

CT-BASED MORPHOMETRIC ANALYSIS OF RENAL PARENCHYMA FOR ASSESSMENT OF CHRONIC STRUCTURAL CHANGES AND CORRELATION WITH ESTIMATED GLOMERULAR FILTRATION RATE

Shakir ullah^{*1}, Aqsa Rao², Chanda Naeem³, Bilal Ahmad⁴, Amjad ali⁵, Asmat Ali⁶

^{*1,2,4,5,6}Department of Radiological Sciences and Medical Imaging Technology, Faculty of Allied Health Sciences, Superior University Lahore

³Assistant Professor, Department Emerging Health Professionals Sciences Technologies, Faculty of Allied Health Sciences, Superior University Lahore

¹shakirullah6762@gmail.com, ²aqsarao352@gmail.com, ³chanda.naseem@superior.edu.pk,

⁴bilalahmadsheikh41@gmail.com, ⁵amjadali143@gmail.com, ⁶aliasmat562@gmail.com

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Corresponding Author: *

Shakir ullah

Abstract

Background: Chronic kidney disease (CKD) is a progressive disorder in which structural damage to the renal parenchyma often precedes changes in biochemical markers such as the estimated glomerular filtration rate (eGFR). CT-based morphometry offers an objective, three-dimensional means of quantifying these structural changes.

Objective: The aim of this study was to evaluate chronic structural changes in the renal parenchyma using CT-based morphometric analysis and to correlate them with eGFR in patients with CKD.

Methodology: This cross-sectional analytical study was conducted at Chughtai Lab on 196 diagnosed CKD patients selected by convenient sampling. Renal length, cortical thickness and renal volume were measured bilaterally on non-contrast CT, and demographic and clinical data, including serum creatinine and eGFR, were obtained from medical records. Data were analysed in SPSS using descriptive statistics, Pearson correlation, one-way ANOVA, independent-samples t-tests and multiple linear regression, with a p-value < 0.05 considered significant.

Results: The mean age was 47.01 ± 18.22 years and the mean eGFR was 59.17 ± 26.02 mL/min/1.73 m². All morphometric parameters showed strong, significant positive correlations with eGFR ($p < 0.001$); renal volume demonstrated the strongest correlation (right $r = 0.976$; left $r = 0.978$), followed by renal length and cortical thickness. All parameters declined progressively across CKD stages I to IV (ANOVA, $p < 0.001$), and a regression model combining all six parameters explained 98.7% of the variance in eGFR ($R^2 = 0.987$).

Conclusion: CT-based renal morphometric parameters are strongly

correlated with eGFR and decline with advancing CKD, indicating that quantitative CT morphometry is a reliable, non-invasive imaging biomarker that can complement the biochemical assessment of renal function.

Chapter 1

INTRODUCTION

Chronic kidney disease (CKD) is one of the most important health problems worldwide, it is an ongoing decrease in kidney function and has structural or functional abnormalities in the kidneys that last for a period of more than three months. It is a condition that impacts about 9-10% of the world's population, and is linked with high mortality rates, morbidity, and health care costs [2].

The disease is also a significant independent risk factor for cardiovascular complications and progression to end-stage renal disease (ESRD) which requires renal replacement therapy (RRT), including dialysis or transplantation. Thus, early detection and correct estimation of the progression of CKD is of paramount importance for prompt intervention and better outcomes of patients [3].

Biochemical markers, such as serum creatinine, have traditionally been used to assess renal function and from which the estimated glomerular filtration rate (eGFR) is calculated. The eGFR is considered to be a good marker of kidney function and is applied to stage CKD. Biochemical values, however, offer scant clues to the structural changes in the renal parenchyma. Renal structural abnormalities (glomerulosclerosis, tubular atrophy and interstitial fibrosis) are frequently observed before marked biochemical abnormalities occur, making the need for imaging-based renal structural abnormalities, which can detect early changes in the kidneys, necessary. Marked biochemical abnormalities generally precede structural abnormalities, such as glomerular sclerosis, tubulointerstitial fibrosis and tubular atrophy, and thus the need for imaging-based structural renal abnormalities that can detect early changes in the kidneys.

Renal imaging is an important tool in the assessment of renal structure and disease. Common means of assessing renal size, shape and parenchymal characteristics include modalities such as ultrasonography (US), computed tomography (CT), and magnetic resonance imaging (MRI). Of these, ultrasonography is the most popular because it is easy to access and non-invasive. Some classic sonographic parameters like renal length and renal cortical thickness have been found to be correlated with renal function [4].

For example, research has shown a strong positive association of renal cortical thickness with eGFR suggesting that renal cortex thinning is a reflection of the decline in renal function. But these measurements are operator-dependent, sometimes lack reproducibility and may not reflect this complex 3D variation in renal morphology [2].

The computed tomographic (CT) imaging of the kidney has proven itself to be a very valuable tool for the detailed evaluation of the renal anatomy and morphology. High spatial resolution of CT and ability to measure renal dimensions, renal volume, and parenchymal characteristics precisely. In contrast to 2D measurements, CT-based morphometric analysis allows for more complete analysis of the kidney in 3D, and thus a more accurate evaluation of structural changes. The ability of CT to quantify small morphological changes, including surface area, surface area to volume ratio (SVR), sphericity and volume, has further improved and may be utilized as potential imaging biomarkers for the progression of CKD [8] [9].

There are microstructural and macrostructural changes in the morphology of CKD. The microstructural changes, such as glomerular sclerosis, tubular atrophy, and interstitial fibrosis, play a role in nephron loss and functional decline

[2][11].

Macroscopically, these alterations are seen as a decrease in kidney size, thinning of the cortex and changes in kidney shape. Several imaging-based studies have demonstrated that reduced renal length, renal cortical thickness, and decreased renal volume are all linked to a drop in eGFR. Simple linear measurements, however, like renal length, are less sensitive and specific as they fail to fully account for the intricate geometric alterations that occur in CKD [12].

In recent years, a number of studies have focused on the role of morphometric parameters from CT images in the assessment of renal structure and function. It has been shown that there is significant correlation between different morphological features and the eGFR in CT images by quantitative analysis. The volume and diameter of the kidneys, for instance, have been correlated with moderate-to-strong positive values with eGFR, and the surface-area-to-volume ratio has been correlated with strong negative values with eGFR, demonstrating that structural remodeling of the kidneys is closely related to functional decline. The results indicate that advanced morphometric parameters can be more accurate and reliable markers of the progression of the CKD than traditional markers [14].

The renal cortex also has an important effect on renal function, because it is the site of majority of the glomeruli involved in filtration. Thus, cortical volume and thickness are regarded as important markers of nephron mass and nephron function. The use of CT-based morphometric analysis in clinical practice has been shown to be associated with the renal function and studies have demonstrated that renal cortical volume, measured using CT correlates with nephron number. In addition, recent developments in the field of artificial intelligence (AI) and automated segmentation methods have enhanced the accuracy and efficiency of renal morphometric analysis, allowing for precise quantification of renal parenchyma and minimizing the observer effect. Moreover, recent progress in the area of artificial intelligence (AI) and automated

segmentation techniques have improved the accuracy and efficiency of renal morphometric analysis, enabled the precise quantification of renal parenchyma and minimizing the observer effect [18].

Although these achievements have been made, there are still some hurdles to overcome when using imaging to assess CKD. Inter-observer variability, lack of standardization and limited sensitivity for early structural changes are often problematic for traditional imaging parameters. Also, numerous studies have used two-dimensional measurements which may not fully reflect the full three-dimensional architecture of the kidney. The morphometric analysis by CT has overcome these drawbacks by offering objective, reproducible and quantitative measurements of renal morphology. The clinical utility of these more advanced parameters is less well established, however, and especially with regard to functional parameters like eGFR [12].

A second significant issue is that renal morphology varies according to demographic variables, such as age, sex and body habitus. Imaging studies have revealed that there is considerable individual variation in kidney size and volume which can affect the interpretation of imaging. Thus, it is important to determine population-specific reference values and standardized measurement procedures to ensure the proper evaluation of renal morphology [11].

The correlation between structural changes and the functional deterioration in nephrology and radiology is a major topic of interest. eGFR is the most commonly used indicator of renal function, but does not provide information about the underlying structural abnormalities. Combining morphometric imaging analysis with functional evaluation may provide a more comprehensive evaluation of CKD. This integrated approach could contribute to enhanced early diagnosis, surveillance and clinical decision making [12].

There has been increased interest in recent years in the use of radiomics and quantitative imaging within renal disease. Radiomics is the extraction of high-dimensional features from medical

images, which allows a detailed characterization of the properties and morphology of the tissue. In the setting of CKD, the use of radiomics analysis of computed tomography (CT) images has demonstrated potential for detection of imaging biomarkers that are associated with renal function and disease severity. These sophisticated technologies could aid in creating non-invasive diagnostic tools and predictive modelling for CKD [13].

With the growing prevalence of CKD and the lack of better data to accurately and reliably measure renal structure and function, there is a need for tools to overcome these limitations. CT based morphometric analysis is a promising technique to analyze chronic structural changes in renal parenchyma and their association with functional parameters like eGFR. This technique can generate detailed quantitative morphologic data of the kidney, which could help to better understand the pathophysiology of CKD and aid in management of patients with the disease.

Thus, the present study was undertaken to carry out morphometric analysis of renal parenchyma by computed tomography (CT) to assess chronic structural changes and to correlate them with estimated glomerular filtration rate (eGFR). The results of this study could help develop imaging biomarkers for CKD and integration of advanced imaging into clinical routine [19].

Chronic kidney disease (CKD) is a serious public health problem worldwide which is accelerating at an alarming rate and is a problem for millions of people in different age groups. The clinic presentation is characterized by the gradual, progressive and irreversible loss of renal function with structural abnormalities preserved for at least 3 months. The CKD pathophysiology is characterized by the gradual damage of the renal parenchyma and the progressive loss of renal function ultimately leads to systemic complications. This steady deterioration can eventually result in end-stage renal disease (ESRD) for which life-sustaining measures such as maintenance dialysis or renal transplantation are necessary [12].

The prevalence of CKD is now estimated to be between 9-10% of the world's population and is a major cause of morbidity and mortality. In addition to renal failure, CKD is an independent and powerful risk factor for rapid cardiovascular diseases, stroke and early death. The socio-economic impact of dealing with advanced kidney failure is immense and causes a significant burden on the health care system, especially in developing countries. Thus, it is imperative to establish reliable tools for early detection, staging and monitoring parenchymal remodeling in order to change the course of the disease [2].

The functional state of kidneys is mainly evaluated by conventional biochemical markers in clinical practice. The most common laboratory parameter used is serum creatinine, which is also used to determine the estimated glomerular filtration rate (eGFR). The eGFR is the key parameter to estimate the severity of kidney failure and to select the treatment. Serum creatinine is a late marker of renal injury, however, because it is not elevated until more than 50% of the functioning nephrons are totally destroyed [21].

This difference between the clinical functioning and the tissue pathology is a big diagnostic problem in nephrology. Significant biochemical changes rarely occur before structural changes, such as glomerulosclerosis, tubular atrophy, and interstitial fibrosis, develop and worsen. The use of eGFR alone may result in late therapeutic window, where interventions may be less effective due to irreversible scarring. Therefore, non-invasive imaging-based biomarkers that can identify early morphological changes are clinically needed [24].

To conclude, the biochemical assessment is the basis of the modern staging of CKD, but it does not have structural specificity for early diagnosis. This is overcome by advanced non-contrast CT-based morphometric and radiomic analysis, which can now generate non-invasive, objective and 3D tissue profiles. Still, there is a definite need for standardized approaches to track these

indices along with functional eGFR in clinical cohorts. Hence, the objective of the present study is to systematically evaluate the renal morphometric parameters obtained with CT and their correlation with eGFR, which will help in the validation of CT as a reliable diagnostic biomarker [10][22].

Rationale Of Study

Chronic kidney disease (CKD) is a progressive disease that involves functional decline and structural changes of the kidney parenchyma; however, assessment of CKD is currently largely based on estimated glomerular filtration rate (eGFR) which does not capture early structural changes. Structural impairment including cortical thinning and renal size reduction may occur without there being any significant changes in eGFR, potentially delaying diagnosis and intervention. Although there are conventional imaging techniques, such as ultrasonography, which are operator-dependent, they are also unable to provide detailed quantitative assessment. CT is a potential tool for studying renal structural changes as it can obtain high spatial resolution and accurate morphometric measurements. However, the relationship between morphometric parameters from CT and renal function is poorly studied. The aim of this study is to examine the correlation between renal morphometry derived from computed tomography (CT) and estimated glomerular filtration rate (eGFR) to identify reliable imaging biomarkers which could aid in the early detection of CKD, aid in monitoring the disease, and aid in a more comprehensive evaluation of CKD progression.

Objective

AIM AND OBJECTIVES

Primary Objective: To evaluate the structural changes of the renal parenchyma with morphometric analysis of CT images.

Secondary Objectives: To see the correlation between the morphometric parameters obtained by computed tomography (CT) and estimated

glomerular filtration rate (eGFR).

METHODOLOGY

3.1. Research Design: Cross-sectional analytical study

3.2. Clinical Settings: Chughtai Lab

3.3. Sample Size=196

$$n = \frac{(Z_{\alpha/2} + Z_{\beta})^2 \cdot (p(1-p))}{d^2}$$

$$n = \frac{(1.96 + 0.84)^2 \cdot (0.50 \cdot 0.50)}{0.1^2}$$

$$n = \frac{7.84 \cdot 0.25}{0.01} = 196$$

3.4. Sampling Technique: Convenient Sampling

3.5. Duration of Study= 4 months after synopsis approval

3.6. Selection Criteria

3.6.1. Inclusion Criteria

1. Diagnosed CKD patients
2. Age ≥ 18 years
3. Undergoing CT scan
4. Available eGFR data
5. Both genders

3.6.2. Exclusion Criteria

1. Acute kidney injury
2. Renal tumors
3. Congenital anomalies
4. Prior renal surgery
5. Poor image quality

6. 3.7. Ethical Consideration

The rules and regulations set by the ethical committee of Superior University was followed while conducting the research and rights of the research participants will be respected.

- Written informed consent (attached) was taken from all the participants.
- All information and data collection was kept confidential.
- Participants remained anonymous throughout the study.
- The subjects were informed that there are no disadvantages or risks on the procedure of the study.
- They were informed that they free to withdraw at any time during the process of the study.
- There were no known risks associated with this research.

We did everything we can to protect the patient's privacy. Their identity was revealed in any publication resulting from this study

3.8. Data Collection Procedure

All patients with chronic kidney disease (CKD) who had undergone non-contrast computed tomography (CT) scans during their clinical investigations were included in the study Data was). A non-probability convenient sampling technique was used to select eligible participants having specific inclusion criteria. Demographic information, such as age and gender, and clinical parameters like serum creatinine and estimated glomerular filtration rate (eGFR), were obtained from medical records. The retrieved CT images were meticulously examined and quantified using dedicated CT imaging software for assessing specific renal morphometric parameters. These parameters were taken, including accurate measurements of renal length, renal cortical thickness and renal volume. All imaging measurements were carried out under standard clinical conditions to ensure high consistency and strict reliability across the dataset.

3.9. Data Analysis

The data collected was compiled and statistically analyzed with the help of SPSS, a specialized

statistical software. Demographic and clinical data of the study population were summarized using descriptive statistics. The continuous variables were expressed as mean $\pm$ standard deviation and the categorical variables were expressed as absolute frequencies and percentages. The correlations between the morphometric parameters derived from the CT and the functional eGFR values were evaluated in a careful manner. Pearson or Spearman correlation coefficient was used respectively for the data that was normally or non-normally distributed. A p value <0.05 was accepted as statistically significant for all statistical evaluations carried out. Lastly, the results of the analyses were organized and displayed in detail in tables and graphical illustrations. This graphical presentation was used to effectively show the objective relationship between the structural and functional renal parameters. All statistical results were recorded systematically to allow for the main structural-functional correlation hypotheses of the research project to be investigated.

Chapter 4 RESULTS

A total of 196 patients with chronic kidney disease were included in the study, and their demographic and clinical characteristics are summarized in the tables and figures below. The mean age of the participants was 47.01 ± 18.22 years (range 20 to 80 years), and there was a slight female predominance, with 104 females (53.1%) and 92 males (46.9%), as shown in the gender frequency table and its bar chart. All 196 participants (100%) had a confirmed diagnosis of CKD. With regard to associated risk factors, hypertension was present in 95 patients (48.5%), diabetes mellitus in 90 (45.9%), obesity in 117 (59.7%), a smoking history in 92 (46.9%), a positive family history of CKD in 101 (51.5%) and a history of nephrotoxic drug use in 103 (52.6%), as presented in the respective frequency tables and accompanying bar charts. The mean duration of CKD was 5.58 ± 2.71 years (range 1 to 10 years). The mean serum creatinine was 3.04

± 1.30 mg/dL and the mean estimated glomerular filtration rate (eGFR) was 59.17 ± 26.02 mL/min/1.73 m² (range 11 to 100), with the corresponding histograms illustrating their distribution. According to CKD staging, 29 patients (14.8%) were in stage I, 71 (36.2%) in stage II, 58 (29.6%) in stage III, 29 (14.8%) in stage IV and 9 (4.6%) in stage V, as shown in the CKD stage table and bar chart.

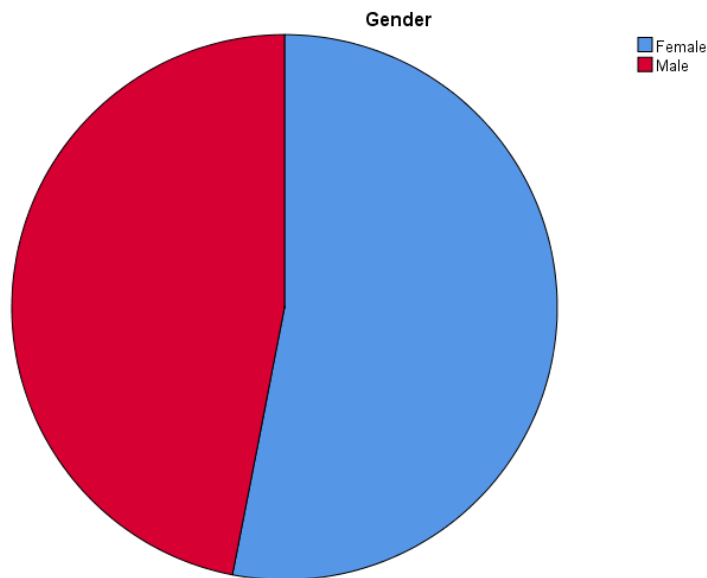
The descriptive statistics of the CT-based renal morphometric parameters are presented in the corresponding statistics tables and histograms. For the right kidney, the mean renal length was 10.79 ± 0.82 cm (range 9 to 12), the mean cortical thickness was 7.55 ± 1.60 mm (range 4 to 11) and the mean renal volume was 129.89 ± 27.25 cm³ (range 72 to 175). For the left kidney, the mean renal length was 10.78 ± 0.83 cm (range 9 to 12), the mean cortical thickness was 7.58 ± 1.70 mm (range 4 to 11) and the mean renal volume was 129.91 ± 26.84 cm³ (range 73 to 178). The histograms show an approximately normal distribution of these parameters and confirm the close similarity between the right and left kidneys. The one-way ANOVA (descriptives and ANOVA tables) demonstrated a progressive and statistically significant reduction in all morphometric parameters across CKD stages I to IV ($p < 0.001$ for every parameter). For example, the mean right renal volume fell from 164.80 cm³ in stage I to 93.28 cm³ in stage IV, and the right cortical thickness declined from 9.78 mm to 5.54

mm over the same range, indicating a clear stepwise structural deterioration with advancing disease.

The relationships between the morphometric parameters and eGFR are shown in the correlation tables. All parameters showed strong, positive and highly significant correlations with eGFR ($p < 0.001$). Renal volume demonstrated the strongest association (right $r = 0.976$; left $r = 0.978$), followed by renal length (right $r = 0.938$; left $r = 0.945$) and cortical thickness (right $r = 0.936$; left $r = 0.940$). The right and left kidneys were also strongly inter-correlated (length $r = 0.882$; cortex $r = 0.878$; volume $r = 0.955$). Independent-samples t-tests (T-Test tables) showed no statistically significant difference in cortical thickness between patients with and without diabetes ($p = 0.995$ for the right and $p = 0.919$ for the left cortex) or between those with and without hypertension ($p = 0.065$ for the right and $p = 0.207$ for the left cortex). Finally, a multiple linear regression model with eGFR as the dependent variable and all six morphometric parameters as predictors (regression tables) was highly significant ($F = 2361.85$, $p < 0.001$) and explained 98.7% of the variance in renal function ($R = 0.993$, $R^2 = 0.987$). Left and right renal volume were the strongest independent predictors ($\beta = 0.296$ and $\beta = 0.279$ respectively), and all six parameters contributed significantly to the model.

Table 4.1: Frequency distribution of study participants by gender

		Gender			
		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Female	104	53.1	53.1	53.1
	Male	92	46.9	46.9	100.0
	Total	196	100.0	100.0	



Statistics

Age	N	Valid	196
		Missing	0
	Mean		47.01
	Std. Deviation		18.219
	Minimum		20
	Maximum		80

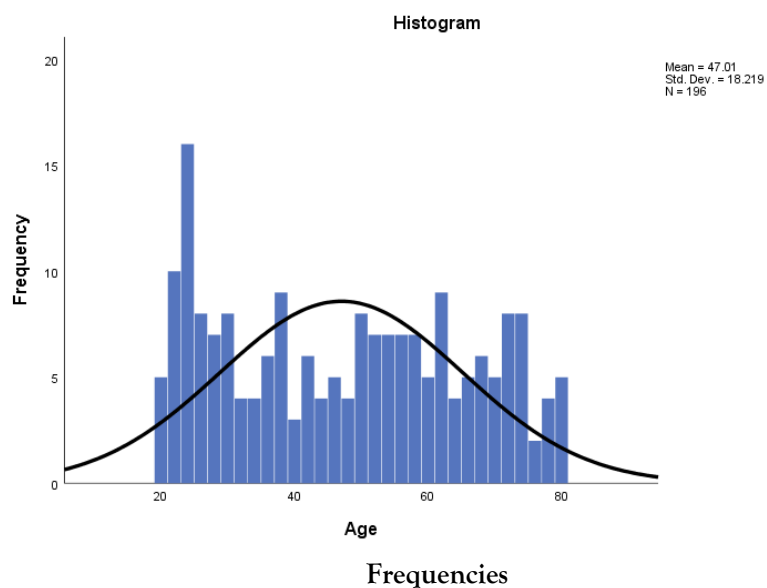


Table 4.3: Frequency distribution of confirmed CKD diagnosis

		CKD			Cumulative Percent
		Frequency	Percent	Valid Percent	
Valid	Yes	196	100.0	100.0	100.0

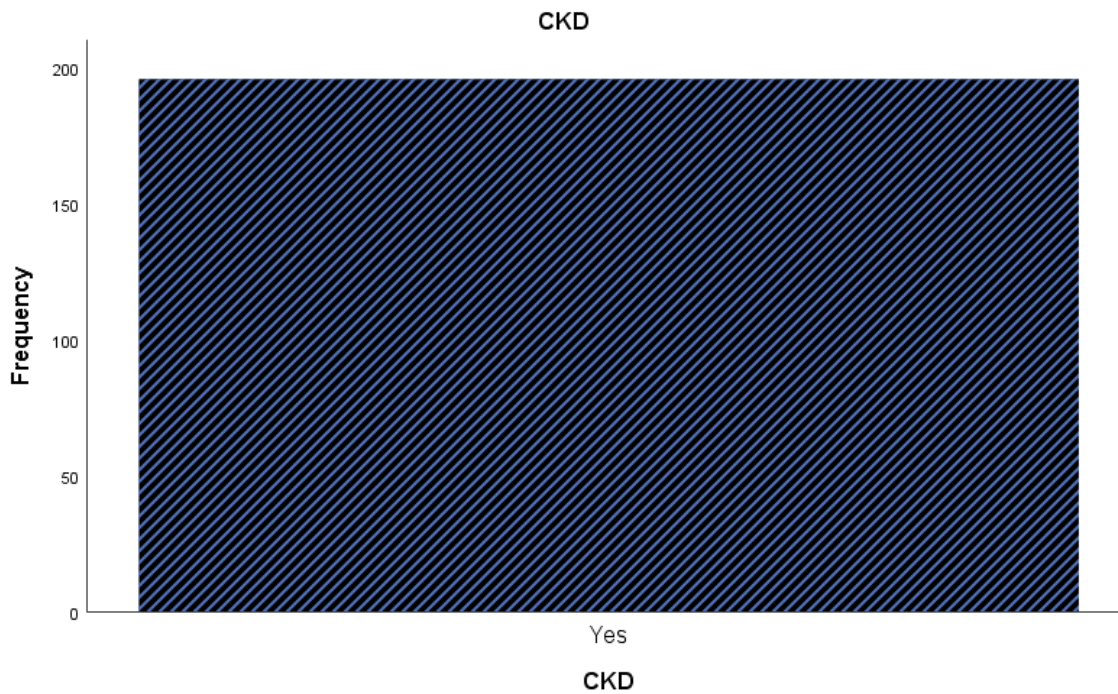


Table 4.4: Frequency distribution of hypertension among the participants

		Hypertension			Cumulative Percent
		Frequency	Percent	Valid Percent	
Valid	Yes	95	48.5	48.5	48.5
	No	101	51.5	51.5	100.0
	Total	196	100.0	100.0	

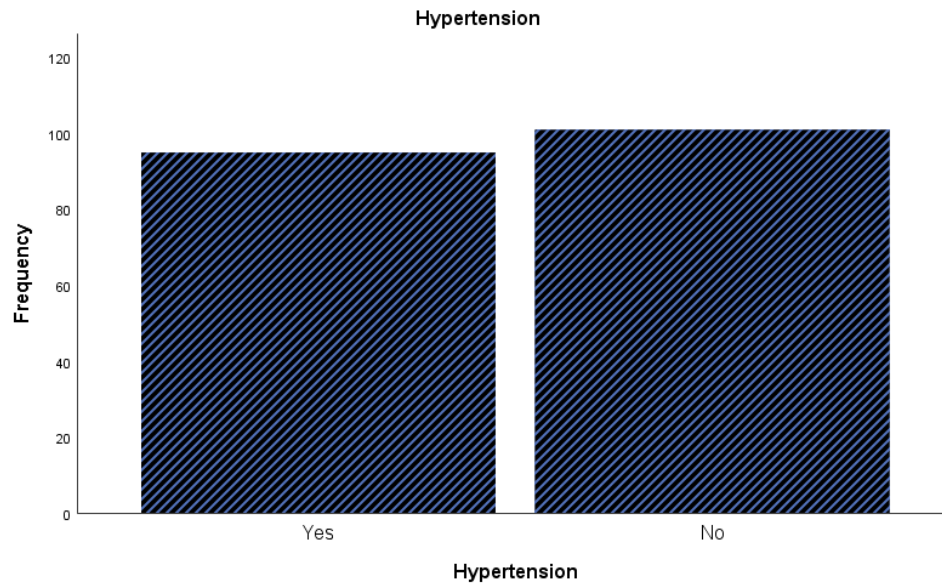


Table 4.5: Frequency distribution of diabetes mellitus among the participants

		Diabetes			
		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Yes	90	45.9	45.9	45.9
	No	106	54.1	54.1	100.0
	Total	196	100.0	100.0	

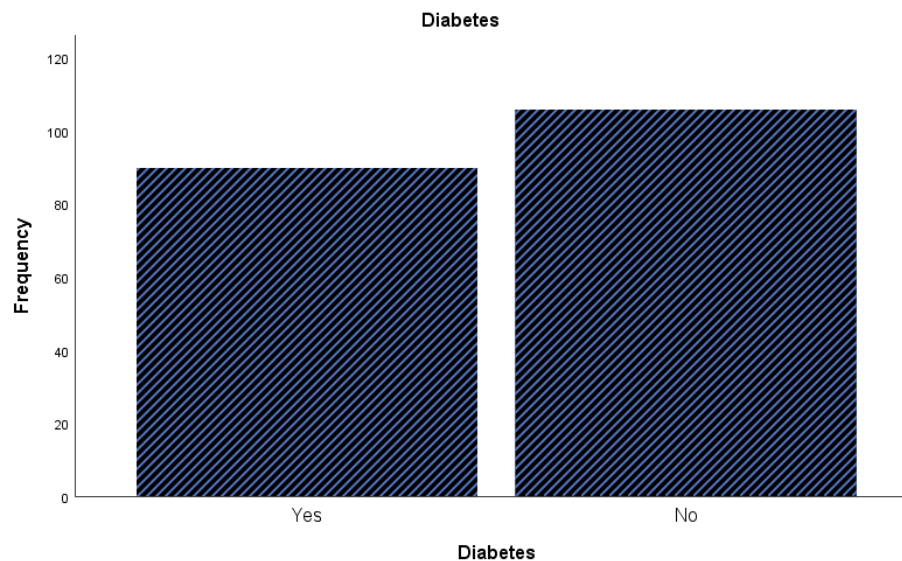


Table 4.6: Frequency distribution of obesity among the participants

		Obesity			
		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Yes	117	59.7	59.7	59.7
	No	79	40.3	40.3	100.0
	Total	196	100.0	100.0	

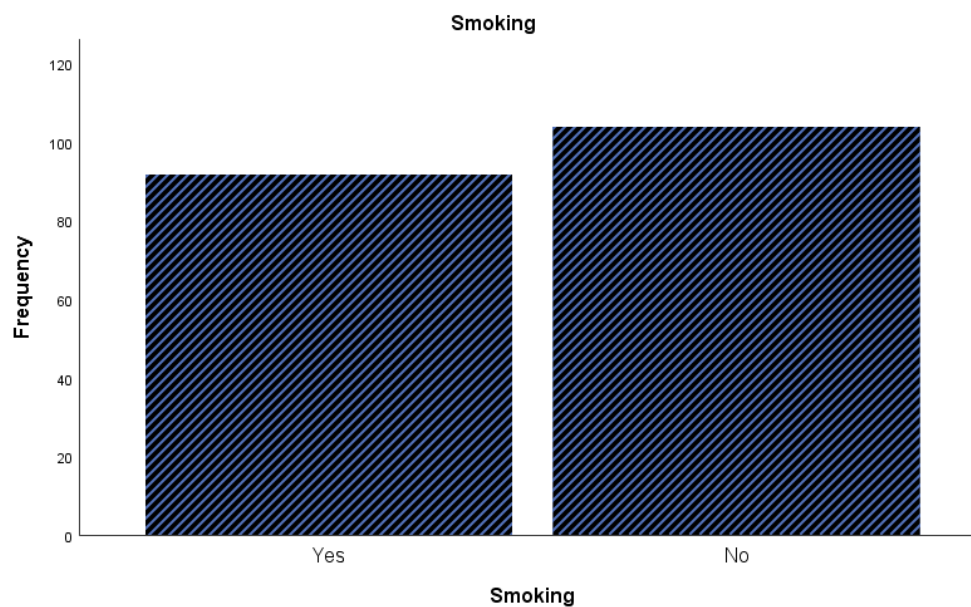


Table 4.7: Frequency distribution of smoking history among the participants

		Smoking			
		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Yes	92	46.9	46.9	46.9
	No	104	53.1	53.1	100.0
	Total	196	100.0	100.0	

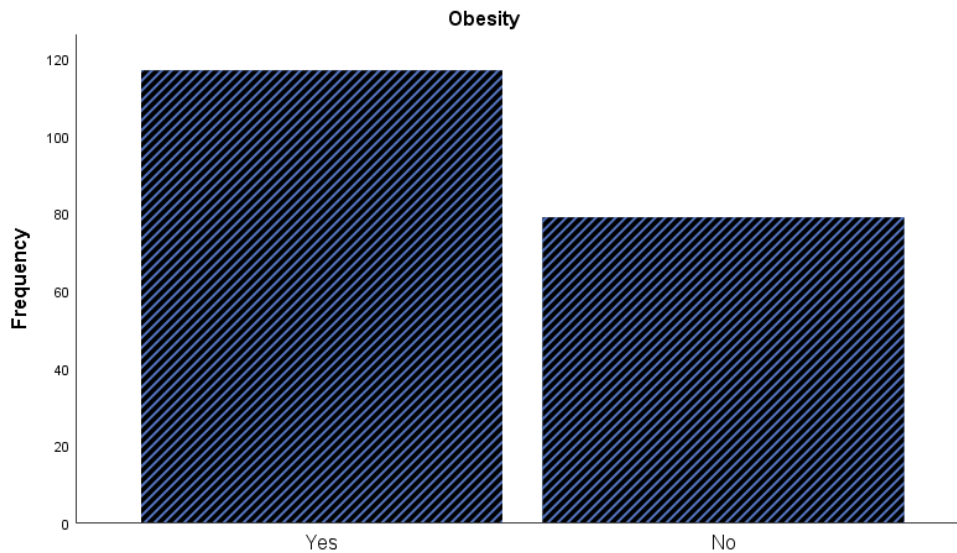


Table 4.8: Frequency distribution of family history of CKD

		Family_History			
		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Yes	101	51.5	51.5	51.5
	No	95	48.5	48.5	100.0
	Total	196	100.0	100.0	

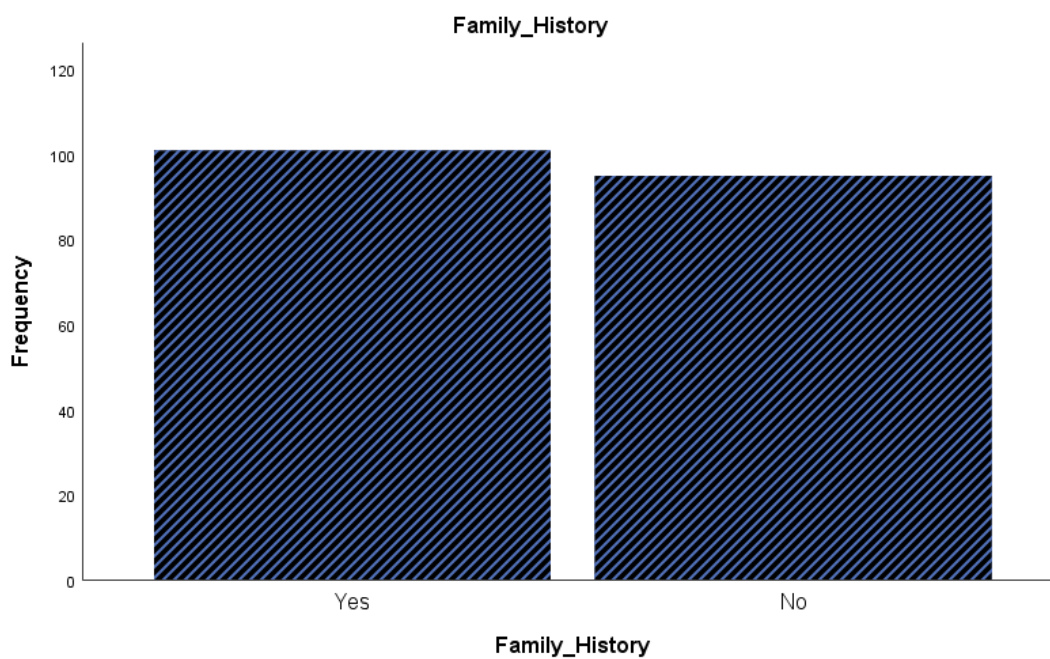


Table 4.9: Frequency distribution of nephrotoxic drug use

		Nephrotoxic_Drugs			Cumulative Percent
		Frequency	Percent	Valid Percent	
Valid	Yes	103	52.6	52.6	52.6
	No	93	47.4	47.4	100.0
	Total	196	100.0	100.0	

Bar Chart

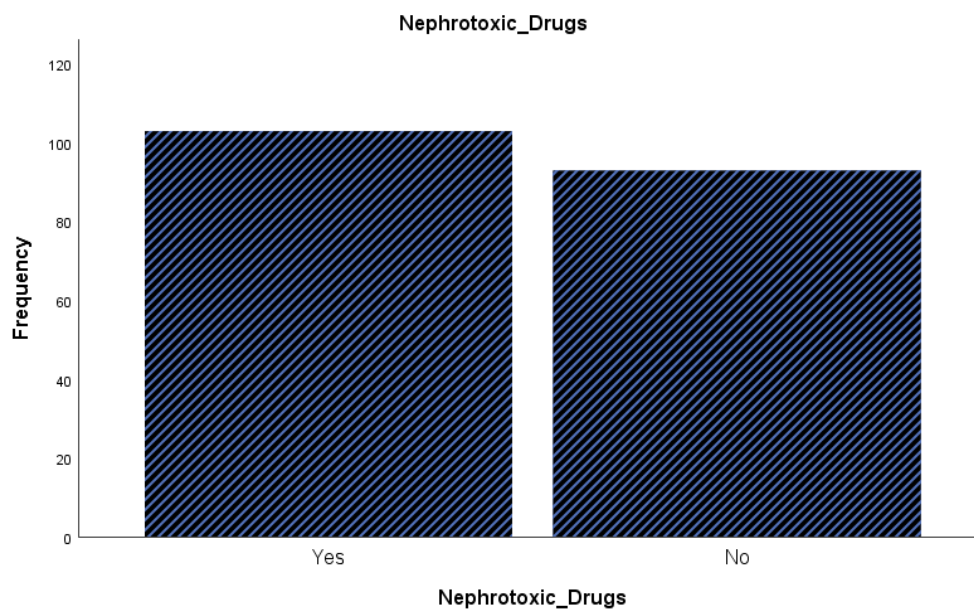


Table 4.10: Descriptive statistics for duration of CKD (years)

		Statistics	
		Duration_years	
N	Valid	196	
	Missing	0	
Mean		5.58	
Std. Deviation		2.707	
Minimum		1	
Maximum		10	

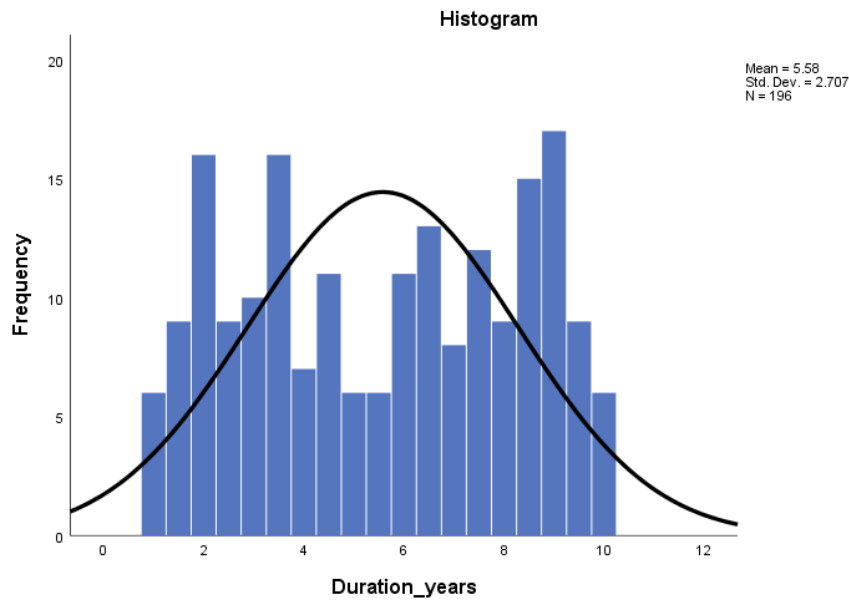
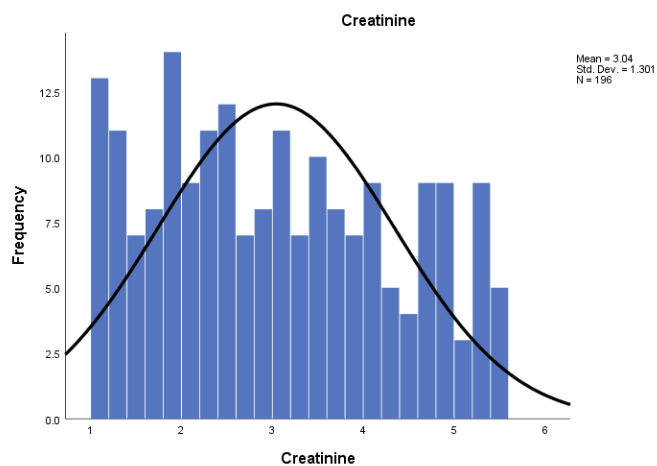


Table 4.11: Descriptive statistics for serum creatinine and eGFR

Statistics

		Creatinine	eGFR
N	Valid	196	196
	Missing	0	0
Mean		3.04	59.17
Std. Deviation		1.301	26.016
Minimum		1	11
Maximum		5	100

Histogram



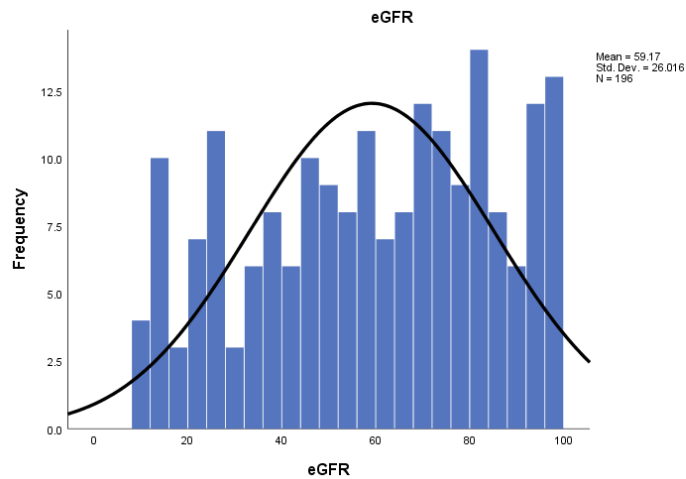


Table 4.12: Frequency distribution of participants by CKD stage

		CKD_Stage			
		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	I	29	14.8	14.8	14.8
	II	71	36.2	36.2	51.0
	III	58	29.6	29.6	80.6
	IV	29	14.8	14.8	95.4
	V	9	4.6	4.6	100.0
	Total	196	100.0	100.0	

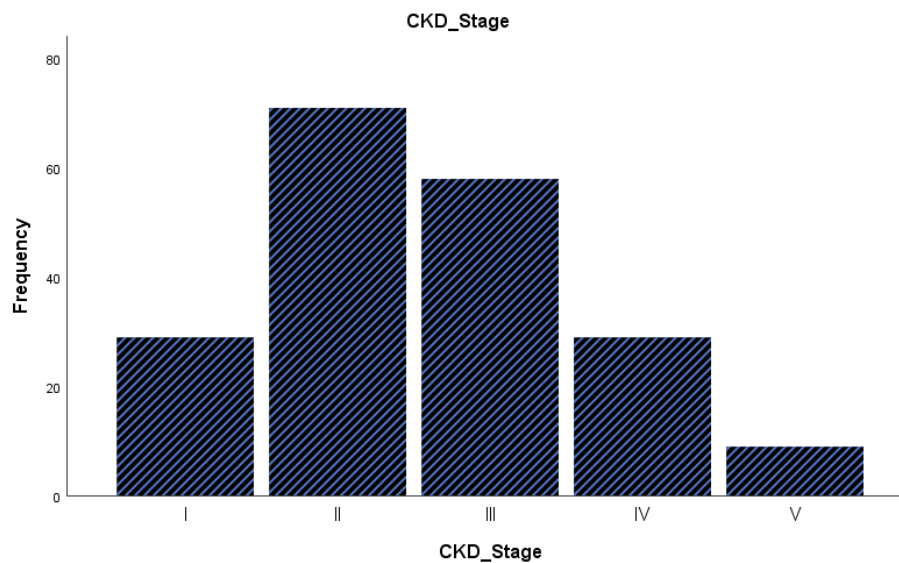
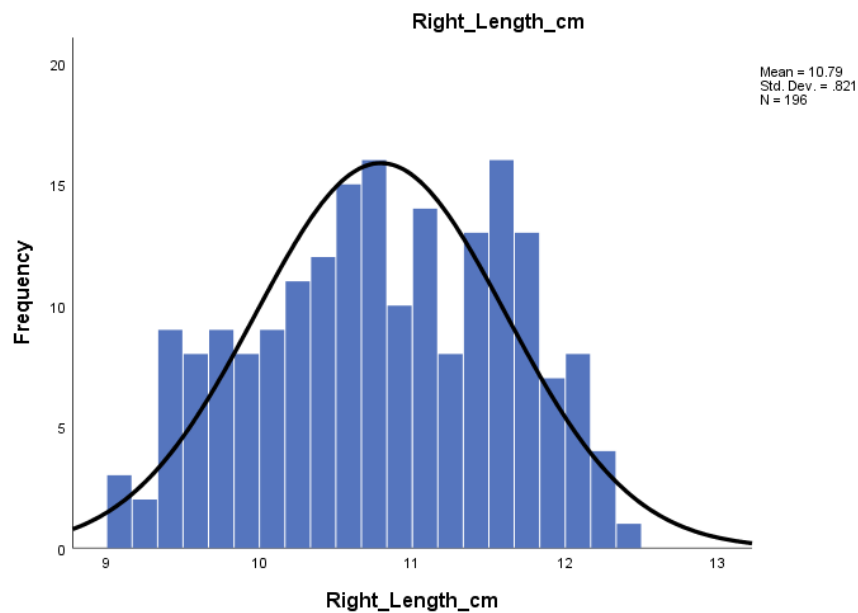


Table 4.13: Descriptive statistics for right kidney morphometric parameters

Statistics		Right_Length_cm	Cortex_Right_m	Volume_Right_c
N	Valid	196	196	196
	Missing	0	0	0
Mean		10.79	7.55	129.89
Std. Deviation		.821	1.595	27.254
Minimum		9	4	72
Maximum		12	11	175

Histogram



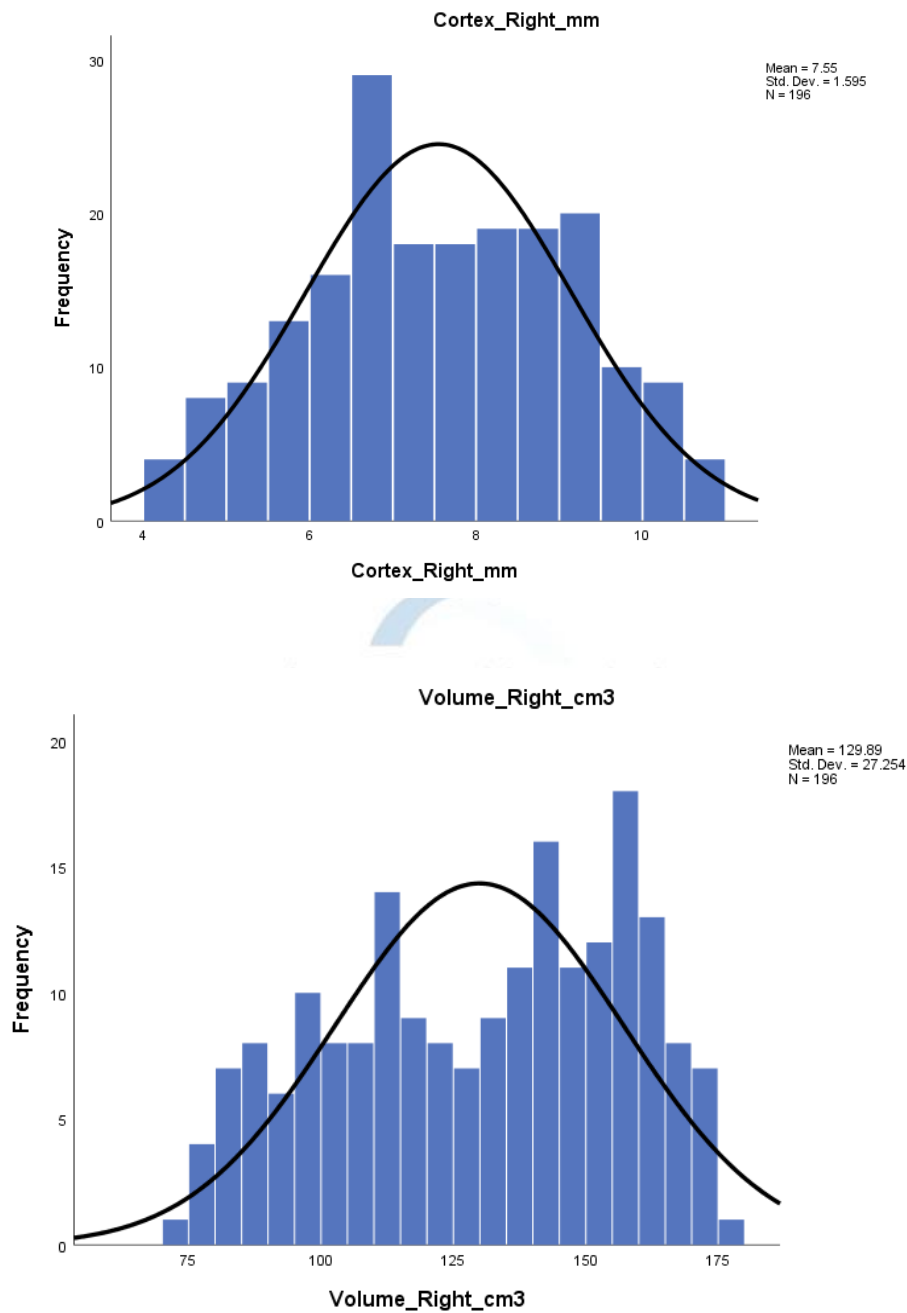
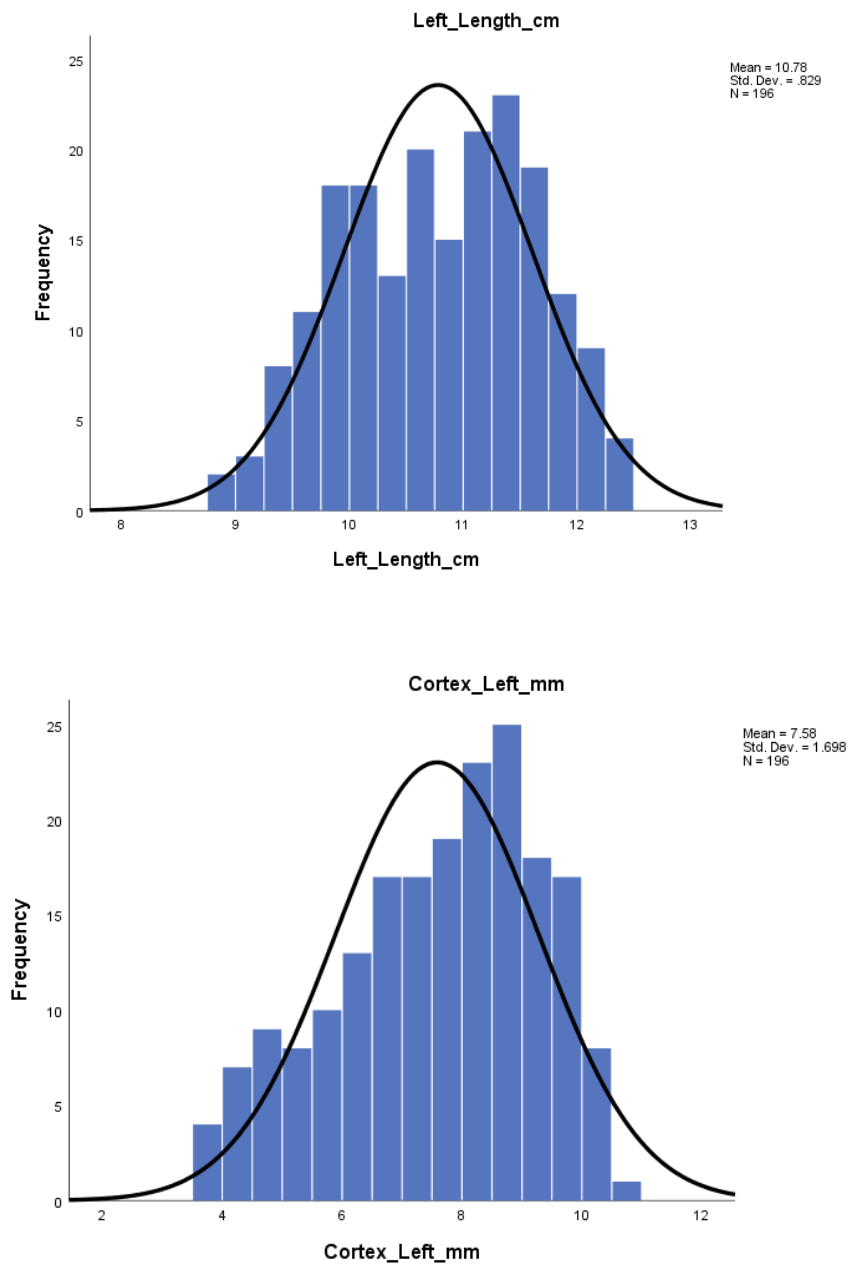


Table 4.14: Descriptive statistics for left kidney morphometric parameters

Statistics		Left Length_cm	Cortex_Left_mm	Volume_Left_cm3
N	Valid	196	196	196
	Missing	0	0	0
Mean		10.78	7.58	129.91

Std. Deviation	.829	1.698	26.839
Minimum	9	4	73
Maximum	12	11	178

Histogram



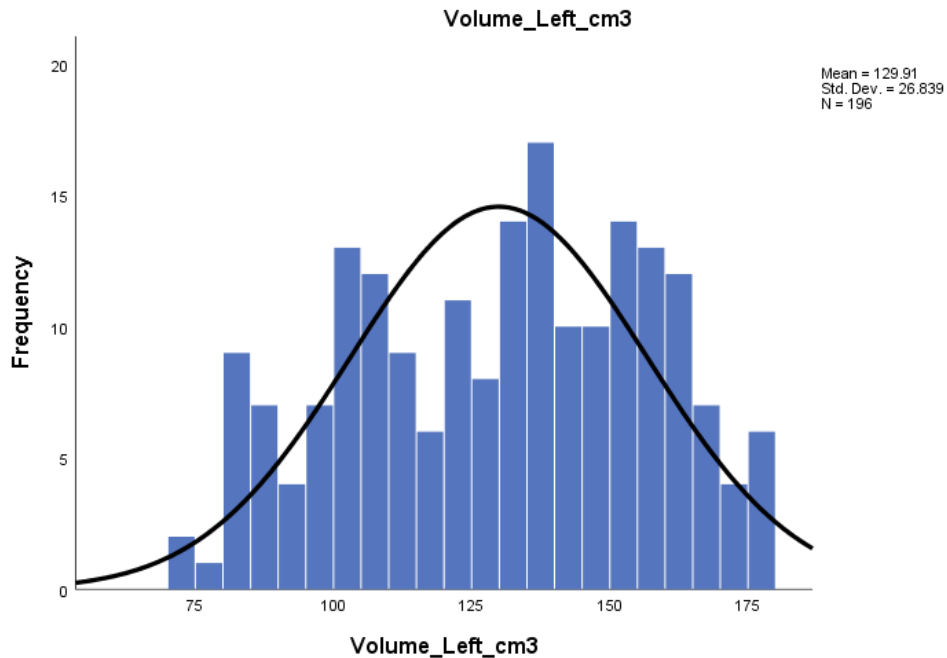


Table 4.15: Correlation of renal length (right and left) with eGFR

		Correlations		
		eGFR	Right_Length_cm	Left_Length_cm
eGFR	Pearson Correlation	1	.938**	.945**
	Sig. (2-tailed)		.000	.000
	N	196	196	196
Right_Length_cm	Pearson Correlation	.938**	1	.882**
	Sig. (2-tailed)	.000		.000
	N	196	196	196
Left_Length_cm	Pearson Correlation	.945**	.882**	1
	Sig. (2-tailed)	.000	.000	
	N	196	196	196

Correlation is significant at the 0.01 level (2-tailed).

Table 4.16: Correlation of cortical thickness (right and left) with eGFR

		Correlations		
		eGFR	Cortex_Right_m	Cortex_Left_mm
eGFR	Pearson Correlation	1	.936**	.940**
	Sig. (2-tailed)		.000	.000
	N	196	196	196
Cortex_Right_mm	Pearson Correlation	.936**	1	.878**
	Sig. (2-tailed)	.000		.000

	N	196	196	196
Cortex_Left_mm	Pearson Correlation	.940**	.878**	1
	Sig. (2-tailed)	.000	.000	
	N	196	196	196

Correlation is significant at the 0.01 level (2-tailed).

Table 4.17: Correlation of renal volume (right and left) with eGFR

Correlations

		eGFR	Volume_Right_cm3	Volume_Left_cm3
eGFR	Pearson Correlation	1	.976**	.978**
	Sig. (2-tailed)		.000	.000
	N	196	196	196
Volume_Right_cm3	Pearson Correlation	.976**	1	.955**
	Sig. (2-tailed)	.000		.000
	N	196	196	196
Volume_Left_cm3	Pearson Correlation	.978**	.955**	1
	Sig. (2-tailed)	.000	.000	
	N	196	196	196

Correlation is significant at the 0.01 level (2-tailed).

Table 4.18: Descriptive statistics of morphometric parameters across CKD stages I-IV

Descriptives

		N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
Right_Length_cm	1	29	11.86	.311	.058	11.74	11.98	11	12
	2	71	11.27	.386	.046	11.18	11.36	11	12
	3	58	10.41	.369	.048	10.31	10.51	10	11
	4	29	9.73	.352	.065	9.60	9.87	9	10
	Total	187	10.86	.784	.057	10.74	10.97	9	12
Left_Length_cm	1	29	11.90	.290	.054	11.79	12.01	11	12
	2	71	11.23	.374	.044	11.14	11.32	10	12
	3	58	10.43	.379	.050	10.33	10.53	10	11
	4	29	9.68	.328	.061	9.55	9.80	9	10
	Total	187	10.84	.789	.058	10.73	10.96	9	12
Cortex_Right_mm	1	29	9.78	.605	.112	9.55	10.02	9	11
	2	71	8.41	.732	.087	8.24	8.58	7	10
	3	58	6.81	.540	.071	6.67	6.96	6	8
	4	29	5.54	.712	.132	5.26	5.81	4	7
	Total	187	7.68	1.506	.110	7.47	7.90	4	11
Cortex_Left_mm	1	29	9.70	.502	.093	9.51	9.89	9	11

	2	71	8.59	.614	.073	8.45	8.74	7	10
	3	58	6.94	.790	.104	6.73	7.15	5	8
	4	29	5.27	.811	.151	4.96	5.57	4	7
	Total	187	7.74	1.582	.116	7.51	7.96	4	11
Volume_Right_cm3	1	29	164.80	5.724	1.063	162.63	166.98	155	175
	2	71	147.83	9.122	1.083	145.67	149.99	128	168
	3	58	116.61	10.353	1.359	113.88	119.33	94	137
	4	29	93.28	7.492	1.391	90.44	96.13	80	108
	Total	187	132.32	25.464	1.862	128.64	135.99	80	175
Volume_Left_cm3	1	29	166.32	7.114	1.321	163.62	169.03	153	178
	2	71	146.10	9.537	1.132	143.84	148.36	125	168
	3	58	117.22	10.470	1.375	114.47	119.98	97	135
	4	29	94.40	7.701	1.430	91.47	97.33	82	106
	Total	187	132.26	25.149	1.839	128.63	135.89	82	178

Table 4.19: One-way ANOVA of morphometric parameters across CKD stages

		ANOVA				
		Sum of Squares	df	Mean Square	F	Sig.
Right_Length_cm	Between Groups	90.000	3	30.000	225.232	.000
	Within Groups	24.375	183	.133		
	Total	114.375	186			
Left_Length_cm	Between Groups	92.509	3	30.836	241.582	.000
	Within Groups	23.359	183	.128		
	Total	115.868	186			
Cortex_Right_mm	Between Groups	343.212	3	114.404	266.427	.000
	Within Groups	78.580	183	.429		
	Total	421.792	186			
Cortex_Left_mm	Between Groups	377.969	3	125.990	263.612	.000
	Within Groups	87.462	183	.478		
	Total	465.431	186			
Volume_Right_cm3	Between Groups	106184.208	3	35394.736	449.071	.000
	Within Groups	14423.624	183	78.818		
	Total	120607.832	186			
Volume_Left_cm3	Between Groups	101943.238	3	33981.079	396.250	.000
	Within Groups	15693.477	183	85.757		
	Total	117636.715	186			

T-Test

Table 4.20: Group statistics for cortical thickness by diabetes status

Group Statistics					
	Diabetes	N	Mean	Std. Deviation	Std. Error Mean
Cortex_Right_mm	Yes	90	7.55	1.579	.166
	No	106	7.55	1.616	.157
Cortex_Left_mm	Yes	90	7.60	1.734	.183
	No	106	7.57	1.675	.163

Table 4.21: Independent-samples t-test for cortical thickness by diabetes status

Independent Samples Test										
		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
Cortex_Right_mm	Equal variances assumed	.091	.764	-.006	194	.995	-.001	.229	-.453	.451
	Equal variances not assumed			-.006	190.179	.995	-.001	.229	-.453	.450
Cortex_Left_mm	Equal variances assumed	.057	.812	.102	194	.919	.025	.244	-.456	.506
	Equal variances not assumed			.102	186.600	.919	.025	.245	-.458	.508

T-Test

Table 4.22: Group statistics for cortical thickness by hypertension status

Group Statistics					
	Hypertension	N	Mean	Std. Deviation	Std. Error Mean
Cortex_Right_mm	1	95	7.77	1.604	.165
	2	101	7.35	1.567	.156

Cortex_Left_mm	1	95	7.74	1.666	.171
	2	101	7.44	1.723	.171

Table 4.23: Independent-samples t-test for cortical thickness by hypertension status

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference		Lower	Upper
Cortex_Right_mm	Equal variances assumed	.058	.810	1.854	194	.065	.420	.227		-.027	.867
	Equal variances not assumed			1.852	192.616	.066	.420	.227		-.027	.867
Cortex_Left_mm	Equal variances assumed	.225	.635	1.267	194	.207	.307	.242		-.171	.785
	Equal variances not assumed			1.269	193.850	.206	.307	.242		-.170	.784

REGRESSION

Table 4.24: Variables entered/removed in the multiple linear regression model

Variables Entered/Removed^a

Model	Variables Entered	Variables Removed	Method
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1	Volume_Left_cm3, Cortex_Right_mm , Left_Length_cm, Cortex_Left_mm, Right_Length_cm, Volume_Right_cm 3 ^b	.	Enter
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a. Dependent Variable: eGFR

b. All requested variables entered.

Table 4.25: Model summary of the multiple linear regression predicting eGFR

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.993 ^a	.987	.986	3.032

a. Predictors: (Constant), Volume_Left_cm3, Cortex_Right_mm, Left_Length_cm, Cortex_Left_mm, Right_Length_cm, Volume_Right_cm3

Table 4.26: ANOVA for the multiple linear regression model

ANOVA^a

Model	Sum of Squares	df	Mean Square	F	Sig.
1 Regression	130243.855	6	21707.309	2361.845	.000 ^b
Residual	1737.066	189	9.191		
Total	131980.921	195			

a. Dependent Variable: eGFR

b. Predictors: (Constant), Volume_Left_cm3, Cortex_Right_mm, Left_Length_cm, Cortex_Left_mm, Right_Length_cm, Volume_Right_cm3

Table 4.27: Regression coefficients for prediction of eGFR from morphometric parameters

Coefficients ^a						
Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-116.492	7.194		-16.193	.000
	Right_Length_cm	2.104	.763	.066	2.757	.006
	Left_Length_cm	5.011	.724	.160	6.927	.000
	Cortex_Right_mm	1.956	.367	.120	5.337	.000
	Cortex_Left_mm	1.614	.358	.105	4.510	.000
	Volume_Right_cm3	.267	.032	.279	8.336	.000
	Volume_Left_cm3	.287	.033	.296	8.612	.000

a. Dependent Variable: eGFR

Chapter 5**DISCUSSION**

The present cross-sectional analytical study was conducted to evaluate chronic structural changes in the renal parenchyma using computed tomography (CT)-based morphometric analysis and to determine their correlation with the estimated glomerular filtration rate (eGFR) in 196 patients with chronic kidney disease (CKD). The principal finding of this study is that all measured morphometric parameters, namely bilateral renal length, cortical thickness and renal volume, showed strong, statistically significant positive correlations with eGFR, and that these structural measurements declined progressively across advancing CKD stages. These observations support the central hypothesis that quantitative CT morphometry reflects the functional status of the kidney and can serve as a reliable, non-invasive imaging biomarker of disease severity [41].

The study population had a mean age of 47.01 ± 18.22 years with a modest female predominance (53.1%) and a mean eGFR of 59.17 ± 26.02 mL/min/1.73 m², indicating a cohort that spanned the full spectrum of CKD from early to advanced disease (stages I to V). The relatively even distribution of traditional risk factors, including hypertension (48.5%), diabetes mellitus (45.9%), obesity (59.7%) and a positive family history (51.5%), is consistent with the multifactorial aetiology of CKD reported in South Asian populations and reinforces the applicability of the findings to routine nephrology practice [44,45,46].

Among all the parameters, renal volume demonstrated the strongest association with renal function, with Pearson correlation coefficients of $r = 0.976$ for the right kidney and $r = 0.978$ for the left kidney ($p < 0.001$). This finding is biologically plausible because renal volume integrates changes in all three dimensions of the kidney and therefore captures the cumulative effect of nephron loss, cortical thinning and parenchymal atrophy that characterise progressive CKD. The superiority of volumetric

measurement over simple linear dimensions is in agreement with earlier CT-based work, which reported that three-dimensional volumetric indices correlate more closely with nephron mass and eGFR than two-dimensional measurements [33,34,43]. The present results extend this literature by confirming the relationship in a moderately sized, single-centre cohort using standardised measurement conditions [43].

Renal length also correlated strongly with eGFR (right $r = 0.938$; left $r = 0.945$), as did cortical thickness (right $r = 0.936$; left $r = 0.940$). The strong correlation of cortical thickness is particularly noteworthy because the renal cortex houses the majority of functioning glomeruli, and cortical thinning is an early macroscopic manifestation of the underlying microstructural changes, such as glomerulosclerosis, tubular atrophy and interstitial fibrosis, that drive functional decline [35,36]. The near-symmetry of the correlation coefficients between the right and left kidneys, together with the high inter-renal correlations (length $r = 0.882$; cortex $r = 0.878$; volume $r = 0.955$), indicates that CKD affects both kidneys in a broadly symmetrical fashion, which is consistent with the diffuse, systemic nature of most chronic nephropathies [35].

The one-way analysis of variance demonstrated a highly significant, stepwise reduction in every morphometric parameter across CKD stages I to IV ($p < 0.001$ for all comparisons). Mean right renal volume, for example, fell from 164.80 cm³ in stage I to 93.28 cm³ in stage IV, while right cortical thickness declined from 9.78 mm to 5.54 mm over the same range. This graded structural deterioration mirrors the progressive functional loss captured by eGFR staging and provides internal validation of the morphometric approach: the parameters not only correlate with a continuous measure of function but also discriminate between clinically defined disease categories. Such stage-wise separation suggests that CT morphometry could complement biochemical staging and potentially identify structural progression before large changes in serum creatinine become apparent [41,50].

To assess the combined predictive value of the morphometric parameters, a multiple linear regression model was constructed with eGFR as the dependent variable. The model explained an exceptionally high proportion of the variance in renal function ($R = 0.993$, $R^2 = 0.987$; $F = 2361.85$, $p < 0.001$), and all six predictors contributed significantly. The standardised coefficients confirmed that left and right renal volume ($\beta = 0.296$ and $\beta = 0.279$ respectively) were the dominant contributors, followed by renal length and cortical thickness. This reinforces the univariate findings and indicates that a composite morphometric assessment, dominated by volumetric data, provides a robust estimate of renal function. While an R^2 of this magnitude should be interpreted with caution in the context of a single-centre dataset, it nonetheless underscores the close structural-functional coupling that exists in CKD [31,32].

In contrast to the strong structure-function relationships, the presence of hypertension or diabetes mellitus was not associated with a statistically significant difference in cortical thickness (hypertension: $p = 0.065$ and 0.207 for the right and left cortex; diabetes: $p = 0.995$ and 0.919). This suggests that, within this cohort, cortical thinning was more closely determined by the overall stage and duration of CKD than by the specific presence of these individual comorbidities. A plausible explanation is that the structural consequences of hypertension and diabetes are already integrated into the eGFR-defined stage by the time patients present for CT, so that these risk factors influence morphology indirectly rather than acting as independent determinants of cortical thickness. This observation should nevertheless be interpreted cautiously, given the cross-sectional design and the absence of adjustment for disease duration and for glycaemic or blood-pressure control [49].

The findings of this study are consistent with, and add to, a growing body of literature exploring quantitative CT and radiomic assessment of the kidney. Previous investigators have shown that CT radiomic signatures can differentiate early

CKD stages from healthy controls, correlate with histopathological fibrosis, and predict baseline renal function in large cohorts. Whereas much of that work has relied on complex radiomic feature extraction and machine-learning pipelines that require specialised software and are sensitive to inter-scanner variability, the present study demonstrates that relatively simple, directly measurable morphometric parameters, namely length, cortical thickness and volume, retain strong correlations with eGFR. This is clinically important because such measurements can be obtained on routine CT workstations without proprietary tools, which makes the approach more readily translatable to everyday radiological practice, particularly in resource-limited settings [1,2,7,31].

The mechanistic basis of the observed structure-function relationship lies in the progressive loss of functioning nephrons that defines CKD. As nephrons are lost, the remaining glomeruli undergo compensatory hyperfiltration and eventual sclerosis, while the tubulointerstitial compartment is progressively replaced by fibrosis. These microscopic processes manifest macroscopically as a reduction in cortical thickness and in overall renal volume, because the cortex contains the bulk of the nephron mass. The strong correlation between cortical thickness and eGFR observed in this study is therefore an imaging reflection of nephron depletion, and the even stronger correlation of renal volume is consistent with volume being the most complete surrogate of total functioning renal tissue. This interpretation aligns with histological studies that have linked cortical volume to nephron number, and it helps to explain why the volumetric indices outperformed the simple linear measurements in the present analysis [40,43].

It is also worth situating these findings within the wider context of renal imaging. Ultrasonography remains the most widely used modality for assessing renal size because it is inexpensive, portable and free of ionising radiation; however, sonographic measurements of renal length and

cortical thickness are operator-dependent, poorly reproducible and confined to two dimensions. The present study shows that CT, with its high spatial resolution and its capacity for true three-dimensional measurement, can quantify renal morphology with sufficient precision to track functional decline. Although CT carries the drawbacks of radiation exposure and, in many protocols, the need for iodinated contrast, the measurements reported here were obtained from non-contrast images, which minimises the risk of contrast-induced nephropathy in a population that is already vulnerable to renal injury. This makes non-contrast CT morphometry an attractive compromise between the accessibility of ultrasound and the anatomical detail of contrast-enhanced or functional imaging [14,36].

Taken together with the regression findings, these results suggest that a composite CT morphometric index could eventually function as a quantitative imaging biomarker of renal function. Such a biomarker would be most valuable in situations where serum creatinine is unreliable, for example in patients with reduced muscle mass, in acute changes in hydration, or where there is discordance between biochemical and clinical findings. A validated morphometric score could also support longitudinal monitoring, allowing clinicians to detect accelerating structural loss before it is reflected in the eGFR, and could contribute to risk stratification for progression to end-stage renal disease. The increasing availability of automated, artificial-intelligence-based kidney segmentation makes the routine extraction of these parameters increasingly feasible, and the integration of morphometric data with clinical and laboratory variables is a logical next step towards a more personalised, imaging-informed approach to the management of CKD [39,47].

The magnitude of the correlations observed in this cohort was notably high, and while this strengthens confidence in the structure-function relationship, it also warrants cautious interpretation. Very strong univariate correlations, together with a coefficient of

determination approaching unity, can, in a single-centre dataset, partly reflect the internal consistency of measurements performed by the same observers under uniform conditions, as well as the wide spread of disease severity captured across CKD stages I to V. External validation in independent populations, using blinded and standardised measurement, will therefore be essential to confirm that the relationships hold at the strength reported here. Nonetheless, even allowing for some optimism in the effect sizes, the consistent direction and statistical significance of every association across both kidneys provide robust support for the underlying biological relationship [38].

Collectively, these results support the incorporation of CT-based morphometric analysis into the assessment of patients with CKD. Because structural changes such as cortical thinning and volume loss may precede or accompany functional decline, quantitative morphometry could serve as an adjunct to biochemical staging, aiding early detection, monitoring of disease progression, and the more comprehensive evaluation of patients in whom serum creatinine alone provides an incomplete picture. The strong and reproducible correlations observed here, obtained under standardised clinical conditions, provide a foundation for the further validation of CT morphometry as an imaging biomarker of renal function [48].

CONCLUSIONS

This study demonstrated that CT-based morphometric parameters of the renal parenchyma, namely bilateral renal length, cortical thickness and renal volume, are strongly and significantly correlated with the estimated glomerular filtration rate in patients with chronic kidney disease. Renal volume showed the strongest correlation with eGFR, and all parameters declined progressively with advancing CKD stage. A multivariable model that combined these parameters explained the great majority of the variation in renal function. These findings indicate that quantitative CT morphometry is a

reliable, reproducible and non-invasive tool that reflects the functional status of the kidney and can complement conventional biochemical markers in the evaluation of CKD. Its integration into clinical practice may facilitate earlier detection of structural change, more accurate staging, and improved monitoring of disease progression.

Limitation

Several limitations of this study should be acknowledged. First, this was a single-centre, cross-sectional study that used a convenient (non-probability) sampling technique, which limits the generalisability of the findings and precludes any inference about causality or temporal progression. Second, the sample size ($n = 196$), although adequate for correlation analysis, was relatively modest and included only nine patients in stage V, which limited the power of the stage-wise comparisons at the extreme of disease. Third, the morphometric measurements were performed on non-contrast CT and may be subject to inter-observer variability and partial volume effects; inter-observer reproducibility was not formally assessed. Fourth, potential confounders such as disease duration, the degree of blood-pressure and glycaemic control, hydration status and body habitus were not fully adjusted for in the analysis. Finally, the absence of histopathological correlation means that the relationship between the observed morphometric changes and the underlying tissue pathology could not be directly confirmed.

Recommendations

Future research should validate these findings in larger, multi-centre and prospective cohorts, with population-specific reference values, in order to enhance generalisability. Longitudinal studies are recommended to determine whether serial morphometric measurements can detect structural progression earlier than changes in eGFR. Standardised and, where possible, automated or artificial-intelligence-assisted segmentation protocols should be adopted to

minimise inter-observer variability and to improve reproducibility across different scanners and institutions. Correlation of CT morphometry with histopathological findings from renal biopsy would help to establish the tissue basis of the observed structural changes. Finally, the integration of morphometric parameters with clinical and biochemical data into combined predictive models should be explored, so that CT-based morphometry can be developed and validated as a routine imaging biomarker for the early detection, staging and monitoring of chronic kidney disease.

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