFR 60–90 vs. < 60 mL/min/1.73 m^2, regardless of planar or SPECT imaging.

TCU was significantly lower in patients with moderate-to-high risk of renal failure defined by the current guidelines [14] than those with low risk; TCV index ($P = 0.074$) also tended to be lower with a borderline significance (Fig. 2E-H). No difference was found in planar or SPECT SRF (all $P > 0.200$) by the risk of renal failure.

Correlation with the Grade of Renal Injuries

Patients with high-grade renal injuries showed significantly lower serum creatinine at follow-up (0.92 [0.78–1.10] vs. 0.75 [0.61–0.87] mg/dL; $P = 0.020$) compared to those with low-grade injuries. GFR tended to be lower for high-grade injuries, but statistical significance was not reached (90.3 ± 30.5 vs. 110.0 ± 32.2 mL/min/1.73 m^2; $P = 0.052$). Planar and SPECT SRF, ICV and TCV (indices), and ICU were significantly lower for high-grade renal injuries than low-grade renal injuries. Volumetric and quantitative parameters showed more marked overlaps between high- and low-grade renal injuries than planar and SPECT SRF (Fig. 3).

DISCUSSION

The present study evaluated the additive value of volumetric and quantitative analyses of cortical integrity using DMSA SPECT for follow-up of renal injuries after non-

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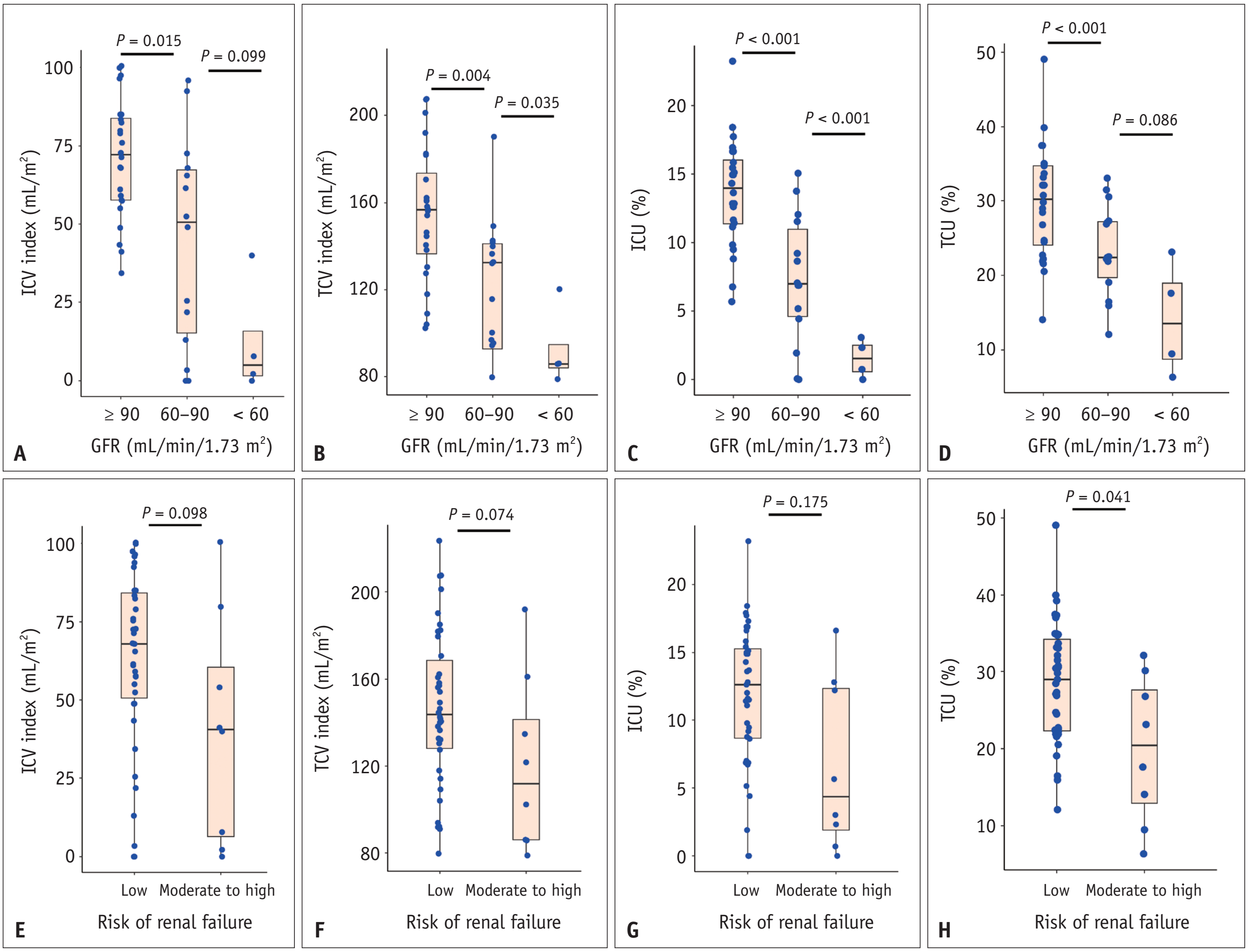

Fig. 2. Comparison of volumetric/quantitative SPECT indices according to GFR strata and risk of renal failure. TCV index and ICU showed significant, stepwise decreases according to stratified GFR, while ICV index and TCU failed to explain further GFR decrease under 60 mL/min/1.73 m^2 **(A-D)**. However, TCU was significantly lower in patients with moderate-to-high risk of renal failure, and the TCV index also tended to be lower with borderline significance **(E-H)**. SPECT = single-photon emission computed tomography, GFR = glomerular filtration rate, TCV = total renal cortical volume, ICU = injured renal cortical uptake (absolute % injected dose), ICV = injured renal cortical volume, TCU = total renal cortical uptake (absolute % injected dose)

operative management. SPECT SRF values were significantly lower than planar SRF values, particularly in severe injuries (kidneys with SRF < 45%). Substantial discrepancies were noted between SRF and volumetric/quantitative parameters, while absolute cortical uptake best correlated with renal function (GFR). Although planar and SPECT parameters significantly differed by the degree of renal injuries, wide overlaps in volumetric and quantitative SPECT parameters were observed between high- and low-grade injuries. Our study suggests the need for individualized assessment of the cortical integrity following renal injuries using DMSA scintigraphy, preferably DMSA SPECT.

Previous studies have searched for incremental values of DMSA SPECT in addition to planar imaging, mainly among patients with suspected pyelonephritis or cortical scarring following infection [15-17]. Although the results are not directly applicable to patients with renal injuries for which the grades of cortical damages vary to a wider extent, differences in SRF between planar and SPECT have been reported, similar to our observation: Reichkendler et al. [12] showed a mean bias of 2.1%, which increased in kidneys with SRF beyond the normal range (SRF difference > 10%); a negative correlation between the difference and mean of SRF values on Bland-Altman plot was described by Cao et al. [18]. Planar and SPECT imaging differ in the method of quantifying the cortical integrity as well as in the method of visualizing the renal cortex. Planar imaging measures all the counts within the two-dimensional renal regions of interest

Korean Journal of Radiology

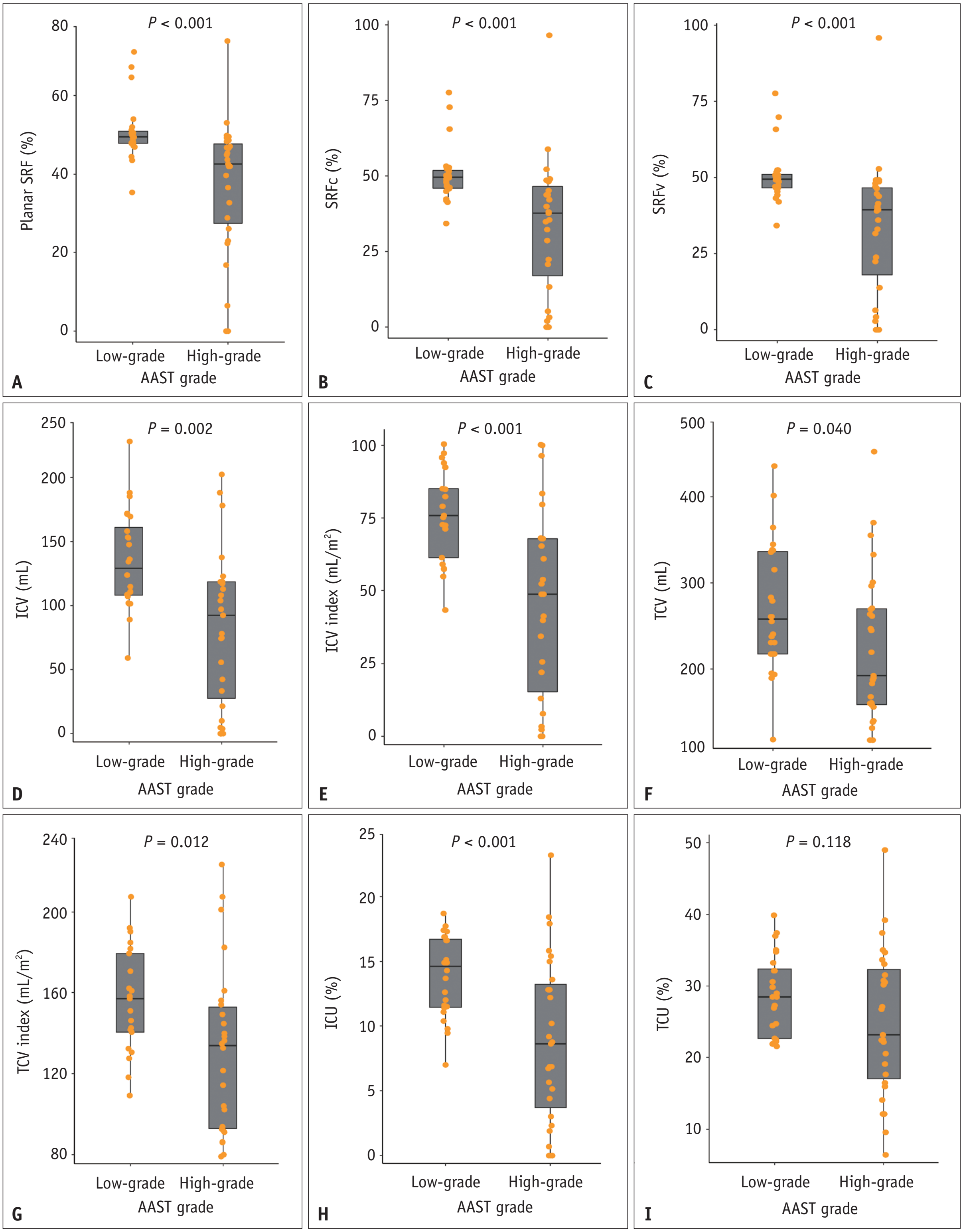

Fig. 3. A-I: Comparison of DMSA imaging parameters between low-grade (AAST grades 1–3) and high-grade (AAST grades 4–5) renal injuries. High-grade renal injuries show significantly lower SRF (planar and SPECT), ICV and TCV (indices), and ICU. However, there are substantial overlaps in these imaging parameters, implicating that the cortical integrity at follow-up can differ by individual. DMSA = dimercaptosuccinic acid, AAST = American Association for the Surgery of Trauma, SRF = split renal function, SPECT = single-photon emission computed tomography, ICV = injured renal cortical volume, TCV = total renal cortical volume, ICU = injured renal cortical uptake (absolute % injected dose), SRFc = count-based split renal function, SRFv = volume-based split renal function, TCU = total renal cortical uptake (absolute % injected dose)

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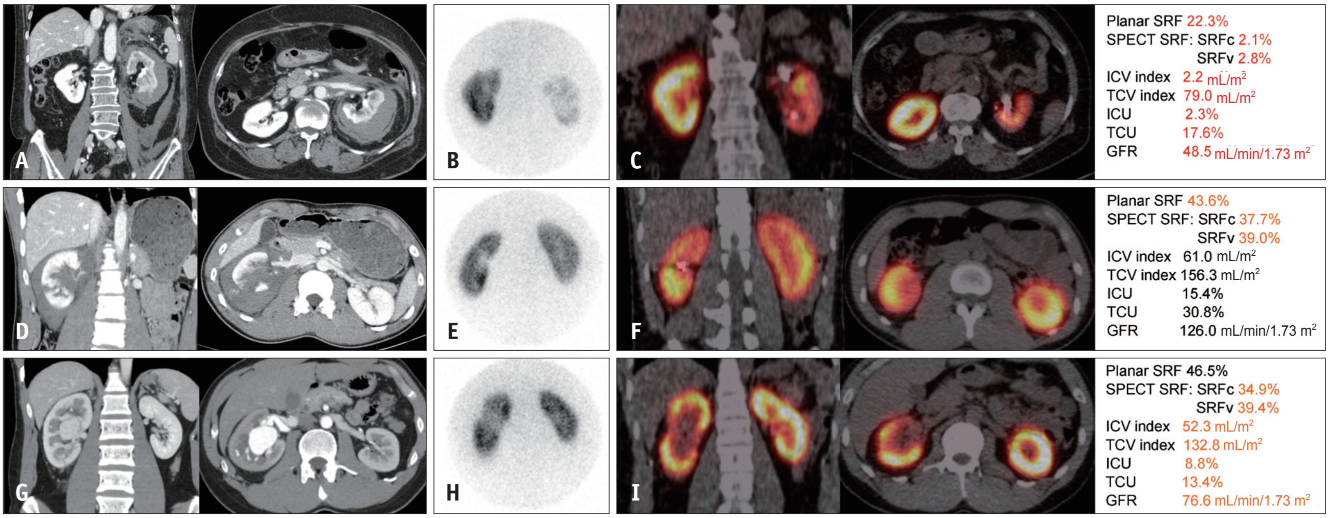

Fig. 4. SRF (planar and SPECT) vs. volumetric/quantitative indices in similar grades of renal injuries. A 69-year-old female with a grade-4 left renal injury due to extracorporeal shock wave lithotripsy underwent follow-up DMSA scintigraphy. SPECT SRF values were lower than planar SRF, correlating to markedly reduced volumetric/quantitative indices and GFR **(A-C)**. Despite the same grade of right renal injury by a traffic accident, a 16-year-old male **(D-F)** showed more preserved cortical integrity than the first patient. In contrast to the subnormal ranges of SRF, volumetric indices and quantitative renal uptake were above the average values in the present study (Table 1), and GFR was well-preserved. A 29-year-old male underwent DMSA scintigraphy at 16 weeks after angioembolization for a ruptured arteriovenous malformation **(G-I)**. Even with similar SRF, volumetric/quantitative indices were lower than those in the second case, correlating with a lower GFR. SRF = split renal function, SPECT = single-photon emission computed tomography, DMSA = dimercaptosuccinic acid, GFR = glomerular filtration rate, SRFc = count-based split renal function, SRFv = volume-based split renal function, ICV = cortical volume of injured kidney, TCV = total renal cortical volume, ICU = injured renal cortical uptake (absolute % injected dose), TCU = total renal cortical uptake (absolute % injected dose)

and compares them between the two kidneys to calculate SRF. On the other hand, a threshold value (e.g., 40% [12] or 43% [18] of global maximum uptake) applies in delineating renal contours on SPECT images, excluding minor activities from the damaged renal cortex. Therefore, it is plausible that SRF from SPECT is lower than that from planar imaging, especially in kidneys with severe injuries, as our data demonstrated. Notably, the SPECT SRF better reflected renal function than the planar SRF. This implies that measuring the amount of functionally compatible renal cortex may be more clinically relevant than including all cortical counts from the damaged, hypo-functioning areas. Further, planar images may have geometrical or attenuation errors in quantifying cortical uptake, even with normalization by calculating the geometric mean [7].

However, the use of SRF is limited in patients with bilateral renal injuries (Supplementary Fig. 1) or complete loss of functional cortex (SRF 0%), which comprised 9% and 6% of our study patients, respectively. Also, SRF alone does not effectively represent the renal functioning capacity following injuries. SRF ignores other factors (e.g., native size difference, compensatory hypertrophy of the uninjured kidney, patient's body profile, etc.) related to a patient's renal function. Thus, comparable SRF values do not necessarily indicate a similar amount of residual functional cortex and filtrating capacity (Figs. 2, 4). Such limitation also applies to the ICV index; both SRF and ICV index failed to explain the further decrease in GFR below 60 mL/min/1.73 m^2, which corresponds to chronic kidney disease stage 3. By contrast, the TCV index can measure the total amount of functional cortex, which further declined in patients with a more marked reduction in GFR (< 60 mL/min/1.73 m^2). Moreover, the formulas of ICU and TCU (absolute % injected dose/mL x functional cortical volume) take into account both 'uptake' and 'volume', making ICU and TCU most significantly associated with renal function among the scintigraphic parameters. TCU could reflect the risk of renal failure as well. Therefore, ICU and TCU may be the most clinically relevant scintigraphic parameter in the follow-up assessment of renal injuries.

Notably, these parameters have substantial discrepancies, and it is insufficient to evaluate the sequelae of renal injuries based on any single scintigraphic parameter. Instead, a comprehensive interpretation of these values provides additive information regarding the pathophysiology of renal dysfunction. For example, an isolated decrease in TCV index with preserved ICV index suggests a need for investigating other potential causes of renal dysfunction; concordant decreases in both parameters suggest underlying medical renal disease apart from renal injuries (Supplementary Fig. 2).

Correlations between the grades of initial trauma (e.g., AAST grades) and planar SRF have been reported in previous studies [19-22]. However, our data showed significant overlaps in the scintigraphic parameters between high- and low-grade renal injuries, especially in TCU (Fig. 3). This is not surprising as Overs et al. [21] already reported variable ranges of SRF (0%–49%) among children with high-grade (AAST grades 4–5) renal injuries at follow-up (≥ 6 months from index trauma). This implies that the residual cortical integrity after non-operative management would not always match the AAST grade and that the cortical preservation (or recovery) can substantially differ among individuals. Although SRF was less varied by AAST grades, SRF was not sufficiently associated with the actual renal function or the risk of renal failure, as described above. Our results reaffirm the recommendations of the current guidelines that suggest individualized investigations for cortical integrity in patients with high-grade renal injuries [3,6], and at the same time, the need for a more individualized selection of patients with low-grade renal injuries who should undergo follow-up imaging studies.

This study further extends these recommendations to a preferred use of SPECT imaging. By virtue of minimal extrarenal DMSA activity, these indices are simple and easy to measure (time spent for measurement < 5 minutes, data not shown). Volumetric and quantitative parameters from DMSA SPECT are reproducible and can provide clinically relevant information. Additional radiation exposure by hybrid SPECT/CT imaging was minimal (median 1.2 mSv) and can be avoided by omitting low-dose CT scans. Therefore, the DMSA SPECT parameters can be reliably used in future clinical trials to prove their prognostic implications, which were beyond the scope of the present study.

This study had limitations. The cameras used to measure planar and SPECT SRF were different to meet the clinical workflow in daily practice. However, SRF, by its definition, is the relative difference between the two kidneys, with no or little consideration necessary for variability by potential systematic errors from different cameras; the same SPECT camera measured all volumetric indices. Future studies should demonstrate long-term prognostic values of DMSA scintigraphy in patients with renal injuries to gain more clinical relevance. The renal contours in our study were delineated based on a relative threshold (40% of global maximum uptake), which was pre-specified before patient enrollment. Absolute quantification of renal uptake was based on delineating renal contours with a relative threshold [13,23]. A more individualized definition of threshold [24] or advanced segmentation technique [25] may contribute to a more precise evaluation of renal cortical integrity with DMSA SPECT.

In conclusion, volumetric quantification of renal cortical integrity with DMSA SPECT can provide additive, clinically relevant, and comprehensive information than planar imaging or SRF alone. Residual cortical integrity can vary among similar degrees of renal injuries, implicating the need for individualized imaging assessment using DMSA scintigraphy.

Supplement

The Supplement is available with this article at https://doi.org/10.3348/kjr.2023.0149.

Availability of Data and Material

The datasets generated or analyzed during the study are not publicly available due to the restriction by the Chonnam National University Hospital Institutional Review Board (CNUH IRB) to keep the patient data security, but are available from the corresponding author on reasonable request.

Conflicts of Interest

The authors have no potential conflicts of interest to disclose.

Author Contributions

Conceptualization: Sang-Geon Cho, Seong Hyeon Yu. Data curation: Sang-Geon Cho, Seong Hyeon Yu. Formal analysis: Sang-Geon Cho, Seong Hyeon Yu. Funding acquisition: Sang-Geon Cho, Seong Hyeon Yu. Investigation: Sang-Geon Cho, Seong Hyeon Yu. Methodology: Sang-Geon Cho, Seong Hyeon Yu. Project administration: Sang-Geon Cho, Seong Hyeon Yu. Resources: Ho-Chun Song, Taek Won Kang. Software: Ho-Chun Song, Taek Won Kang. Supervision: Ho-Chun Song, Taek Won Kang. Validation: Ki Seong Park, Jahae Kim, Jang Bae Moon, Taek Won Kang. Visualization: Sang-Geon Cho, Seong Hyeon Yu. Writing—original draft: Sang-Geon Cho, Seong Hyeon Yu. Writing—review & editing: Ki Seong Park, Jahae Kim, Jang Bae Moon, Taek Won Kang, Ho-Chun Song.

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