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A potential imaging-based predictor for renal functional outcomes after partial nephrectomy for localized renal masses

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Abstract

Background To determine whether postoperative renal parenchymal volume from first post-operative computed tomography (CT) is a significant prognostic factor for chronic kidney disease (CKD) on the long-term follow up after partial nephrectomy (PN).

Methods This retrospective study included 319 patients who underwent PN for T1 localized renal cell carcinoma (RCC) between September 2006 and December 2020. Kidney volume data of first postoperative CT and preoperative CT was made with a three-dimensional rendering software. Time-dependent cox proportional-hazards regression analysis was used to find important risk factors that indicate the development of new-onset CKD following PN, adding kidney volume data to various clinical parameters.

Results Of the 319 patients who underwent PN for T1 localized RCC, a total of 13 patients (4.0%) had new-onset CKD at last follow up and developed it at a median follow up of 46 months. Univariate analyses of the Cox proportional hazards model showed that age, hypertension, preoperative/postoperative eGFR, and total kidney volume/kilogram body weight were potential risk factors associated with new-onset CKD development. In multivariable cox proportional models, the likelihood-ratio test confirmed that overall performance of models was improved by including total kidney volume ($p = 0.008$).

Conclusions Renal parenchymal volume of first postoperative CT was a significant risk factor of CKD development on long-term follow up in patients with T1 RCC after PN. Therefore, first postoperative imaging studies will be able to help predict CKD development, as well as to assess the success of the surgery and to monitor recurrence or complications.

Keywords Renal cell carcinoma, Partial nephrectomy, Chronic kidney disease, Computed tomography, Prognosis

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Background

Partial nephrectomy (PN) has become the standard surgical treatment for renal cell carcinoma (RCC) with a tumor diameter < 7 cm (T1a/b) [1]. Compared to radical nephrectomy (RN), partial nephrectomy (PN) has been shown to better preserve postoperative renal function and reduce the risk of cardiovascular events [2, 3]. Nevertheless, in a large cohort of RCC patients without preoperative CKD, approximately 25% developed de novo CKD stage 3 or higher following PN [4]. Recent studies in patients with renal cell carcinoma and upper tract urothelial carcinoma have demonstrated that surgically induced CKD is independently associated with increased all-cause mortality, highlighting the prognostic importance of postoperative renal function preservation [4, 5]. Multiple studies have investigated predictive variables of long-term renal functional outcome after nephrectomy. Several perioperative factors such as increasing age, sex, diabetes mellitus, Charlson Comorbidity Index (CCI), and reduced baseline preoperative estimated glomerular filtration rate (eGFR) have been identified as significant predictors of postoperative CKD [6–8].

Recently, computed tomography (CT) has become a widely available imaging modality for preoperative staging of RCC. CT-based prediction models have also been developed using various imaging features such as renal volume, tumor size, location, and margin [9–11]. According to the 2021 AUA guidelines, the first postoperative abdominal imaging for patients with localized T1-stage renal cell carcinoma is recommended within 6 to 12 months following surgery [12]. Furthermore, postoperative CT scans have revealed that the parenchymal volume of the operated kidney is reduced to varying degrees by approximately 20% or more and that compensatory hypertrophy is mostly observed in the contralateral kidney [13].

We hypothesized that the volume of preserved renal parenchyma following surgery could be predictive of postoperative renal function and serve as a potential prognostic indicator. From first postoperative CT, we wanted to extract additional information using CT volumetry reflected on postoperative parenchymal volume changes in both kidneys. The present study aimed to determine whether postoperative renal parenchymal volume could be a significant prognostic factor for CKD with a long-term follow-up.

Methods

Study populations

This retrospective study was approved by the Institutional Review Board (IRB) of our institution **(IRB No. 4-2020-0533)**. The requirement for informed consent was waived by the IRB due to the retrospective nature of this study. Between September 2006 and December 2020, a total of 338 patients who underwent partial nephrectomy performed by a single surgeon for renal tumors were identified through a review of electronic medical records (Fig. 1). Inclusion criteria were: patients with T1 localized renal cell carcinoma (size < 7 cm, confirmed by pathologist), normal contralateral kidney, and available CT taken in 6–24 months of follow-up after surgery, including corticomedullary or nephrogenic phase. Among these patients, 19 patients were excluded if one of the following exclusion criteria was met: (1) patients who were converted to RN ($n = 4$) (2), those who had preoperative eGFR < 60 mL/min/1.73 m^2 ($n = 8$) (3), those who had pathologically confirmed benign lesions (e.g., oncocytoma, angiomyolipoma) ($n = 1$) (4), those who had recurrence

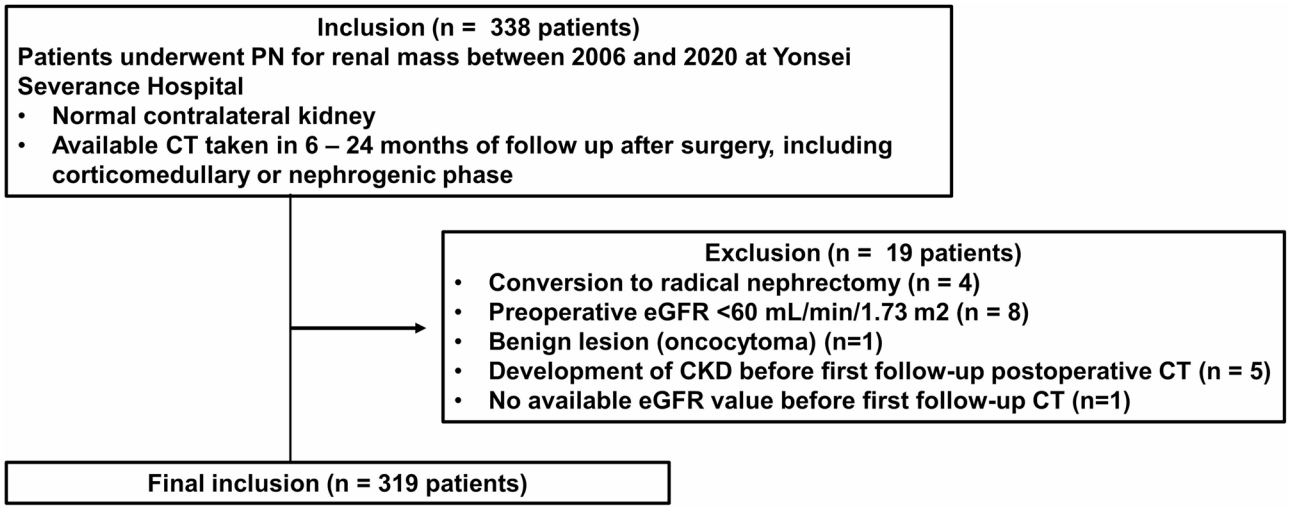

Fig. 1 Flow diagram for selecting study patients. PN, partial nephrectomy; CT, computed tomography; eGFR, estimated glomerular filtration rate; CKD, chronic kidney disease

of renal cell carcinoma after partial nephrectomy (5), those who had developed CKD before first follow-up postoperative CT ($n = 5$), and (6) those who did not have available eGFR value before the first follow-up postoperative CT ($n = 1$). Finally, 319 patients were included in the evaluation.

The following patient demographics and perioperative variables were collected: age, sex, height, weight, body mass index (BMI), American Society of Anesthesiologists (ASA) physical status score, and comorbidities including diabetes mellitus (DM), hypertension, and dyslipidemia. Tumor-related and operative data included pathological tumor size, histopathology, R.E.N.A.L. nephrometry score (categorized as low [4–6], intermediate [7–9], and high complexity [10–12]), clamp type (total clamping = 2, selective clamping = 1, off-clamp = 0), total operative time, and renal function parameters (preoperative and postoperative serum creatinine and estimated glomerular filtration rate [eGFR], with postoperative values measured on postoperative day 1). Regarding renal function evaluation, eGFR was calculated using the Modification of Diet in Renal Disease formula. eGFR was measured in the same laboratory preoperatively and postoperatively on day 1; at 1, 3, 6, and 12 months; and then annually up to 7 years. The latest eGFR was defined as the value of eGFR at the last follow-up. Patients who had new-onset CKD upgrading into stage III or greater (i.e., eGFR < 60 mL/min/1.73 m^2 for at least two measurements) were analyzed.

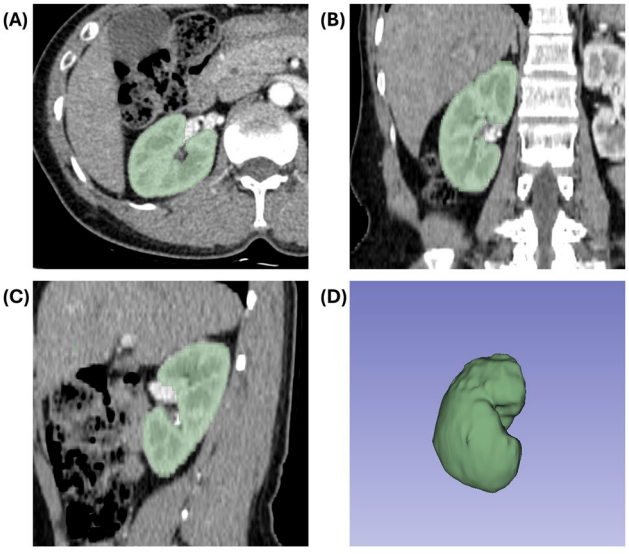

Fig. 2 3D segmentation process images obtained from 3D-slicer are shown. The renal parenchyma (**A**; axial, **B**; coronal, **C**; sagittal image, **D**; 3-dimensional image) were segmented semi-automatically and the volume was measured afterward

CT image acquisition and Segmentation of renal parenchyma

Multiphase kidney CT was performed with one of three helical CT scanners (Discovery CT 750 HD, GE Healthcare; iCT256, Philips Healthcare; or Somatom Definition Flash, Siemens Healthcare). CT protocols were as follows: 3.0-mm slice thickness, 100-kVp tube voltage, and variable tube current. Abdominal scans were carried out in the craniocaudal direction with coverage of both kidneys. After pre-contrast imaging, a nonionic contrast agent (IOBRIX® inj.240; Taejoon Pharm Co., Ltd., Seoul, Korea) was injected intravenously through a high-pressure syringe at a rate of 3–4 mL/s with a bolus tracking method. The corticomedullary phase (CMP) and nephrographic phase (NP) were scanned for 20–45 s and 120 s after contrast agent injection, respectively. Additionally, CT images included coronal and sagittal reformatted images.

Among a total of 319 patients having first postoperative CT, 170 patients had available preoperative CT. Kidney volume data of first postoperative CT and available preoperative CT were made with a three-dimensional (3D) rendering software (3D-slicer, NIH, version 4.13.0). All CT scans from included patients were segmented using the 3D Slicer software. Initial segmentation was performed by a junior radiologist with three years of residency training. The software semi-automatically detected and delineated the functional renal parenchyma, and manual editing was performed as needed to exclude the renal pelvis, calyces, and sinus fat from the segmented volume (Fig. 2). All segmentations were subsequently reviewed and finalized by a board-certified radiologist with over 20 years of experience in genitourinary imaging. In cases of uncertainty or discrepancy, consensus was reached between the two readers to ensure accuracy and consistency.

To extract topological information from various structures of the kidney, the volume of each segmented structure was calculated. The volume was determined by multiplying the number of segmented voxels with the pixel spacing (x, y) and the slice thickness (z). Finally, volumetric data were derived from the operated kidney (ipsilateral to the tumor), contralateral non-operated kidney, and total kidney volume (sum of ipsilateral and contralateral kidneys). Using the above-mentioned method similarly, the kidney volume in the preoperative CT was measured by excluding tumor from total kidney parenchyma.

Statistical analysis

Descriptive statistics were used to summarize clinical characteristics and outcomes. Data are expressed as mean ± SD for continuous variables and frequency (percentage) for categorical variables. To evaluate potential

selection bias arising from the availability of preoperative CT imaging, baseline clinical and demographic characteristics were compared between patients with and without preoperative CT. Continuous variables were compared using independent samples t-tests, and categorical variables were analyzed using chi-square or Fisher's exact tests, as appropriate (Supplementary Table 1).

Table 1 Demographics and clinical characteristics

Characteristics	Mean ± SD or *n* (%)
Age, mean ± SD	52.9 ± 11.8
Sex, male, n (%)	218 (68.3%)
CKD development, n (%)	13 (4.1%)
Median follow-up length, months	57.5 ± 22.8
Height, cm, mean ± SD	166.4 ± 12.7
Weight, kg, mean ± SD	70.3 ± 12.3
BMI, kg/m^2, mean ± SD	25.2 ± 3.3
ASA score	
1	121 (38.1%)
2	160 (50.3%)
3	37 (11.6%)
HTN, yes, n (%)	95 (29.8%)
DM, yes, n (%)	38 (11.9%)
Dyslipidemia, yes, n (%)	51 (16.0%)
Tumor size, cm, mean ± SD	2.8 ± 1.4
Total OP time, min	140.8 ± 62.6
CLAMP TYPE	
0	73 (22.9%)
1	98 (30.7%)
2	148 (46.4%)
Preoperative eGFR (mL/min/1.73 m^2)	87.4 ± 11.7
Immediate postoperative eGFR	79.8 ± 12.4
6-month postoperative eGFR	82.5 ± 15.3 (available in 198 patients)
1-year postoperative eGFR	82.4 ± 13.9 (available in 314 patients)
Preoperative creatinine (mg/dL)	0.8 ± 0.2
Immediate postoperative creatinine	0.9 ± 0.2
6-month postoperative creatinine	0.9 ± 0.3 (available in 150 patients)
1-year postoperative creatinine	0.9 ± 0.2 (available in 179 patients)
R.E.N.A.L. score (complexity)	
vLow	151 (47.3%)
Intermediate	126 (39.5%)
High	42 (13.2%)
Postoperative total kidney volume (PostTKV), ml	277.7 ± 80.3
Postoperative operated kidney volume (PostOKV), ml	141.3 ± 50.2
Preoperative TKV (PreTKV), ml (*n* = 170)	318.18 ± 63.9
PostTKV/Body weight (BW), ml/kg	3.99 ± 1.05
PostOKV/BW, ml/kg	2.02 ± 0.66
PreTKV/BW, ml/kg (*n* = 170)	4.63 ± 0.77

**Abbreviations*: *PostTKV* postoperative total kidney volume, *PostOKV* postoperative operated kidney volume, *eGFR* estimated glomerular filtration rate

Time-dependent Cox models were constructed because the kidney volume changed over time during the follow-up period (Supplementary Tables 2 and 3). Kaplan–Meier curve analysis was performed to show CKD-free survival probability after PN surgery. CKD-free survival (CFS) time was defined as the duration between the date of the first postoperative CT scan and the date of CKD progression.

Univariate Cox proportional hazards regression analysis was performed to find important risk factors that could indicate the development of new-onset CKD following PN. Variables with P-values below 0.05 in univariate analysis were included in the multivariable Cox proportional hazards regression analyses to develop predictive models.

The C-index was used to evaluate the performance of the Cox proportional hazard model. The C-index indicates the proportion of samples that are correctly ranked when samples are listed in the order of predicted survival time. A value of 0.5 indicates that the model is no better at predicting an outcome than random chance and a value of 1 means that the model perfectly predicts an outcome [14, 15].

The comparison of C-index in different Cox proportional hazard models was based on the method developed by Kang et al. [16]. Likelihood ratio test (LRT) was used to compare values of the goodness of fit between different cox proportional hazard models in predicting CKD development. *P*-values of less than 0.05 were considered statistically significant. All statistical analyses were carried out using R software version 4.3.1 (R Foundation for Statistical Computing, http://www.r-project.org).

Results

A total of 319 patients with RCC who received PN at Yonsei Severance Hospital from September 2006 to September 2020 were enrolled, including 218 (68.3%) males and 101 (31.7%) females. The median follow-up duration was 58 months (IQR: 37–82 months). A total of 13 (4.0%) patients had new-onset CKD at the last follow-up (median follow-up: 46 months). Other descriptive characteristics for the overall population are listed in Table 1.

Among the 319 patients included in the study, 170 (53.3%) had available preoperative CT data. Baseline characteristics were compared between patients with and without preoperative CT to evaluate potential selection bias. Except for tumor size and clamp type, no statistically significant differences were found in age, sex, body mass index (BMI), comorbidities (including hypertension, diabetes, and dyslipidemia), renal function parameters, or tumor-related variables between

patients with and without preoperative CT (all $p > 0.05$) (Supplementary Table 3). Kaplan–Meier analysis demonstrated that CKD-free survival rates at 1-, 3-, 5- and 7-year were 99.4%, 98.7%, 96.7%, and 93.3%, respectively (Fig. 3).

Univariate analyses using the Cox proportional hazards model identified several significant predictors of new-onset CKD development (Table 2). These included age at surgery ($P = 0.001$), hypertension ($P = 0.005$), and multiple renal function parameters such as preoperative eGFR ($P = 0.002$), immediate postoperative eGFR ($P = 0.008$), 6-month postoperative eGFR ($P = 0.001$), and 1-year postoperative eGFR ($P = 0.001$). In addition, higher serum creatinine levels at 6 months ($P = 0.005$) and 1 year ($P = 0.003$) were also significantly associated with CKD progression. Furthermore, total kidney volume per kilogram of body weight was significantly associated with CKD-free survival ($P = 0.005$) (Table 2).

Two different Cox proportional hazards models were fit for CKD-free survival (Table 3). The first model (Model A) included age, HTN, and preoperative eGFR. The second model (Model B) included three predictors from Model A, plus total kidney volume/kilogram body weight. In Model B, presence of HTN at the time of surgery (HR: 4.21, 95% CI: 1.20–14.81, $P = 0.025$) and lower preoperative eGFR (HR: 0.94, 95% CI: 0.89–0.98, $P = 0.007$), and smaller total kidney volume/kilogram body weight (HR: 0.95, 95% CI: 0.91–0.99, $P = 0.020$) were significant predictors. The discrimination power of the two Cox proportional hazard models was evaluated based on the C-index value. The C-index of model B (0.892) was slightly higher than that of model A (0.875). Bootstrap-based internal validation showed optimism-corrected C-indices of 0.8633 for Model A and 0.8830 for Model B.

The likelihood-ratio test also confirmed that the overall performance of model B was improved by including total kidney volume (Table 4).

In multivariable Cox regression analysis adjusted for age, hypertension, and preoperative eGFR, patients in the lowest tertile (Q1) of postoperative kidney volume-to-body weight ratio had a significantly higher risk of CKD development compared to those in the middle (Q2) and highest (Q3) tertiles. The hazard ratios were 0.13 (95% CI: 0.016–0.998, $p = 0.05$) for Q2 and 0.11 (95% CI: 0.014–0.889, $p = 0.04$) for Q3, respectively, indicating a markedly reduced risk in patients with higher postoperative renal volume. Based on the distribution of postoperative kidney volume-to-body weight ratio, patients were stratified into three groups using tertile cut-off values: Q1: Low volume group (< 3.74 mL/kg), Q2: Intermediate group (3.74–4.37 mL/kg), Q3: High volume group (> 4.37 mL/kg). Patients in Q1 demonstrated substantially worse CKD-free survival compared to those in Q2 or Q3, as shown in Fig. 4.

Discussion

The present study showed that kidney volume estimated by the first post-operative CT was a significant predictor of postoperative CKD development. We also found that HTN and lower preoperative eGFR were predictive variables of postoperative renal function on a long-term follow up, which considerably aligned with results of Ali et al. [17]. They developed a nomogram to predict 5-year

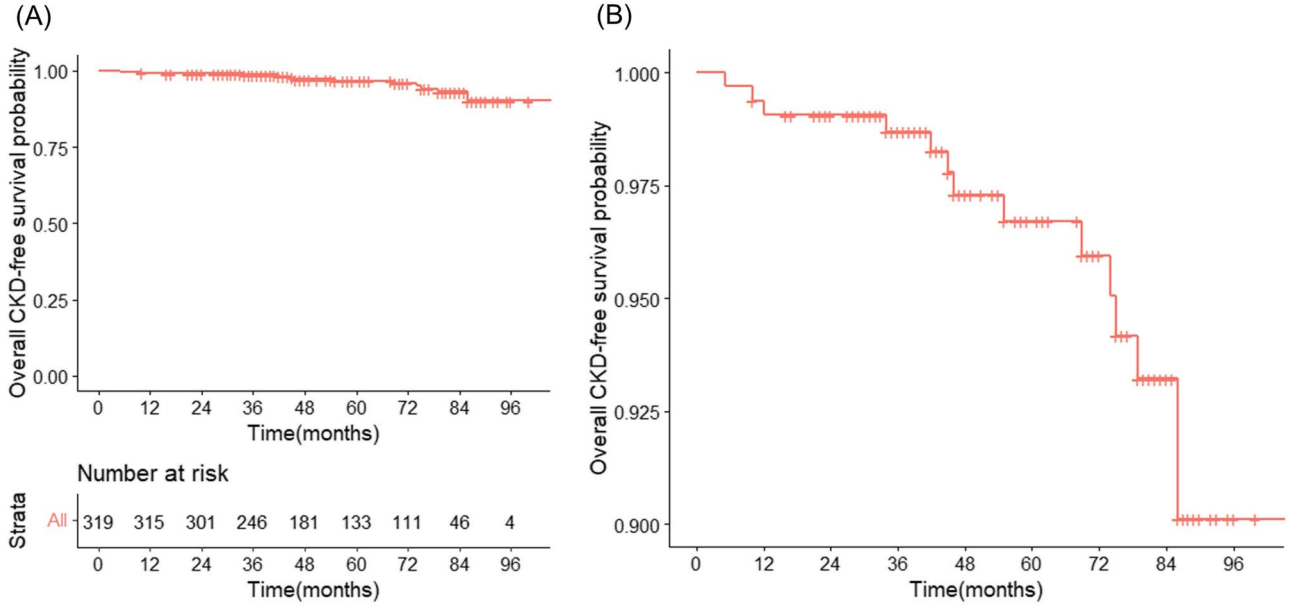

Fig. 3 **A**, Kaplan–Meier curve showing CKD-free survival probability after PN surgery. **B**, Magnification of the curve with overall CKD-free survival probability of more than 0.9 which clearly demonstrate CKD-free survival rates over time. CKD, chronic kidney disease

Table 2 Univariate analysis of factors associated with CKD

Variables	HR (95% CI)	*p*-value
Age	1.1 (1.04–1.16)	0.001
Sex		
F	Ref.	Ref.
M	0.84 (0.28–2.59)	0.727
BMI	1.08 (0.93–1.25)	0.286
ASA		
1	Ref.	Ref.
2	2.24 (0.65–7.76)	0.202
3	3.72 (0.65–21.33)	0.141
HTN (yes)	5.5 (1.69–17.88)	0.005
DM (yes)	1.6 (0.35–7.28)	0.551
Dyslipidemia (yes)	0.9 (0.2–4.07)	0.875
Tumor size	1.15 (0.83–1.6)	0.264
TOTAL OP TIME	1 (0.99–1.01)	0.827
CLAMP_TYPE		
0	Ref.	
1	1.43 (0.26–7.8)	0.680
2	1.15 (0.24–5.57)	0.866
Preoperative eGFR (mL/min/1.73 m^2)	0.92 (0.88–0.97)	0.002
Immediate postoperative eGFR	0.95 (0.91–0.99)	0.008
6-month postoperative eGFR	0.88 (0.84–0.93)	0.001
1-year postoperative eGFR	0.87 (0.83–0.92)	0.001
Preoperative creatinine	1.84 (0.33–10.27)	0.524
Immediate postoperative creatinine	1.74 (0.34–8.78)	0.521
6-month postoperative creatinine	5.22 (1.64–16.60)	0.005
1-year postoperative creatinine	5.36 (1.75–16.40)	0.003
R.E.N.A.L. score		
Low complexity	Ref.	
Intermediate complexity	1.78 (0.42–7.45)	0.431
High complexity	4.41 (1.05–18.58)	0.043
PostTKV	0.99 (0.99-1.0)	0.070
PostOKV	0.99 (0.98-1.0)	0.173
PreTKV ($n = 170$)	0.98 (0.96-1.0)	0.013
TotalTKV/BW	0.95 (0.93–0.97)	0.005

**Abbreviations*: *PostTKV* postoperative total kidney volume, *PostOKV* postoperative operated kidney volume, *eGFR* estimated glomerular filtration rate

CKD-free survival after on-clamp PN using variables including age, tumor size, presence of diabetes mellitus, sex, and preoperative eGFR in Korea. One of the primary goals of PN is to preserve postoperative renal function, while ensuring patient safety and achieving an oncological cure. Previous analyses showed that approximately 25% of patients with preoperative eGFR greater than 60 mL/min/1.73 m^2 progressed to CKD stage III or greater after PN [4]. Progression of CKD was found to increase the risk of cardiovascular disease and all-cause mortality [4, 5, 18]. Thus, if alternative treatment options are feasible, surgical approach should be determined with sufficient consideration of high-risk patients for CKD.

Recently, many studies have used CT or Magnetic Resonance Imaging (MRI) volumetry for predicting renal function after nephrectomy. Some studies have demonstrated that preoperative parenchymal or cortex volume on CT/MR renal volumetry estimated by three-dimensional image reconstruction can predict postoperative renal function in patients with RCC after PN [9, 19]. While volume and function are separate characteristics, CT volumetry is also a dependable method for estimating split kidney function (SKF) and predicting the post-donation function of the remaining kidney [20]. Parenchymal volume analysis using routine cross-sectional imaging has emerged as a reliable and practical tool to predict postoperative renal function, offering improved accuracy over nuclear renal [21]. Also, recent advances in AI-based modeling have demonstrated that fully automated approaches using CT-derived renal segmentation can accurately predict postoperative GFR, offering a scalable alternative to traditional clinical models [22].

Renal volume by CT/MR volumetry has become increasingly important for predicting renal function. However, studies using renal volume calculated by postoperative images are insufficient. After PN, the parenchymal volume of the operated ipsilateral kidney decreases while that of the contralateral kidney increases. Median parenchymal volume changes of the total kidney were approximately – 5% within 1 year after PN [13]. In the present study, operated ipsilateral or contralateral kidney volume was not a significant predictor of new-onset CKD development in univariate cox regression analysis, contrary to total kidney volume. This result might

Table 4 Comparisons of model A and model B in the values of prognosis prediction

Model	Log likelihood	Degrees of Freedom	χ^2	*p*-value
Model A	−55.069	3	-	-
Model B	−51.553	4	7.0318	0.008

Table 3 Multivariable analysis of factors associated with CKD

	Model A			Model B		
Predictors	Estimates	95% CI	p-value	Estimates	95% CI	p-value
AGE	1.07	1.01–1.14	0.024	1.06	1.00–1.12	0.058
HTN	3.19	0.96–10.57	0.058	4.21	1.20–14.81	0.025
preop eGFR	0.94	0.90–0.99	0.016	0.94	0.89–0.98	0.007
Kidney volume/BW * 10				0.95	0.91–0.99	0.020
C-index	0.875 (se = 0.044)			0.892 (se = 0.026)		

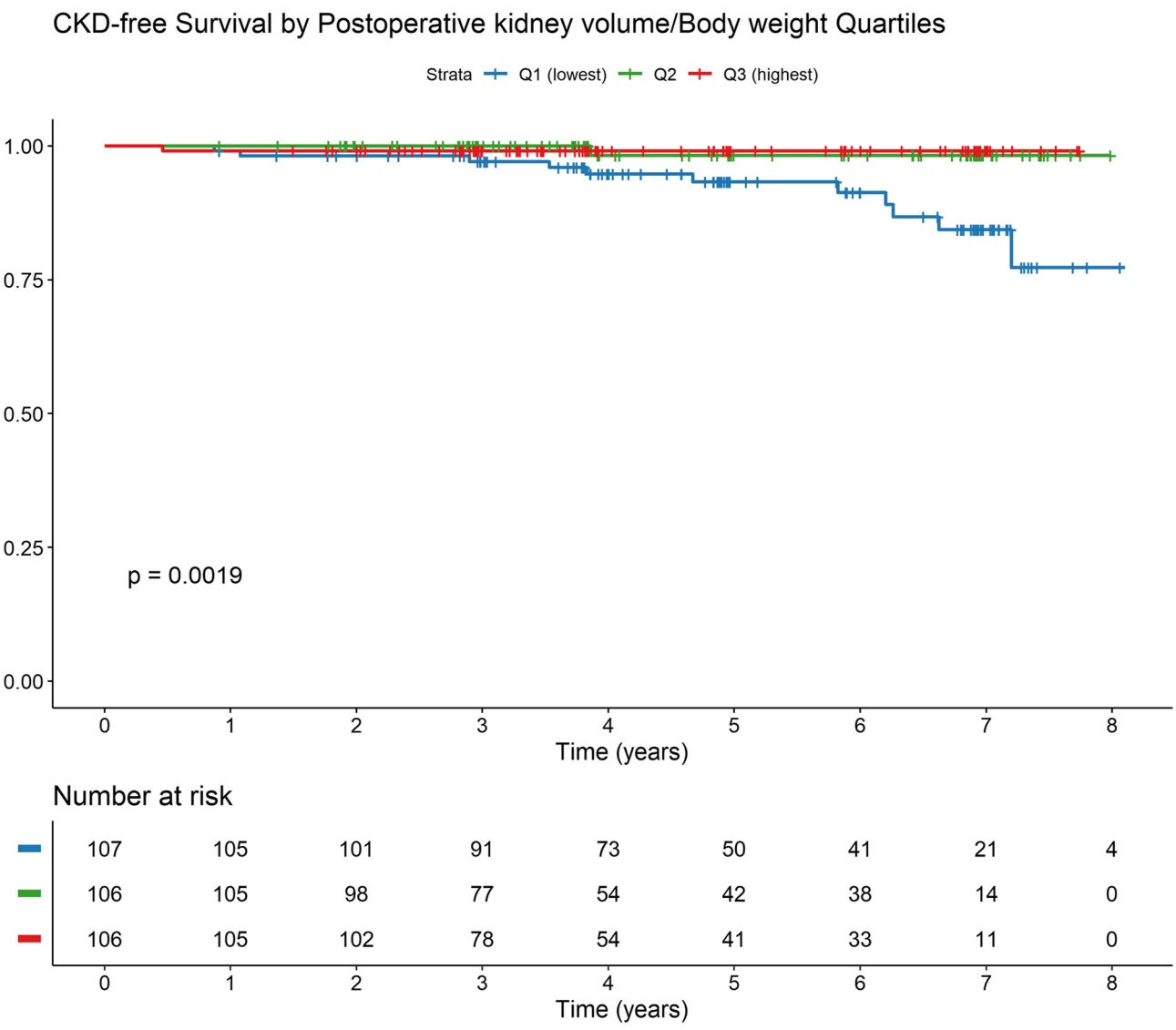

Fig. 4 Kaplan–Meier curves for CKD-free survival stratified by postoperative kidney volume per body weight tertiles. Patients in the lowest tertile (< 3.74 mL/kg) exhibited significantly worse CKD-free survival compared to those in the higher tertiles ($p = 0.0019$)

be explained because overall renal function was more reflected in the volume of the entire kidneys, not just one of the kidneys. Multiple contemporary studies have confirmed that renal functional decline after partial nephrectomy is driven primarily by loss of parenchymal volume, with ischemic and systemic factors playing a considerably lesser role [23–27]. Over the past decade, growing evidence has shifted the paradigm from ischemia duration to parenchymal volume preservation as the primary driver of renal functional recovery following partial nephrectomy [28].

While most previous studies have focused on how much renal volume was lost or preserved, our study demonstrates that the absolute postoperative volume of the entire kidney alone can serve as a significant predictor of CKD development.

The primary purpose of obtaining early postoperative imaging after partial nephrectomy (PN) is to evaluate surgical success and to detect potential recurrence or complications. However, in patients with pT1 tumors, the recurrence rate after PN is relatively low, approximately 2%, with a 3-year recurrence-free survival of nearly 99% and a median time to recurrence of 19 months [29, 30]. Moreover, while postoperative complications can include genitourinary, wound-related, and infectious events, their overall incidence is about 20%, and major complications occur in only 5.6%, with most arising within the first 30 postoperative days [31, 32]. Given the low likelihood of recurrence or complications during early follow-up, initial postoperative imaging can offer additional value beyond standard oncologic surveillance. Specifically, CT-based volumetric analysis may provide clinically

meaningful information regarding renal parenchymal volume, which, as demonstrated in our study, may serve as a surrogate marker for postoperative renal function. This highlights the dual role of postoperative imaging in offering both structural and functional insight after PN.

Our final cox proportional hazards model contained four variables, including first postoperative CT volumetry data. By examining the C-index and likelihood ratio test, it was found that the model had a better performance to predict CKD-free survival outcomes. Considering this, patients with smaller postoperative total kidney volume/kilogram body weight might need a more rigorous postoperative assessment and surveillance of renal function.

The present study has several limitations. First, since our study was retrospective in nature, confounding variables or selection bias might have an impact on the results. Second, this study had a single-center design, suggesting that results need to be validated by multi-center study with larger numbers of subjects. Third, the number of patients who developed CKD stage III or greater was low, which may limit the statistical power and increase the risk of overfitting. although the number of CKD events was limited, we addressed the risk of overfitting by using bootstrap-based internal validation and found that the optimism-corrected C-indices remained high (> 0.86). In addition, multicollinearity among variables was not significant (all VIFs < 2). However, penalized regression was not performed, which may be considered in future studies. Fourth, among a total of 319 study patients, only 170 preoperative CT scans were available. Of patients included in our study, nearly half of these patients were referred to our hospital for a small RCC. Because CT images taken from outside hospitals were different from ours and from each other in protocols such as dynamic phase, slice thickness, and multiplanar reformation, making a segmentation using preoperative CT scan might not be accurate or consistent.

Conclusions

Renal parenchymal volume of the first post-operative CT was a significant risk factor of postoperative CKD development on long-term follow-up in patients with T1 RCC and normal preoperative renal function after PN. Consequently, first post-operative imaging studies will help predict CKD development for long-term follow-up, assess the success of surgery, and monitor recurrence or complications. Based on these results, patients with smaller kidney volume should have a more rigorous postoperative assessment and surveillance of renal function.

Abbreviations

BMI	Body mass index
BW	Body weight
CKD	Chronic kidney disease
CT	Computed tomography
DM	Diabetes mellitus
eGFR	Estimated glomerular filtration rate
HTN	Hypertension
MRI	Magnetic Resonance Imaging
PN	Partial nephrectomy
RCC	Renal cell carcinoma
RN	Radical nephrectomy
TKV	Total kidney volume (including both operated and contralateral kidneys)
OKV	Operated kidney volume (ipsilateral to the tumor)

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12894-025-01907-3.

Supplementary Material 1.

Acknowledgements

Not applicable.

Authors' contributions

S.M.A.: Study conception, Data analysis/interpretation, Visualization, Writing - Original Draft.D.C.J.: Study conception, Methodology, Data acquisition, Writing - Review & Editing, Funding acquisition.M.H.M.: Data analysis/interpretation, Writing - Review & Editing.J.W.L.: Software, Data curation.K.H., Y.K.: Statistical analysis.All authors read and approved the final manuscript.

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Data availability

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

Declarations

Ethics approval and consent to participate

The study has been approved by the institutional review board of the Severance Hospital, South Korea (IRB No. 4-2020-0533) and it conforms to the provisions of the Declaration of Helsinki. The informed consent was waived due to the retrospective design of the study by the institutional review board of the Severance Hospital, South Korea.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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